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Revealing the Foggara as a Living Irrigation System through an Institutional Analysis: Evidence from Oases in the Algerian Sahara

RESEARCH ARTICLE

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ABSTRACT

The foggara in the Algerian Sahara has often been portrayed as a traditional ingenious but immutable irrigation system incapable of keeping up with the radical socioeconomic and environmental transformations of the 20th and 21st centuries. Yet, oasis populations continue to use a large number of foggaras. The aim of this study was to reveal the importance of institutions in adapting and preserving the living character of foggaras. Adapting the physical infrastructure and the institutions governing the use of contemporary foggaras are key to adapt to change, weaving different threads of tradition and modernity to maintain collective action and keep the foggaras flowing. We show that Ostrom's design principles are not only an interesting lens to explore the durability of long-standing self-governing irrigation systems, but also, when these principles are challenged, to characterize transformations of the foggara at a time of contested change.

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1 INTRODUCTION

The survival of oases in the Touat, Gourara and Tidikelt regions despite the harsh environmental conditions of the Algerian Sahara is often explained by the presence of ingenious foggara irrigation systems that bring invisible groundwater to the surface (Bisson, 2003). A foggara is typically composed of an underground channel, several hundred meters or even kilometers in length with well-shafts at regular intervals. The foggara drains the top of the phreatic aquifer and through gravity, brings the water to a distribution structure (*kasria*). This structure divides the discharge and provides a continuous supply of water to different farmers according to their water rights. For many centuries, the foggara has enabled uninterrupted irrigation and access to drinking water in hostile conditions. Similar irrigation systems with different names, continue to function in North Africa, Southern Europe, South-West Asia, China and Latin America. In Iran, for example, the *qanat* was invented some 3000 years ago and still provides 15% of irrigation water supply (Ahmadi et al., 2010).

Despite their longevity, there has been general concern in the literature about the decline of these historical systems since the beginning of the 20th century (Bensi, 2020). For instance, Beaumont (1968, 178) warned that in Iran "*a traditional system of irrigation, in balance with the environment, will go out of existence to be replaced by a modern system which will prove very easy to abuse*". Likewise, massive radical transformations took place in the Algerian Sahara following French colonization and subsequent Independence, including rapid urbanization, the discovery of oil, social emancipation, and the promotion of entrepreneurial Saharan agriculture (Hamamouche et al., 2018). In this context, many foggaras were abandoned.

Depending on their disciplinary background, the authors attributed the decline of foggaras in the Algerian Sahara to either the drop in groundwater levels linked to mechanized pumping for modern agriculture in the vicinity, or to social emancipation and the expansion of alternative, more attractive economic sectors. Researchers in the natural sciences have focused on the physical infrastructure that drains groundwater and that has the further advantage of functioning without energy by transporting the water by gravity to downstream irrigators (Remini et al., 2014). The survival of a foggara depends on a rich aquifer to ensure the continuous skimming of groundwater. Pumping in the foggara catchment area disrupts this process and threatens the existence of foggaras. From a technical point of view, the accelerated use of groundwater will eventually dry up the foggara, reducing it to an ingenious but immutable irrigation system that cannot adapt. However, this point of view disregards the existence of irrigation institutions that work to ensure the continued supply of labor and effort invested in constructing, adapting and long-term maintenance of the foggara.

Social scientists revealed the importance of social organization in explaining the long-standing functioning of foggaras and hence of the oases (Bendjelid, 2011; Marouf, 2017). Trans-Saharan trade connected the oases to the outside world and brought in a servile workforce to construct and maintain the foggaras (Scheele, 2010). The hierarchical organization of the foggara system can be qualified as social injustice, because it relied on sharecroppers, a disadvantaged social category (Vos et al., 2020). Social scientists therefore attributed the decline of the foggara to the emancipation of former sharecroppers: "[it] *becomes obsolete not because a more sophisticated technology replaces it, but because it imposes a work of servile traditions. The latter has become incompatible with the conception of dignity that the agrarian revolution had contributed to provide to everyone*" (Granier, 1980, 662). The development of modern agriculture and other economic sectors provided attractive alternative employment, especially for sharecroppers (Bisson, 2003). Otmane (2010, 264), therefore, concluded that "*over time, the foggara as infrastructure will disappear* [and] *the social life developed around it will lose its meaning*". Hence, both natural and social scientists adopted a patrimonial point of view, considering that the unchangeable foggara could only be preserved by maintaining the same infrastructure and the same social organization.

Few observers believed in the capacity of such self-governing irrigation systems to survive the rapid but deep socio-economic and environmental transformations of the 20th century. In Algeria, these analyses built on, and contributed to, a discourse on the "decline" of foggaras and, by extension, of "traditional" oasis agriculture, that was considered to be no longer adapted to modern needs (Dubost & Moguedet, 1998). It was unfavorably compared with the promising "modern" Saharan agriculture developed in new agricultural extensions outside oases using pumped groundwater. Yet, according to the National Agency for Hydraulic Resources, many foggaras are still in use today. A survey in 2016 showed that out of 2,000 foggaras in the oases of Touat, Gourara and Tidikelt, 672 functional foggaras continue to function with an average perennial flow of 1.8 m^3/s. According to the Agricultural Services, the irrigated areas in the 'traditional' sector increased from 9,800 hectares in 1980 to 15,121 hectares in 2014. A large part of these areas is irrigated by foggaras and the rest by individual or collective wells drilled in ancient oases or in the vicinity. In a surprising twist, the flows in foggaras are sometimes even boosted by groundwater pumped by the same modern devices that threatened their very existence

(Bisson, 1992). Whether or not this will result in a further drawdown of the aquifer will depend on how the pumped water is used and on whether the community is able to ban individual boreholes in the vicinity, drawing attention to the institutions governing water use.

However, the debate among local and national decision makers and scholars concerning the Algerian Sahara is still focused on "how should we preserve foggaras?" (e.g. Remini et al., 2014), when, in our opinion, other questions are forgotten, including: "are foggaras really declining?" and "how are oasis communities adapting to new conditions and constraints?" We were particularly interested in the role of institutions in shaping foggara dynamics and how these institutions have themselves changed to adapt the foggara system to external changes. The purpose of this paper is thus to reveal the importance of institutions in adapting and preserving the living character of foggaras (and thus challenge the hypothesis of general decline), thereby contributing to a wider view of their sustainability. We thus distinguish between preserving with a narrow patrimonial view (immutable physical infrastructure and institutions) and preserving by adjustment and adaptation (the living character of foggaras as announced in the title), which is the perspective we develop in this paper.

In the following section (section 2), we present the case study by describing the working principle of the foggara, its social organization and the recent changes challenging it. We then present the analytical framework we used to analyze the irrigation institutions and the methodology. We present our results (section 3) in three parts: a descriptive part with a set of case study narratives where foggaras are still active based on an ethnographic study (3.1), an analytic part where we analyze the foggara in the light of Ostrom's design principles (3.2.1), and a summary part where, based on this analysis and our observations, we explain how, in several places and in different configurations, local communities have maintained and even created new foggaras (3.2.2). In the discussion, we first challenge the hypothesis of a general decline of foggaras (4.1). We then discuss how Ostrom's design principles are adjusted and compensated for when foggaras are adapted over time (4.2). We conclude on some research perspectives.

