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WHEN THE FOGGARA ENSURES THE WATER SECURITY OF THE OASES

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ABSTRACT

This article evokes for the first time the water security of oases ensured by foggara. It was during our many visits to the oases of the Algerian Sahara that we discovered the important role played by the foggara in the rational management of water. During the period 1998-2022, surveys and interviews were conducted with the ksourian population, the owners of the foggaras and the elderly people who lived through the era of the digging of the foggaras. The consultation of the archives and the very rich data in information has been beneficial for our research work. The results obtained from this study are original. The oasis is one of the first regions on the planet that has ensured its water security thanks to foggara. This ancestral hydraulic system designed in a hostile region has allowed water to flow continuously in quantity and quality and without damaging the environment. This durable hydraulic structure that evolves over time is made up of two parts: collection – transport and distribution of water. The upstream part is made up of a ramified gallery network that changes each time there is a water deficit. The downstream part is made up of a triangular network of seguias, which divides the water into micro quantities. The water of a foggara is of very good quality due to its flow in the gallery of several kilometers and the absence of storage and stagnation of water.

Keywords: Foggara, Water Security, Oasis, Sahara, Water, Food security.

INTRODUCTION

Today, climate change is accelerating, and drinking water is becoming scarce, causing a decline in the stock of fresh water. According to the United Nations, in October 2022, the world population reached the threshold of 8 billion inhabitants, and therefore, the demand for drinking water has become greater than the quantity accessible to humans. Several regions of the world are currently affected by water shortages; others may have water problems in the short and medium term. Arid and semiarid regions will be the most affected on the planet since they are easily threatened by global warming. Like all Arab countries, Algeria will not be spared by this phenomenon. In the last two decades, we have witnessed two droughts, one of which took place at the end of the 1990s when Algeria experienced a serious water shortage. The slicks have seen their static level drop by several meters depth, similar to that of the Mitidja plain. Reservoir dams were dry, and hydraulic services exploited the dead volume of the dam by a pumping system (Remini, 2020). The second severe water shortage occurred 20 years later (in 2021). Several dams did not record water inflows throughout the year. This time, it was the turn of the Boukourdane dam to experience a drying up of the water reservoir. The hydraulic services supplied the population with water from the dead section. This disruption of the climate brings long droughts that last 6 to 7 months and erases the notion of the seasons. However, such periods are followed by flash floods that can drain large volumes of water in two or three days that may have fallen in two or three months during a normal season. This new situation leads to a rapid rise in surface water, thus causing flooding, the consequences of which are harmful, thus causing material and human damage. This phenomenon of climate change has a direct impact on the country's water security, which has become a hot topic. Norman (2010) defined water security as “sustainable access at the watershed scale to sufficient quantities of water of acceptable quality to ensure the protection of human health and that of ecosystems”. For our definition, “Ensuring the water security of a region means providing water in quantity and quality while protecting the environment” (Remini, 2022). Water security must be the subject of specific management of water resources. Everyone’s business, particularly scientists, must seriously study this problem to propose the best solutions to increase the country's freshwater stock. These results in overcoming the three steps of saving, improving and ensuring the country's water security. The history of water management in Roman cities and oases proves that water security is not today but rather centuries old. The control of the transfer of large quantities of water over several kilometers by the Roman aqueducts proves that the Romans (Ammari and Remini, 2016) ensured the water security of the Roman villages. For the oases of the Sahara, water management was much more complicated since these wetlands were developed in an arid environment (Sahara). Thanks to their genius and their know-how, the peasants invented a hydraulic system for more than 20 centuries; it is the foggara system (Remini, 2017, Remini, 2011). Thanks to this genius system, the oasis dwellers were able to provide water for the irrigation of the palm groves and the domestic supply of ksour despite an arid climate. This paper evokes for the first time the role of foggara in ensuring the water security of oases for more than 20 centuries. The design of a hydraulic development based on two hydraulic networks, the capture of groundwater using galleries and the distribution of surface water using seguias, will be the subject of this study. The role of Kial el ma in the management and sharing of water in foggara will be discussed in this paper. Indeed, such a study will surely help us find solutions to address climate change and ensure the water security of our country.