2. CASE STUDY, ANALYTICAL FRAMEWORK & METHODS

2.1 THE FOGGARAS OF TOUAT, GOURARA AND TIDIKELT: WORKING PRINCIPLE, SOCIAL ORGANIZATION AND RECENT CHANGES

Originally, the oases of Touat, Gourara and Tidikelt were irrigated by springs and small streams located on the edges of the Tadmaït plateau. The first known foggara in the area was the Hannou foggara in Tamentit oasis, which dates back many centuries and was originally a well (Capot-Rey, 1962). Many hypotheses have been put forward concerning the origin of foggaras in the study area: "*chronicles that speak of Tamentit are imprecise or contradictory. For some, the first foggara dug at Tamentit was the work of an Arab from Egypt … for others, these foggaras were dug by the Barmakids. Muslims of Iranian origin, they are supposed to have come to North Africa after the fall of the empire of Harun al-Rashid*" (Capot-Rey, 1962, 227).

Foggaras were often created as small-scale irrigation systems by individuals or small family groups (Bisson, 1957). Many foggaras still bear the name of the original pioneers. Out of the 687 still functioning foggaras, more than 200 are named after a person, a family or a tribe. With time, ownership changed and because there were many heirs, foggaras gradually became collectively managed irrigation systems, but also because they progressively included some non-owners, such as the sharecroppers, who helped maintain and/or extend the foggara.

A foggara is a gravity irrigation system that captures the top of the groundwater table and distributes water to those who own water rights to irrigate oasis agriculture. The operating principle of the foggara is theoretically simple but requires particular know-how and hard work to construct it and maintain it operational. A foggara consists of an underground gallery built on an incline that captures the superficial groundwater table, and includes well-shafts for ventilation and maintenance (***Figure 1***). The gallery is often several kilometers long with well-shafts located 5 to 12 m apart. The well-shafts are a few meters to tens of meters deep depending on local physical conditions. The groundwater is transported through the gallery to the surface by gravity. At the surface, the water distribution device (*kasria* or comb) divides the running water into shares that are proportional to the different owners' water rights and a continuous flow of water is delivered to each owner through unlined canals (*seguia*). A slow drop in the groundwater table, and consequently a diminishing discharge, is inherent to the foggara, which only exploits the top of the shallow aquifer that is scarcely replenished. To increase the foggara flow, the gallery has to be deepened or the upstream part of the gallery extended. When a gallery becomes too deep, the water no longer reaches the oasis by gravity and the community has to use a manual water lifting device or to cultivate lower-lying plots that continue to receive water by gravity. In case of failed aquifers, the foggara dried up completely and the whole village (*ksar*) would have to move away to look for water elsewhere. In other words, the physical infrastructure of a foggara had to be constantly adapted, either to compensate for a diminishing discharge or for increased water demand.

The irrigation institutions in the Touat, Gourara and Tidikelt oases govern the operation and maintenance of

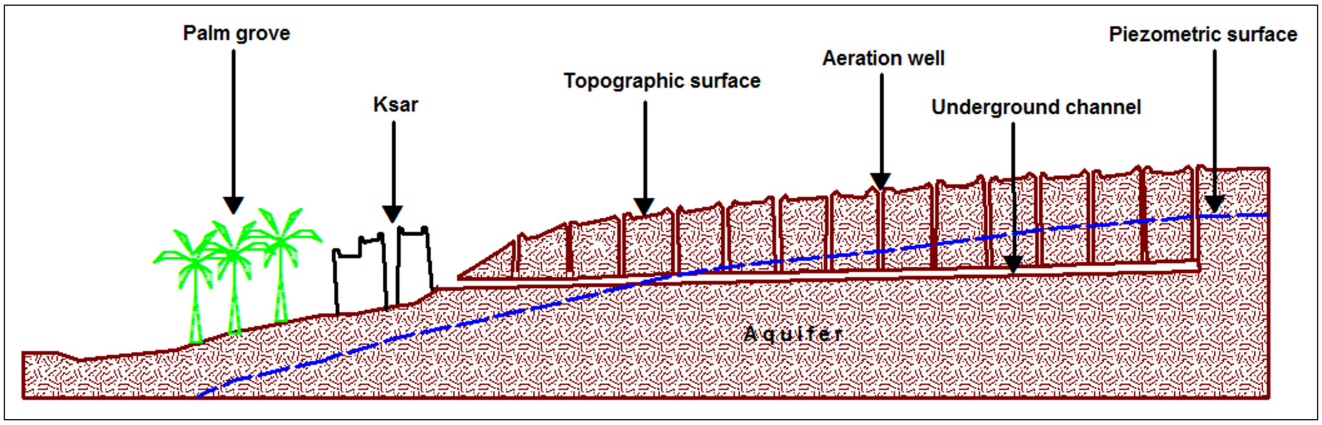

Figure 1 Longitudinal section of a Foggara (adapted from Remini et al., 2014).

foggaras. The *djemâa* is the first authority of the oasis. It is an informal local council that includes influential people and religious figures in the oasis. The task of the *djemâa* is to solve problems and conflicts related to foggaras and, more generally, all aspects of oasis life. Before referring to the *djemâa*, problems that arise concerning the foggara are first handled by the "owners" of the foggara and their leader. These owners (and their ancestors) usually contributed to the construction and maintenance of the foggara and have clearly defined water rights. The leader is generally someone known for his initiative and perfect knowledge of the physical and organizational infrastructure of the foggara. The leader turns to the *djemâa* when a problem cannot be resolved among foggara owners.

The *zawiya* (or religious center) serves as a religious authority and can be referred to for arbitration if the foggara owners and the *djemâa* are unable to solve the problem. The *zawiya* is managed by a *Cheïkh* or *Mokaddem*, who is often a descendant of the holy founder, an influential and respected person in society and a member of the *djemâa*. The *zawiya* plays an important role in the stability of the oases in the entire region.

The oasis society in Touat, Gourara and Tidikelt is stratified and comprises two main social categories: 1) the main land and water owners are noblemen belonging to three main ethnic groups (*Chorfa, Mrabtine and Ahrar*); and 2) sharecroppers (*khammes*), who were disadvantaged and owned only a minor proportion of land and water shares (Marouf, 2017, 9), have a good know-how of oasis agriculture and of maintenance of the foggara.

Since the 1970s, the State has implemented wide-ranging agricultural development programs alongside existing oases for the benefit of the peasants who previously depended on using foggaras. Many former sharecroppers saw these extensions as a means for social emancipation and as a way to challenge existing social hierarchies by obtaining access to land and water (Hamamouche et al., 2018). Agriculture in these extensions is generally based on the individual exploitation of pumped groundwater through subsidized boreholes enabling irrigation of larger areas than that irrigated by the foggaras. In parallel, the State established a limited number of programs to rehabilitate foggaras on the explicit condition that the community would set up new, and more formal, associations for their management. These associations enact more democratic procedures through the election of a managing board and a president.

Collective action plays a key role in maintaining the foggara well-shafts, gallery and periodically, the unlined canals (*seguia*). All the actions undertaken for maintenance, water sharing, and conflict resolution are dictated by rules that all irrigators must respect. Today, foggaras are changing as they have to compete with more powerful pumping techniques outside the oases. The co-existence of the "traditional" and the "modern" system can lead to problems as the new irrigation schemes have caused 1) a remarkable drawdown of groundwater tables, 2) the sharecroppers are no longer interested in the foggaras, and spend less time keeping the foggaras functioning since they are now farming in the extensions or have migrated to cities. Both these problems have led to a decrease in the flows in foggaras (Bisson, 2003). However, the strategies used by irrigators to preserve and adapt the foggara in reaction to the new agricultural extensions may also be inspired by the extensions, both in terms of infrastructure (e.g. the use of boreholes to reinforce the flow of foggaras) and irrigation institutions (e.g. the recognition of former sharecroppers as water owners). While such interventions run counter to the dominant romanticized perception of foggaras as an 'immutable' cultural heritage that needs to be preserved, we argue that such interventions are precisely about keeping them alive.

2.2 USING OSTROM'S DESIGN PRINCIPLES TO ANALYZE THE RESULTS OF AN ETHNOGRAPHIC STUDY

We first conducted an ethnographic study on foggaras in the oases of Touat, Gourara and Tidikelt. In line with well-established analytical approaches to community-managed

irrigation systems, we associated "*an anthropological approach to societies built around irrigation with a more strictly technical reading of the irrigation systems implemented by these societies and the knowledge that they imply*" (Bédoucha and Sabatier, 2013:45; see also Van der Kooij et al., 2015; Aubriot et al., 2018). We visited a selection of oases of the area using foggaras and analyzed jointly the history and recent changes of the physical irrigation infrastructure, current practices of water distribution and maintenance of the foggaras, together with the knowledge and social organization of the communities around water. This study, compiling data from different sources (literature, interviews, observations, see Section 2.3) provided us with a thorough understanding of this particular hydrosocial territory (Boelens et al., 2016), both from the inside through the eyes of a geographer who lived all his life in these oases and conducted most of the field visits and interviews (the first author), and from a more distant and comparative perspective through the eyes of the other authors who also visited these same oases. From this first phase, we appreciated a diversity of adaptations of foggaras which are illustrated by a selection of emblematic case studies from two oases presented as the first part of our results (see Section 3.1).

Based on the information gathered in the first phase, the second phase consisted in an institutional analysis using Ostrom's Design Principles (DPs) (Ostrom, 1990, 1993) motivated by different reasons. First, we consider these principles to be an interesting lens to explore the long-enduring foggaras irrigation institution as a self-governing irrigation system. The aim of our analysis was not to measure whether or not foggaras comply with all the design principles but rather to organize the knowledge gathered about the sustainability of the foggaras. Garrido (2016) warned against erecting the design principles as a necessary coherent requirement for long-term irrigation institutions. Using the case of Valencia, on which Ostrom's framework (partly) relies, Garrido demonstrated that even when not all the DPs are fulfilled, irrigation institutions are very resilient. By analyzing the irrigation system in the light of Ostrom's DPs, he concludes that "*granted that the commons are not condemned to an unavoidable 'tragedy', one should not over-idealize them either, at the cost of turning them into myths*" (Garrido, 2016, 128). Nevertheless, we argue that a dialogue between field realities and Ostrom's analytical framework is a powerful way to understand the role of institutions in ensuring the sustainability of irrigation systems. We intentionally include in our analysis the political and socio-economic linkages between foggara communities and the outside world, as most assumptions underlying DPs need to account for such connections (Tang & Tang, 2001).

Second, we posit that the DP lens can reveal institutional changes at a time of particular and contested change, this being the case of foggaras, which are threatened by a rapid decline in groundwater tables as well as social emancipation. This is counterintuitive, as Ostrom (1990, 69) defines a long-lasting irrigation system as one that has been in operation for several generations, at the core of which the DPs maintain the irrigation infrastructure and ensure the compliance of the community with rules-in-use. However, we argue that the DP lens, which is subject to stress in periods of rapid change, provides for interesting reading of rapidly evolving institutions. Moreover, the introduction of pumped groundwater in foggaras dates back to the early 1990s in our study area, providing the chance to read these DPs under stress for a period of nearly thirty years, that is, more than a generation.

The purpose of our research was thus to document our analyses of recent adaptations of foggaras in Touat, Gourara and Tidikelt and to use Ostrom's DPs to reveal the complex interactions and adaptations that take place in infrastructure, institutions, and social organization of foggaras from an institutional perspective. We analyzed a number of case studies where foggaras are either still maintained, have been transformed by introducing pumped groundwater, or even newly created, to understand how local communities keep foggaras alive, by restoring or by finding an alternative to the potential loss of a DP that was respected in the past or was compensated for and that would be threatened by recent changes in the area.

2.3 METHODS AND DATA COLLECTION

We used three kinds of resources for this study:

a- The literature focusing on social, economic, and hydraulic aspects of foggaras to understand the organization of shareholders, the construction and maintenance of foggaras, water sharing rules, and finally, conflict resolution mechanisms. Literature included scientific papers, government reports and personal archives of stakeholders.

b- Semi-structured interviews were conducted on the maintenance/construction of foggaras and water sharing with 18 leaders of foggara associations, traditional leaders, and local experts from oases in Touat, Gourara and Tidikelt during the period July to September 2016. Four meetings were held with these experts to discuss the adaptations of rules, norms and strategies in foggaras in the face of recent socio-economic and groundwater transformations. We also held meetings with government agents entrusted with projects on current and future rehabilitation of foggaras, who supplied us with statistical data.

c- Since 2010, we have conducted several field surveys to thoroughly understand current adaptations of foggaras. Between July and September 2016, we

surveyed 18 foggaras located in 13 oases in the Gourara, Tidikelt and Touat regions (see ***Figure 2***). The sample was selected based on geographical criteria, the presence of new irrigation schemes in the vicinity and the state of the foggaras (permanent or with problematic water flows).