STUDY REGION AND WORK METHODOLOGY

Study region

More than 2390 foggaras have been made in the Algerian Sahara, of which more than 270 foggaras are in service today. Figure 1 shows the location of the different types of foggaras that have been built in the national territory. As shown in Figure 1, Adrar is the capital of the foggaras since more than 70% of the foggaras are within these borders, i.e., 2100 foggaras. Two types of foggaras have been highlighted: volumetric foggara and hourly foggara. Seven types of foggara have been located according to the water source of capture in the Algerian Sahara. These are the foggaras: Albian (Aquifer of the Continental Intercalaire) (Remini, 2022; Remini 2023a; Remini, 2023b; Remini et al, 2011; Remini, 2017; Remini and Achour, 2016; Remini et al, 2014; Remini and Achour, 2013a), Erg (Erg aquifer) (Remini and Achour, 2013b; Ghachi et, Remini, 2018; Ghachi et al, 2021. Remini et al, 2011) Oued (Inferoflux aquifer) (Remini and Abidi Saad, 2019; Remini and Achour, 2013c) Garden (Infiltration water) (Remini et al, 2015), Ain (natural water source) (Remini and Achour, 2017; Hamdaoui and Remini, 2020), groundwater (Ouakda foggara) (Remini and Rezoug, 2018), mountain sheet (Kenadsa foggara) (Remini et al, 2014).

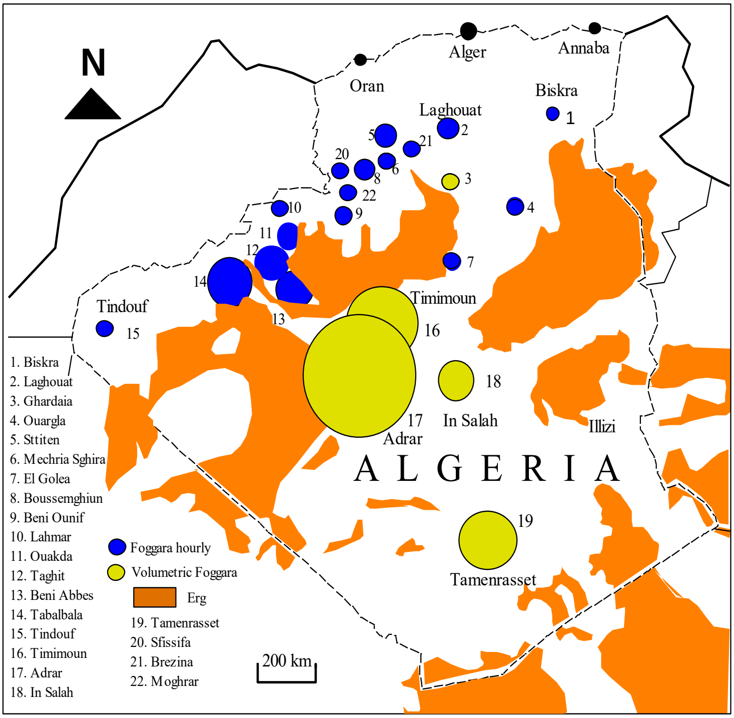


Figure 1: First map of foggaras (Remini, 2022; Remini, 2023a; Remini, 2023b)

Methodology of work

During the period 1992-2023, we traveled the national territory at the rate of 2 to 3 visits per year on average. Visits and meetings with the ksour population were conducted to obtain more data and information. It was by visiting the foggaras several times that we understood that this hydraulic system is the only one in the world that can do both functions at the same time: supply water in quality and quantity and thus protect the environment. It is after these years of work on the foggaras for the different axes that we decided to write this modest paper.