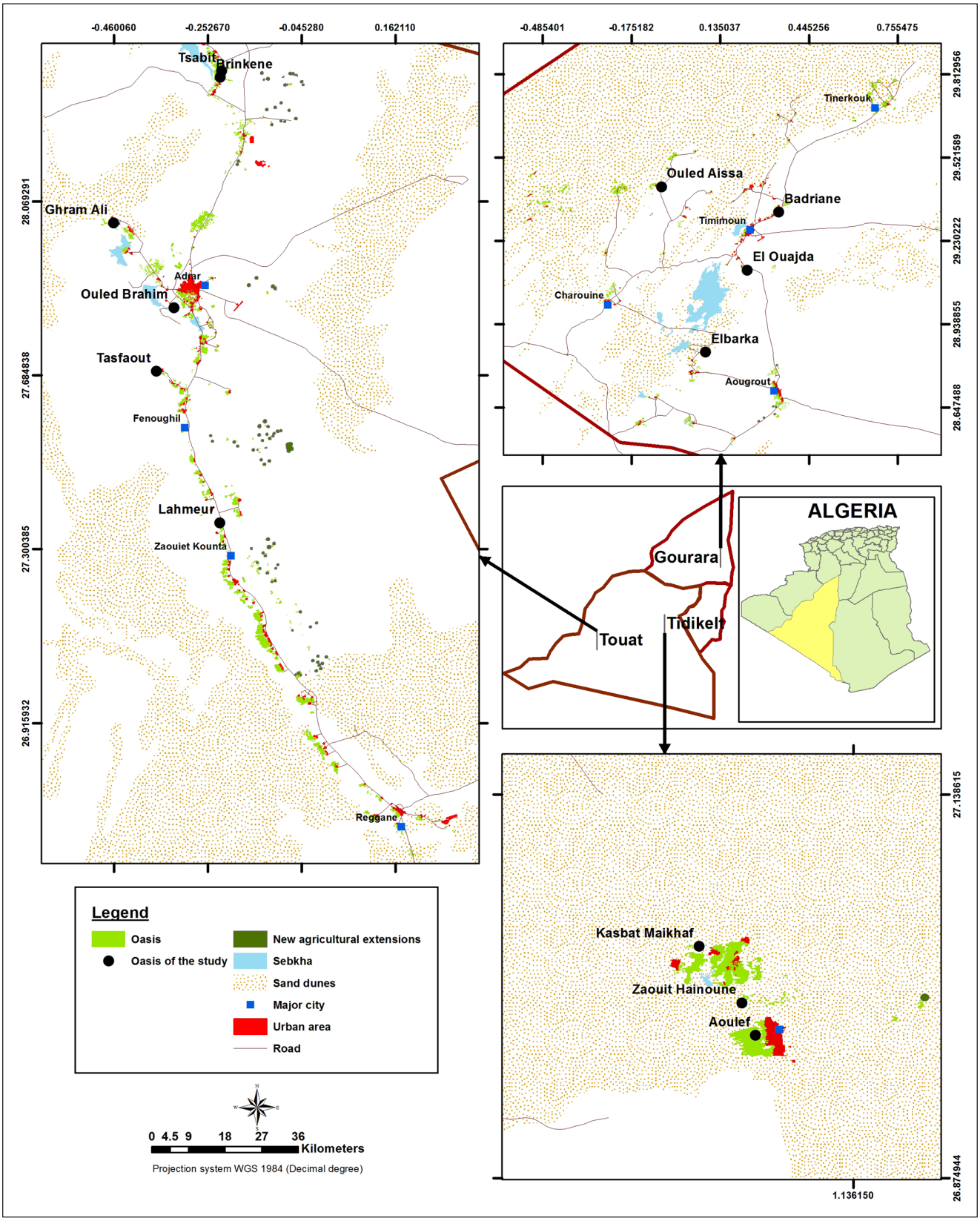

Figure 2 Map of the study area.

3 RESULTS

3.1 CASE STUDIES OF FOGGARAS ADAPTING TO CHANGE

Before analyzing the foggara in the light of the commons theory, we present some cases where foggaras have been adapted over the past decades and are still used for irrigation today. We will present the different challenges faced by communities to keep the foggaras alive and the adaptations they devised to address these challenges. We focus on two oases, Tasfaout and Ghram Ali, but we compare these two cases with observations made in eleven other oases (***Table 1***).

3.1.1. The Tasfaout oasis: keeping foggaras alive by giving sharecroppers water shares

When we visited the Tasfaout oasis (40 km south of Adrar city) in August 2016, maintenance works were underway on three foggaras. Maintenance had been in progress for

FOGGARA	OASIS	REGION	CHALLENGES FACED	ADAPTATIONS MADE
– Cheman	– Tasfaout	– Touat	– Individual wells in catchment area – Exclusion of sharecroppers from water rights	– Formal ban on wells – Sharecroppers provided with water rights – Maintenance carried out by owners and sharecroppers
– Ouled M'hammed	– Brinken	– Touat	– Individual wells in catchment area – Exclusion of sharecroppers from water rights – Sharecroppers refuse to carry out maintenance	– Formal ban on wells – Foggara owners learned how to do maintenance
– Saiba	– Tsabit	– Touat	– Exclusion of sharecroppers from water rights	– Waiting for court decision
– Akhabi	– Badriane	– Gourara	– Exclusion of sharecroppers from water rights	– Waiting for court decision
– Guermekker	– Ghram Ali	– Touat	– Exclusion of sharecroppers from water rights – Diminishing discharge	– Sharecroppers provided with water rights – Maintenance carried out by owners and sharecroppers – Borehole installation
– Amrane – Takareft – Abbou – Aït Wamane	– Lahmeur	– Touat	– Exclusion of sharecroppers from water rights – Diminishing discharge	– Sharecroppers provided with water rights – Maintenance carried out by owners and sharecroppers – Borehole installation
– -Ben Drâou	– Kasbat Maikhaf	– Tidikelt	– Attractivity of jobs in tertiary sector – Labor shortage for maintenance	– Paid labor, mainly carried out by students of owners' families
– Ighjar	– Zaouit Hainoune	– Tidikelt	– Attractivity of jobs in tertiary sector – Labor shortage for maintenance	– Paid labor, mainly carried out by students of owners' families
– Arkes	– Ouled Brahim	– Touat	– Conflict over water shares with sharecroppers – Sharecroppers refuse to carry out maintenance – Reduction in discharge	– Owners collect money – Maintenance carried out by paid labor
– Elfidilia	– Elbarka	– Gourara	– Reduction in state subsidies for maintaining foggaras – Sharecroppers refuse to carry out maintenance – Reduction in discharge	– Owners collect money – Maintenance carried out by foggara owners and by paid labor
– Tourfine	– Aoulef	– Tidikelt	– Flood damage foggara	– Owners collect money for rehabilitation, calling on village community solidarity – Oasis community solicits state support
– Boussaid – Mahri – Goujdil	– Ouled Aissa	– Gourara	– Sharecroppers & owners invest in agricultural extensions, abandoning foggaras – Reduction in state subsidies in extensions	– Rehabilitation of foggaras and adaptation of rules – Installation boreholes
– Kbira	– El Ouajda	– Gourara	– Sharecroppers refuse to carry out maintenance – Attractivity of jobs in tertiary sector	– Foggara owners learned how to do maintenance – Formal ban on wells

Table 1 Challenges faced by and adaptions made in the studied foggaras.

more than 40 days on the biggest foggara (Cheman, see ***Table 1***) with a flow of 12 l/s (ANRH, 2011). Sixty-five owners were organized in teams and everyone had to take part or pay a worker to replace him. Each team had to work for a specified number of days and all the well-shafts and the gallery had to be maintained. The teams were mainly composed of young people accompanied by old men with more experience and know-how (***Picture 1***).

Interviews with foggara owners revealed that sharecroppers had obtained water rights to the foggara through complex and sustained negotiations, despite continued disagreement between the two social categories in the oasis. Noblemen drew their power from belonging to the original group of foggara owners and from the creation of the formal foggara association, approved by local authorities, while former sharecroppers were indispensable because of their know-how and the labor required to maintain the foggara. All owners of water shares, noblemen, and sharecroppers alike, now have to participate in the works, revealing a change in local norms (***Table 1***). According to an old sharecropper: "*contribution is mandatory… otherwise, the person is reported to the djemâa and is then poorly regarded by society*."

Foggara dynamics in the Tasfaout oasis are also influenced by the fact that owners protect the foggara by limiting other farmers' access to groundwater through individual boreholes. In the past, families who had no share or only a small share in the water from the foggaras tried to create a new irrigation scheme upstream of the oasis as part of State-led agricultural development programs. All these initiatives met with outright refusal from foggara owners, who justified their refusal by the impact of boreholes on foggaras observed in other oases. However, this meant they were obliged to deal with conflicts due to sharecroppers' limited access to foggara water and the fact that it was impossible for them to obtain access to pumped water. As a result, the ownership of the foggaras was progressively broadened to include sharecroppers by extending the physical network. In turn, the sharecroppers remained very active in maintaining the foggaras, which even increased the discharge, but also obliged the former noblemen to pay the workers who undertook the maintenance.

Similar tensions between different social categories can be observed in other oases. In Brinken oasis (***Table 1***), located northwest of the city of Adrar, a dozen foggaras are still working, even though sharecroppers still do not have any water shares. Some of the sharecroppers dug wells upstream of the oasis close to foggaras, but they were never able exploit them because the foggara owners objected. Today, the descendants of foggara owners do the maintenance themselves, and continue to exclude former sharecroppers from access to foggara water. In many cases, including the oases of Tsabit and Badriane (***Table 1***), the social conflicts are still waiting for court decisions.

Picture 1 Two young men (one inside the well, not visible in the photo), accompanied by an elder, on duty maintaining a well (August 2016).

3.1.2. The Ghram Ali oasis: supplying pumped groundwater to foggaras and arranging for paid family labor

Since 1991, the Guermekker foggara in Ghram Ali oasis (see ***Table 1***), located 20 km from the city of Adrar, has been supplied with groundwater pumped through a borehole, operated by solar and wind power. The pumped water is connected to the main foggara channel, and the water sharing device (*kasria*) and water distribution are still subject to the former rules. In fact, institutional changes already occurred before the introduction of pumped water, as sharecroppers had been progressively included as foggara owners and consequently entitled to a water share. Whenever the foggara discharge dropped, requiring rehabilitation, the sharecroppers would negotiate water shares as a counterpart for their work and know-how. A contemporary manifestation of this negotiation was observed in nearby Lahmeur oasis (Idda et al., 2017). The sharecroppers had been very active in obtaining State support for the construction of a borehole to supply pumped groundwater to five foggaras in 1992. In return, they negotiated increased water shares of the now operational foggaras.

The inhabitants of Ghram Ali oasis are attracted by work in other sectors in the nearby city of Adrar. Out of 33 foggara owners we interviewed, 17 are employed in State administrations, meaning that half the labor force is now occupied elsewhere. To ensure maintenance, each owner makes a financial contribution and the foggara leader recruits employees from the families of the foggara owners, so it is basically paid family work. According to the leader of the foggara, all the members had paid for the maintenance works done in July 2016.

A similar situation was observed in the oases of Kasbat Maikhaf and Zaouit Hainoune (***Table 1***), where the foggaras are maintained less frequently, i.e., not every year. The total cost is estimated and each owner pays a contribution that is proportional to his water shares (*habba*). In 2016, for example, each owner paid about US$0.9 per *habba* for the maintenance of the Ben Drâou foggara and US$0.55 for maintenance of the Ighjar foggara. According to a foggara leader, only student members of owners' families are recruited, as "*this allows our know-how to be transmitted to young people and helps their families purchase school supplies*".

These are examples of the dynamics and adaptations to foggaras in Touat, Gourara and Tidikelt, despite a modernist discourse in the public and scientific arenas, portraying foggaras as a traditional immutable object related to an ancient way of life. In reality, adaptation is an ancestral characteristic of the oasis community in general and of foggaras in particular. Different parts of the foggara can be adapted, including, as we saw in the above examples, the infrastructure, the social and economic organization, and the rules-in-use. Wells and boreholes were dug to overcome aquifer drawdown and topographic constraints. To maintain the workforce, foggara owners allowed sharecroppers to obtain water shares and land ownership or trained their descendants to further develop and maintain foggaras. The main objective is to maintain agricultural activity, which is indispensable for food security, but which is also a symbol of identity and well-being for peasants, and results in the upkeep of the oasis palm groves and gardens. It is therefore not surprising that strong and efficient institutions have been set up to maintain foggaras as a source of life.

3.1.3. Renewed interest in foggaras

In several oases we visited between 2015 and 2016, we observed renewed interest in foggaras their owners had sometimes neglected for more than a decade. In Ouled Brahim oasis (***Table 1***), for example, following a conflict over the water shares and in the wake of economic development in nearby Adrar city, the owners had not contributed to maintenance of the Arkes foggara since 1986. In 2015, following a reduction in flow rates, they collected money for the maintenance of the underground gallery for a period of two months. Similar renewed interest was observed for foggaras in the Elbarka oasis (***Table 1***).

An emblematic example is the Tourfine foggara in Aoulef oasis (***Table 1***) which is 12 km long and in 1998 had a flow rate of 11 l/s. The foggara and the plots were abandoned following silting up caused by floods in 2009. In 2015, the owners created a formal association to claim State support for rehabilitation of the foggara. They chose the oasis imam as the leader of the association. They started with the contribution of money based on water shares. The originally planned contribution of US$12 for shares of more than 10 units (*habba*) and US$8 for shares of less than 10 units turned out not to be sufficient for rehabilitation. They then gave all the oasis inhabitants the right to finance the works and subsequently obtain a bigger share of the water flow than they had of the former water flow. In the words of the imam, "*to encourage this operation, we did not give it an economic character, but instead focused on solidarity. We said that the participants would make a profit in the case of surplus water; otherwise, God would reward them for their contributions to the safeguard of a public good which is the only resource for some poor families*".

Similarly, in the case of the Ouled Aissa oasis (***Table 1***), agricultural plots and foggaras were no longer maintained properly after a new agricultural extension was established in the 1980s. Foggara owners were tempted to farm outside the old oasis attracted by State subsidies. Two decades later, many owners returned to their old plots because of

difficulties of individual work in the newly created extension and the reduction of State subsidies for small-scale farmers. This return was accompanied by new individual or collective boreholes or by adapting and adjusting the institutions of foggaras. In the following section, we observe these changes through the lens of Ostrom's design principles.

3.2 RECENT ADAPTATIONS TO FOGGARAS IN THE LIGHT OF OSTROM'S DESIGN PRINCIPLES

Foggaras qualify as long-lasting self-organized irrigation systems (Ostrom, 1990, 1993). This can be explained by their capacity to adapt to environmental and socio-economic changes. The first particularity of a foggara, which exploits the top of the shallow aquifer, is that water resource overexploitation is inherent to its design, materializing through reduced discharge, which then requires extension or deepening of the gallery. In the past, the reduction in discharge was generally slow and communities had time to carry out such labor-intensive adaptations to the infrastructure. In parallel, they often re-negotiated water ownership in such circumstances with the aim of acquiring extra labor to extend and maintain the foggara. The sustainability of foggaras is, therefore, mainly related to maintaining collective action in adapting the foggara in a hostile environment. Today, as the agricultural extensions use modern pumping techniques in a context of social emancipation and economic transformations, groundwater decline happens more rapidly, and communities thus have to react faster. We will use the lens of design principles to, first, understand the longevity of foggaras, and second, to show how foggaras have been adapted over the past 30 years, even though these design principles have been seriously challenged by the pace of events.