RESULTS AND DISCUSSION

An overview of water security

The water security of a region, as we have defined it, is to supply water in a continuous manner in quantity and quality in space and time without damaging the environment. Such a mission becomes more complex in arid environments. Only the oases have managed to resist in these environments' hostile to life. This thanks to the know-how and oasis genius. The oases fed by the foggaras system remain a good pedagogical example for teaching water security. This ancestral hydraulic system has produced hundreds of wetlands (oases) in an arid zone, which is a paradox. More than 20 centuries of existence are more than enough to prove its effectiveness. The best thing about the foggara system is that it is a sustainable means, 20 centuries ago and today in 2023, the foggara still works despite competition with new water collection techniques. Yes, the foggara system has adequately ensured the water security of the oases without damaging the environment. More than 1,000 foggaras have been continuously and uninterruptedly exploiting the waters of the Continental Intercalary aquifer for centuries without posing any problems to the aquifer in terms of quantity or quality. If today, we have the chance to taste delicious dates, it is thanks to the foggara that has enabled farmers to develop date palm oases (Fig. 2).

Today, the foggaras system attracts many curious people and scientists from all over the planet who are interested in the mechanism and how it works to profile and propose techniques that adapt to global warming.

Figure 2: Dates from the oases of the Algerian Sahara (Photo. Remini, 2022)

Evolution of wells in the Algerian Sahara

At the very beginning in the Sahara, man settled as soon as he found a spring of water (Ain) gushing. He builds his house and landscapes his garden (Fig. 3). Over time, these gushing sources are extinguished and disappear following the drawdown of the water table.

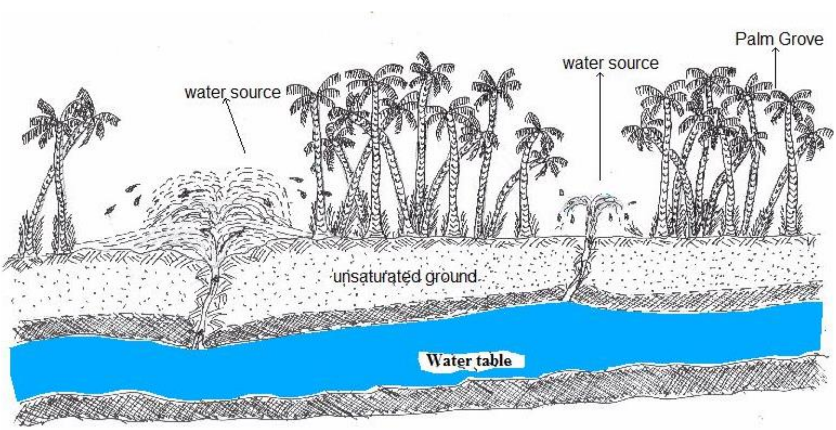


Figure 3: Diagram of natural water sources (Diagram Remini, 2019)

By avoiding leaving the premises and going elsewhere while leaving these goods, the man goes in search of water by digging the first vertical well to draw the water that is in the basement. He uses the rope to lift the delou filled with water (Fig. 4). At this stage, two parameters come into play: the energy E (human) and the quantity of water Q.

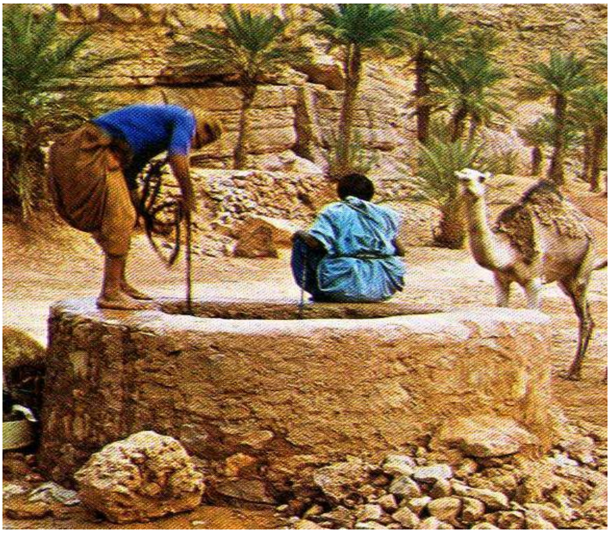


Figure 4: Man draws well water only by rope (Photo. Heritage)