3.2.1 Reading foggaras through the lens of design principles

Clearly defined and continually adjusted boundaries

The water shares of a foggara used for irrigation belong to those who sponsored the construction of the foggara, and their descendants. However, all oasis inhabitants can use the water for domestic use. This means that all inhabitants of the oasis have a stake in maintaining the flow of the foggara. The water flow is generally stable in the short term but will decrease if wells are dug or other foggaras are created in the catchment area. The community therefore identifies a protection area where all further exploitation of water is prohibited on the basis of traditional techniques. One of the techniques used to determine the resource boundaries consists of putting tar in a suspected well. A taste or smell of tar in the foggara in the following days is proof the groundwater resource is being tapped and the suspected well will be prohibited for further exploitation.

Interestingly, while the resource boundaries and those of the users are clearly defined (the first design principle), the foggara institutions are geared towards incorporating change in the resource and users' boundaries. New members can obtain a water share in three ways. First by inheritance, leading to successive subdivisions of plots and water shares, but no impact on the foggara flow or on the extent of the irrigated area. Second, members can sell, rent, and trade water shares to other irrigators or donate all or a part of their water shares to religious institutions. Third, in the case of a decline in water flow or the need to increase the water flow, foggara owners can agree to expand its infrastructure, thus enabling, perhaps counterintuitively, the inclusion of new water owners who, through their contribution in labor force, will make the expansion possible. This was the case in Tasfaout oasis described in the previous section, where sharecroppers became foggara owners in exchange for their labor in extending and maintaining the foggara.

Congruence between appropriation and provision rules

Following Cox et al. (2010), we distinguish two sub-principles for this second design principle. Sub-principle 2A assumes congruence between the capacity of the natural resource system to provide water and the appropriation rule. The particularity of the foggara is that such congruence is a dynamic process of continuous adjustment of the foggara to the resource base. By design, it is sensitive to changes in the water tables, as it provides a flow that drains the aquifer according to its level: the greater the decrease in the water level, the greater the decrease in flow. Typically, even when community users decided to make just a small increase in the foggara flow, extending the foggara required considerable labor and investment. These days, the resource base can be extended by installing a deep tube-well with the help of the State. However, obtaining State authorization and a subsidy is equally a difficult and time-consuming process (Idda et al., 2017).

The sub-principle 2B is often interpreted as congruence between the costs incurred by users and the benefits they receive (Cox et al., 2010). Each member of the foggara receives a water share proportional to his contribution in constructing and maintaining it (Hamadi, 1982). This happens, first, when a group decides to collectively dig a new foggara. The water shares are decided based on the work carried out by each member, and in practice, on the number of workers recruited. Second, when the foggara is extended and new members are included, each member is responsible for digging part of the extension. Generally, the new members receive 50% of increase in the water flow and the rest goes to the community. When the extension is difficult to achieve, arrangements may be made to provide

more than this proportion to new members.

Water sharing in foggaras is about allocating a proportion of the discharge to each user, depending on his contribution (and often of his ancestors) to the construction and rehabilitation of the foggara. The water distribution is, therefore, based on providing a continuous discharge to each user. Foggara water is shared between users in a small triangular sharing basin with openings named *kasria* (comb). The widths of these openings are proportional to water shares. This particular sharing technique ensures continuous water flow and a permanent water share for each peasant, enabling daily irrigation. If the discharge of the foggara is 10 l/s and there are 24 water owners, for instance, one of the owners may have 1/8th of the discharge (1.25 l/s), a second one 1/24th of the discharge (0.42 l/s), a third one 1/48th of the discharge (0.21 l/s), and so on. The distribution of the foggara water is occasionally checked using a copper plate (*louh*) with holes of several dimensions that represent measurement units (see ***Picture 2***). This task is performed by the water master (*kial al-ma*)[1] using the *louh*, assisted by an accountant (*Hassab*) with experience in calculating water shares. Water shares are logged in a register (*Z'mam*) kept by noblemen or by a religious representative (the *Imam*).

Annual gauging is undertaken to control shares and make changes in the case of water sales or inheritance. Each foggara has a theoretical flow, which was measured when the foggara was first constructed, and a real flow, which changes with each new gauging. Water shares are proportional to the original discharge and are all adjusted proportionally depending on the real discharge.

Collective-choice arrangements: the crafting of rules concerns the larger oasis community

This third principle states that all users can participate in crafting the rules. While some rules are crafted locally by foggara users, most rules are common to all foggaras in Touat, Gourara and Tidikelt. The crafting of rules involves the larger oasis communities, because foggaras are essential to the survival of oases by providing drinking water to all. In particular foggaras, the village elders represented in the *djemâa* often have to deal with delicate situations (reduction in flow, lack of maintenance, collapse, rules are not respected, conflicts) at the request (or not) of the foggara leader. Except in critical conflicts that require meetings behind closed doors, all users can attend the meeting. Foggara owners and village inhabitants alike can suggest solutions that are often based on jurisprudence in the area concerned. Inhabitants sometimes express solidarity by offering to participate in kind (work) or give cash.

Monitoring

The fact there are no water turns in foggaras reduces the need for monitoring of water sharing, which is the fourth design principle. The only part of the foggara that requires

Picture 2 The flow measurement device (*louh*) is used by the water master to check the water shares of different water owners of particular foggaras (April 2017).

control is the water distribution structure (*kasria* or comb), where water distribution is physically enshrined in the openings of the comb. Water owners, and other community members often drop by to check the comb and to remove any objects that could hinder the flow of water. The slightest physical change in the comb openings is subject to investigation. Typically, the *kasria* is then checked by a respected member of the community and discussed by all group members. Monitoring participation in maintenance is another essential point and is usually carried out by the group leader with the assistance of all the members. For both aspects, monitoring is not attributed to a designated controller, as this would entail additional costs, but is the collective responsibility of the inhabitants of the oasis.

Graduated sanctions

As foggaras were formerly the only system that provided water for drinking and for agriculture, violation of rules was limited in the past, and remains so even today. The non-participation of a member in maintenance activities generally has a plausible explanation (e.g. illness), that is understood by the other group members. In the case of an offense, sanctions are first applied by group members and include seizing agricultural produce or paying a fine proportional to the severity of the offense. The sanction can never include reducing the water share or excluding the member from the foggara, as this would endanger the life of his family. However, as shown in the case of Tasfouat, for peasants, reporting an offense to the village djmâa (which can be considered a graduated sanction, the fifth design principle), is a substantial threat, as they fear for their social reputation.

Conflict-resolution mechanisms

As explained in the preceding section, conflicts have occurred regularly throughout the long history of foggaras and conflict-resolution mechanisms (the sixth design principle) are well established. These conflicts are often the result of different interpretations of rules or of particular social and environmental challenges, for example antagonism between different social categories, and are resolved in different socio-institutional arenas. The first arena involves the foggara owners, where most conflicts are first discussed. The second arena is the village *djmâa*, as all villagers have a stake in the foggara. A regional religious institution (*zawiya*), is contacted for arbitration only when these first two arenas are unable to deal with a conflict. Similarly, certain religious scholars and judges, historically based in the Tamentit oasis (Touat), can be called on for conflict resolution in foggaras, however today, the modern judiciary is increasingly called on for arbitration.

Minimum recognition of rights to organize

This seventh principle requires that external authorities recognize the users' right to devise rules for foggaras. Historically, the oases in our study area were caravan relays between North and West Africa. Water owners had the right to self-organize but always within the standard norms of the area. This explains the relative homogeneity of design principles of different foggaras in the area which also allowed communities to solve their conflicts and problems by taking advantage of the experience acquired in other oases. Foggaras are still self-organized irrigation systems today. When the State rehabilitates foggaras, it requires farmers to set up a formal association, but it does not impose a change in the rules-in-use. On the contrary, by funding rehabilitation and maintenance works, the State indirectly recognizes these 'traditional' irrigation systems.

Nesting

Nesting refers to the organization of foggaras in several hierarchical stratified levels, representing the eighth design principle (Ostrom, 1990). We have shown how foggaras are institutionally embedded in the oasis, as the owners of the foggara (and their leader) refer to the village authority (*djemâa*). Indeed, foggaras are not only important for the survival of the gardens of the oases, but also through the supply of drinking water. We have also shown how in turn, these oases are part of the larger region through an ensemble of widely shared norms and design principles (for example pertaining to conflict resolution).

3.2.2 Institutional adjustments to adapt to recent changes

Socio-economic changes in the Sahara have profoundly altered the way the foggara works. The functioning of some foggaras was challenged as some design principles were no longer respected, but there have also been cases where these challenges were overcome through institutional adjustments of the community (***Table 2***).

In what follows we will explain some of these challenges (and the way they were dealt with) in more detail.

Resistance to violations of the 1st design principle

The oasis communities of Tasfaout, Brinken and El Ouajda opposed the creation of a state-sponsored irrigation scheme in the foggara catchment area, and thus ensured that the boundary of their resource base was respected (see ***Table 2***). This reveals resistance by the community to violation of the 1st design principle (clearly defined boundaries). However, the community then had to deal with internal social conflicts, because, first, the former sharecroppers had no rights to foggara water for irrigation,

DESIGN PRINCIPLES	CHALLENGES TO DESIGN PRINCIPLES	INSTITUTIONAL ADJUSTMENTS
1. Clearly defined and continually adjusted boundaries	Installation of individual (often state-sponsored) boreholes in catchment areas of foggaras	Ban on boreholes Including sharecroppers as foggara owners
2. Congruence between appropriation and provision rules	Providing pumped groundwater to foggaras, breaking the link between available water resources and use	Favor frugal irrigation by sharing water over several foggaras Ban on installation of other boreholes
3. Collective-choice arrangements	Sectoral approach to water by the state separating drinking water supply from irrigation	Maintain the community interest in foggaras
4. Monitoring	Physical rehabilitation changing the hardware of the foggara	Preserve water distribution device for monitoring
5. Graduated sanctions	Local norms related to social reputation weakened by state judiciary	Social reputation remains important, but the community has difficulties to apply graduated sanctions
6. Conflict-resolution mechanisms	State legal power weakening community conflict-resolution mechanisms	Creation of formal associations crafting new rules that are socially constructed and recognized by the state
7. Minimum recognition of rights to organize	The state does not recognize community institutions and requires users to create a formal association	Users take the official framework of association to continue crafting rules
8. Nesting	Ageing of regional water masters and potential loss of their knowledge and capacity of arbitration	For the time being, the water masters are still called upon, but their succession is not assured.

Table 2 Synthesis of the challenges to design principles and institutional adjustments to these challenges by the community.

and second, they were not allowed to dig wells in the new irrigation scheme. In the end, the sharecroppers were included as foggara owners, providing them access to the resource base.

Adapting to the elimination of the 2nd design principle

In places with groundwater drawdown, the State provided subsidies to support some foggaras with pumped groundwater. This has implications for principle 2A, as there is no longer congruence between available water resources and water use with groundwater tables declining much faster than they would under the classical foggara (***Table 2***). However, field evidence shows that communities persist in what can be called "frugal" irrigation. In Lahmeur oasis, for instance, the pumped groundwater was shared between five foggaras and discharges of these foggaras remain close to usual flows (Idda et al., 2017). Also, the community prevented the installation of individual boreholes in the catchment area (***Table 2***). This explains why the borehole, installed in 1992, is still functioning more than a generation (almost 30 years) later. There is a decline in groundwater tables, but the community has managed to control the speed of the decline.

Second, constant water flow results from an external factor, i.e., the State subsidizing the boreholes, and no longer depends on collective action, which implies that design principle 2B is no longer fulfilled. However, close observation shows that the congruence of costs and benefits of users is maintained, as former sharecroppers, who were active in obtaining the financial support of the State through social mobilization, were allocated new water shares by adjusting the rules-in-use (***Table 2***). Moreover, a new formal water users association was created to manage the borehole, while maintaining the informal community organization (group of foggara owners and *djemâa*) for the distribution of water (Idda et al., 2017). The new association and its rules formalized the State intervention, while linking it to the local (informal) governance of the water use. The lens of design principles is thus a good tool to reveal the power of institutions and their flexibility in overcoming constraints and avoiding conflicts.

Adapting to the challenges to the 6th principle

Due to the legal power of the State and new job opportunities that offer economic alternatives, enforcing the application of community rules is becoming increasingly difficult. In some cases, foggara owners are no longer able to apply the classical sanctions to members who violate management rules through the habitual conflict-resolution mechanisms (principle 6), because of State regulations (***Table 2***). The traditional community organization (*djemâa*) has consequently weakened. To maintain foggaras, and in response to the formal demands of local State authorities, peasants organized themselves in formal, State-approved, water users associations. Some individuals or social categories (young peasants or sharecroppers), who felt marginalized in the traditional institutions, would engage with formal associations, for example by presenting themselves as candidates for election to the board. The establishment of new formal institutions

governed by formal rules alongside the local institutions, considered informal, created many difficult situations and conflicts. Generally, these water users' associations never completely replaced the traditional institutions, and the situation can be qualified as co-habitation of formal and informal institutions (see Bekkari & del Castillo, 2011, for a similar case in community irrigation in Morocco). These associations were required by the State as a condition for receiving aid for the rehabilitation of foggaras and adopted by the communities, but the association's role was often limited to complying with administrative procedures. Once the rehabilitation was complete, the communities would revert back to informal organization to manage the foggara. However, these local institutions adjusted to the new context, for example by including former sharecroppers in the group of owners, or by using paid family labor. Such adjustments can be partly attributed to the co-existence with modern institutions that may represent a threat to the former leaders of traditional institutions, or simply a source of inspiration. The associations strengthened the hand of marginalized social groups in their long-standing negotiation with water owners. In several cases, the young descendants of sharecroppers obtained water shares or the participation of the descendants of foggara owners in maintenance operations.

Embodiment of the 2nd and the 4th design principles in the physical infrastructure

The water distribution device (*kesria*) classically permitted the monitoring of water sharing by visual checks by the oasis community (principle 4, ***Table 2***). Irrigators preserve these devices even if the physical infrastructure is modernized (***Picture 3***) to be sure water sharing remains transparent for all members of the community and which relies on the congruence between appropriation and provision rules (principle 2, ***Table 2***). The continued presence of the *kesria* in today's foggara materializes the integration of foggara institutions in the new socio-economic and administrative order. The strength of these long-standing management institutions made it possible to maintain collective action.