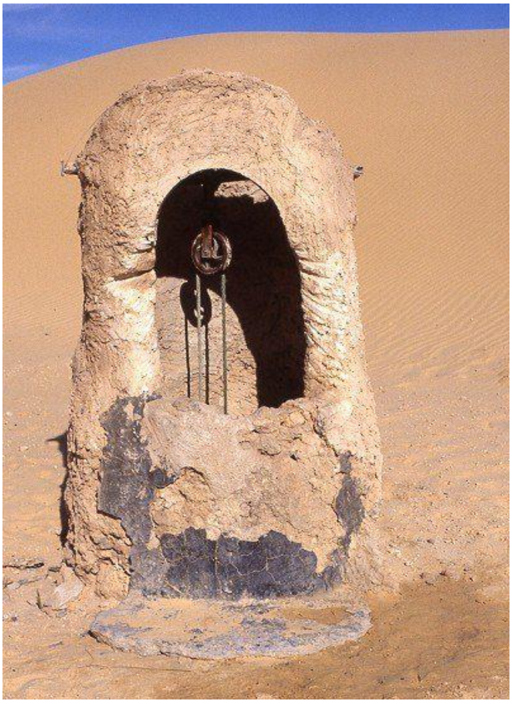


Figure 5: Pulley well in the Righ Valley (Photo. Remini)

The man begins to think about improving the performance of the well, which is a function of energy and flow. The population of the ksar increases, and the needs for domestic water as well as irrigation increase in power. In this case, the performance of the well must be improved to cope with the new situation. Therefore, to increase the yield of the well, it is necessary to increase the quantity of water extracted Q while decreasing the human energy E. With the appearance of the wheel, man invented the wooden pulley. Such an object has contributed greatly to the improvement of the life of the Ksourian population. This is how the pulley greatly reduced the energy and facilitated the extraction of water, which influenced the increase in the daily flow of the well (Fig. 5).

Then, with the appearance of moments of forces, man invented the pendulum well used in regions characterized by a shallow depth of the static level of the water table (between 2 and 3 m). With little effort, humans can draw a significant volume of water (Fig. 6).

Figure 6: Pendulum well in the Boussemghoun oases (Photo. 2017)

Always the man trying to improve the flow of water and decreasing the energy. It is thus for depths of the static level of the water table removed (between 10 to 20 m) that the man introduced the animal (donkey or dromedary) to tow the delou by means of a rope. In this case, human effort is reduced solely to guiding the animal to perform the latter's back and forth, which results in the ascent and descent of the delou (Fig. 7).

Figure 7: Animal traction well (Photo. Heritage)

Each time the man improves the yield of the well by reducing the human effort E and increasing the flow Q until the discovery of the foggara, a hydraulic system with zero energy and a continuous flow of water from the aquifer toward the ground surface.

Birth of the foggara

Foggara is defined as a slightly inclined horizontal well to drain groundwater to the ground surface (Remini, 2017) (Fig. 8). The foggara is a hydraulic system that works with energy equal to zero. The realization of a foggara is classified as one of the greatest ancestral projects and required several years of digging approximately ten kilometers of gallery.

The foggara is considered one of the greatest ancestral hydraulic projects. This megaproject was carried out by rudimentary means (Fig. 9). Approximately 2,390 foggaras with 5,000 km of galleries and 700,000 ventilation shafts have been made over the past 20 centuries (Remini, 2022). Paradoxically, the digging of a foggara begins from the exit of the gallery to the last well (sea well) in the opposite direction to the flow. However, the digging of an underground drain cannot go beyond approximately twenty meters, 14 meters on average (Remini, 2011).

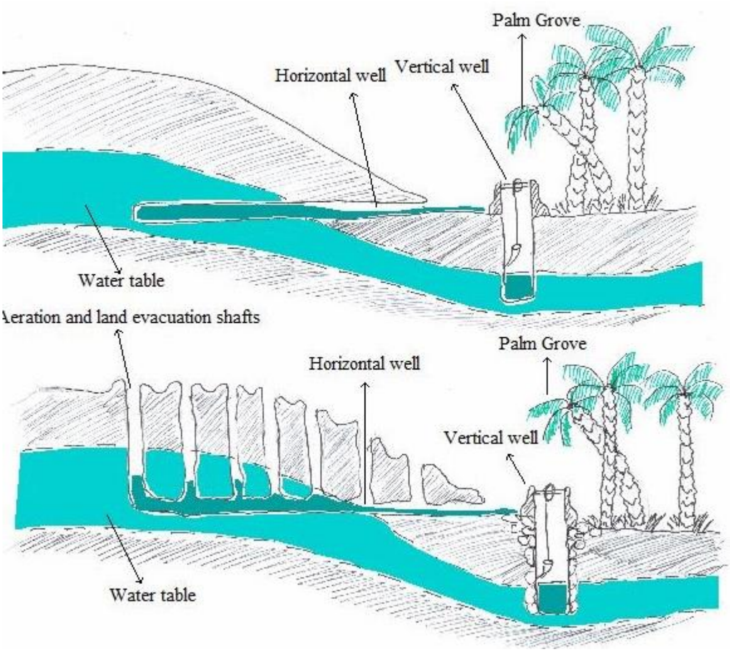


Figure 8: Diagram of a horizontal well (Diagram Remini, 2023)

Figure 9: Materials used in foggaras digging (Remini and Ghachi, 2019)

In this case, the workers need oxygen to breathe and light. The digging of the first vertical well is essential. The digging of the second vertical shaft takes place approximately fifteen meters from the first shaft. Two teams begin digging the section of the gallery between the two shafts. After the digging of the third well, the second section of the gallery will be started from the second and the third well and so on until the arrival at the last well (mother well). During the execution of the project, these wells, which can exceed 1000 for a length of more than 7 km, have a double role: the evacuation of the embankment and the aeration. This is how a team of two people equipped with a winch is set up on the edge of a shaft to evacuate the soil removed from the gallery (Fig. 10).

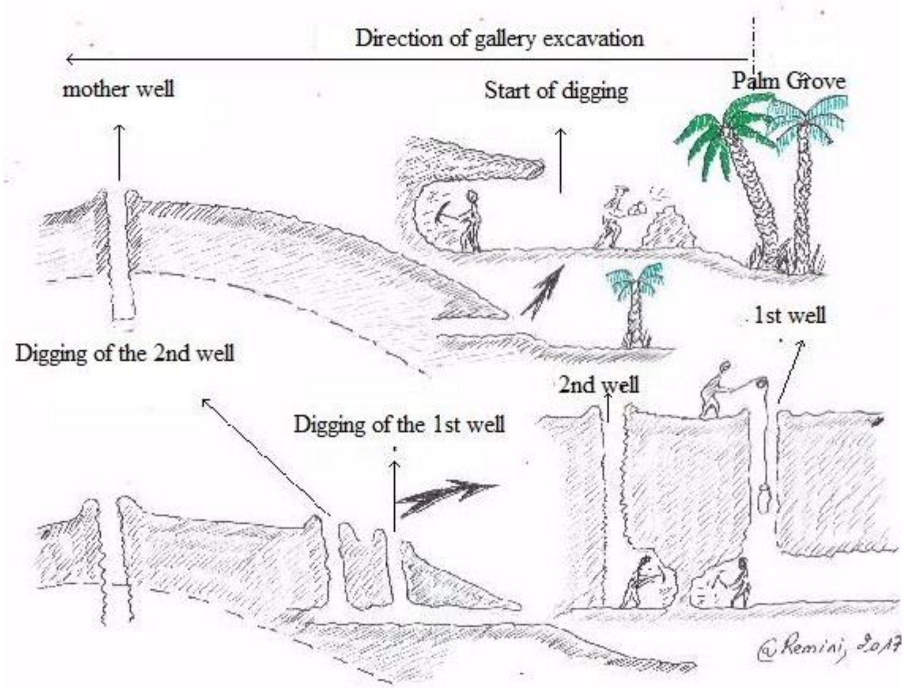


Figure 10: Probable diagram of the digging stages of a foggara (Remini, 2020)

Once the project is completed, we obtain a foggara that consists of an underground gallery of low slope that can reach 20 km equipped with several ventilation shafts with a depth that can reach 45 m (fig. 11).