4. DISCUSSION

4.1 LIVING FOGGARAS CHALLENGE THE HYPOTHESIS OF A GENERAL DECLINE

Our findings challenge the hypothesis of a general decline of foggaras in the Touat, Gourara and Tidikelt oases. Peasants continue working in traditional oases while adapting the foggara to recent transformations, thus revitalizing oasis agriculture (Hadeid et al., 2018). There is even a remarkable return of peasants to foggara and

Picture 3 Replacing traditional channels by modern pipes while keeping the use of the water sharing basin (*kesria*) to ensure the visibility of water distribution for all. On the picture, the channel upstream of the *kesria* (top of the picture) has been replaced by a concrete pipe carrying all of the discharge of the foggara. In the *kesria*, part of the foggara discharge is diverted to smaller pipes that go left and right on the picture. What is remaining is the combined discharge of several water owners that will be transported in the big concrete pipe further downstream, where there is another *kesria* to sub-divide between these owners. (April 2017).

to oasis agriculture, evidenced by the maintenance of degraded foggaras; the rehabilitation of certain abandoned foggaras; the incorporation of new technologies and the adaptation of irrigation institutions. About one third of all foggaras in this area (672 out of 2,000) are still operational. This renewed interest can also be explained by current reductions in public subsidies for smallholders – today public policies for the Sahara focus more on large-scale entrepreneurial agriculture – and some of the difficulties encountered in the small-scale extensions, including water shortage, mechanical failure of costly tube-wells, and the harsh conditions that had to be confronted individually in these extensions. Returning to the fold, to foggaras and to the oases, thus expresses the secular need of oasis communities to overcome climate hostility by maintaining collective action and their traditional way of life, including family farming that is made possible by the spatial proximity between the foggara, the *Ksar* (homes), and their gardens in which inhabitants can enjoy privacy and acceptable temperatures outdoors.

However, we showed that when returning to foggaras, these smallholders, often former sharecroppers, renegotiate existing water shares and obtain access to land and water, often successfully challenging the social hierarchies that were at the basis of the creation of foggaras. This leads to adjustments in traditional institutions or the crafting of new institutions adapted to the new context. Similarly, Remmington (2018) shows in the case of *daudi aflaj* in Oman, that "*where traditional knowledge systems are inflexible to change, they start to break down*". When *bayadirs* (the social group responsible for physical labor of *aflaj*) were not provided with access to land and water by *aflaj* owners, they would migrate. While our results show that including sharecroppers as foggara owners was an effective way to maintain collective action, this was not possible in all cases. Recent social reconfigurations have cushioned inequalities between social groups to a certain extent and young descendants of foggara owners are also adapting by carrying out the required maintenance themselves to keep foggaras alive.

4.2 DESIGN PRINCIPLES AS AN ANALYTICAL FRAMEWORK FOR UNDERSTANDING CURRENT ADAPTATIONS OF TRADITIONAL IRRIGATION SYSTEMS

The purpose of this research was to, first, revisit the understanding of the functioning of the long-standing foggara and, second, its capacity to adapt to recent changes. By analyzing several case studies, we show how oasis communities do make the adjustments required to adapt and preserve their agriculture, the irrigation system on which this agriculture relies, and indeed, their way of life. Despite rapid and deep-seated technical and socio-economic transformations, flexible attitudes were crucial to maintaining foggaras for many centuries and this is still the case nowadays. The limited focus of many scholars and decision makers on foggaras necessarily limits understanding and hence results in a pessimist forecast. Foggara cannot be reduced to the ingenuity of its hydraulic device, the hierarchical social organization or even to its capacity to provide irrigation and drinking water in a hostile context. As shown by the case studies reported here, analyzed through the lens of Ostrom's design principles, the foggara combines all of these elements, while relying on collective action underlain by strong, adaptable institutions. Thus, changes to 'ancient' foggaras should be qualified in relation to the efficacy of institutions and their capacity to maintain collective action and solidarity in this arid environment.

If today the foggara is known as a long-standing system, this results from the strength of its institutions and its adaptive capacity. Foggaras were never stable, due to the natural decline in water levels they themselves caused and constantly evolving social relations. This is precisely why these foggaras have an adjustment capacity that allows them to adapt and overcome different constraints without affecting their general functioning. We show that most design principles were fulfilled or compensated for. However recent changes not only disrupted the physical infrastructure and the social organization, but also challenged the way these principles were fulfilled, therefore justifying the questions asked in the introduction about the decline of foggaras and the adaptation of the oasis peasantry. We have shown that foggaras have sometimes changed profoundly – only parts of the physical infrastructure are maintained or the social organization and the irrigation institutions have been completely revisited – but the perception of foggaras as flexible living systems remains valid. These systems recombine and weave together new and ancient physical infrastructure and institutions, thus perpetuating the foggara, while Ostrom's design principles are adjusted and compensated for in the process.

5 CONCLUSION

Going back to our research questions about the sustainability of foggaras and their supposed decline, we conclude that the wide range of adaptations observed in the physical infrastructure and in the institutions of contemporary foggaras, associated to the multiple ways communities have devised to overcome challenges to their design principles, testify to the fact that foggaras remain at

the core of life in the oases of Touat, Gourara and Tidikelt. These foggaras can be considered as living and evolving infrastructures of the oasis society and their degree of vitality is an excellent indicator of the vivacity of the oasis communities concerned.

While the current research has revealed the importance of institutions in adapting and preserving the living character of foggaras for a limited number of cases, it would be interesting to further investigate why and how such transformations take place (or not), for example by including some abandoned foggaras in future studies. The physical durability of the foggara, linked to, for instance, the characteristics of the aquifer, competing water uses and risks of pollution, the length and depth of the underground channel and the access wells in relation to the characteristics of the soil, etc., should then be explicitly integrated in such investigations (Ahmadi et al., 2010). The results of this study also provide interesting perspectives to further analyze the sense of place in communities to relate the identity of the oasis population, the durability of the foggara system and the resilience of the oasis society (Bendjelid, 2011; Bousquet et al. 2021).

From a methodological perspective, we think that some of our thoughts about our use of Ostrom's design principles are worth sharing. Since Ostrom's (1990) seminal work, an important challenge facing the research community investigating the commons, has been to design analytical frameworks based on a diversity of case studies to study long term sustainability of socio-ecological systems (SES) (see Ostrom, 2009). In this study, we showed that if sustainability conforms to some general principles, the observed adjustments in these principles can help describe, analyze and characterize transformations of the foggara, seen as an SES, in response to external changes. Communities of course do not consciously modify their SES to comply with design principles. But we argue that the relations we observed between the changes in the SES and the challenges to design principles can be generalized. Furthermore, what we identified as relations or "mechanisms ensuring design principles" can clearly be related to infrastructures in the broad understanding of Anderies et al. (2016). We suggest these relations can be formalized within the coupled infrastructure systems framework of Muneepeerakul and Anderies (2020), which has already proven to be useful to study SES adaptations to change (e.g. Therville et al. 2018; Bonté et al., 2021). Our results suggest that by focusing on the way the design principles are re-crafted in the face of deep socio-economic and environmental change, the use of the coupled infrastructure system framework may gainfully shift from the study of SES adaptations to the study of their transformations.

NOTE

1 More details on the UNESCO website dedicated to *foggaras*: *https://ich.unesco.org/en/USL/knowledge-and-skills-of-the-water-measurers-of-the-foggaras-or-water-bailiffs-of-touat-and-tidikelt-01274?USL=01274*.

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The authors have no competing interests to declare.

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