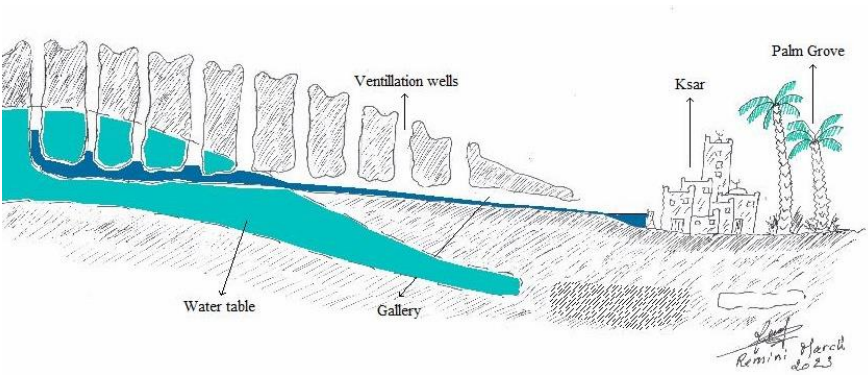


Figure 11: Gallery of foggara, which constitutes the collection and transport of water (Remini, 2023)

Foggara is considered one of the most beautiful inventions in the history of hydraulics. Moreover, it is classified among the 7 wonders of the world. Thanks to its success, foggara has spread to the four corners of the planet. All foggaras are located along the diagonal of the arid countries from Algeria to China. This is how traces of foggaras are found in 52 countries on the planet (Figs. 12 and 13) (Remini et al, 2014). Today, there are still foggaras in service in 10 countries, of which Iran is the first country in the world with a high number of foggaras (Fig. 14).

Figure 12: Diagonal of foggaras in the world (Remini, 2011; Remini et al, 2014) (NASA Worldviews)

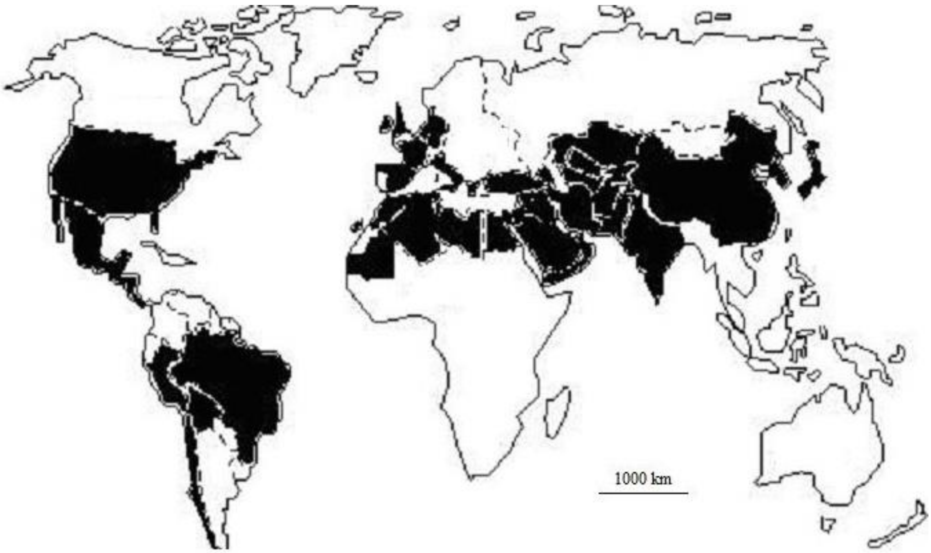


Figure 13: Countries that have foggaras (Remini et al, 2014c)

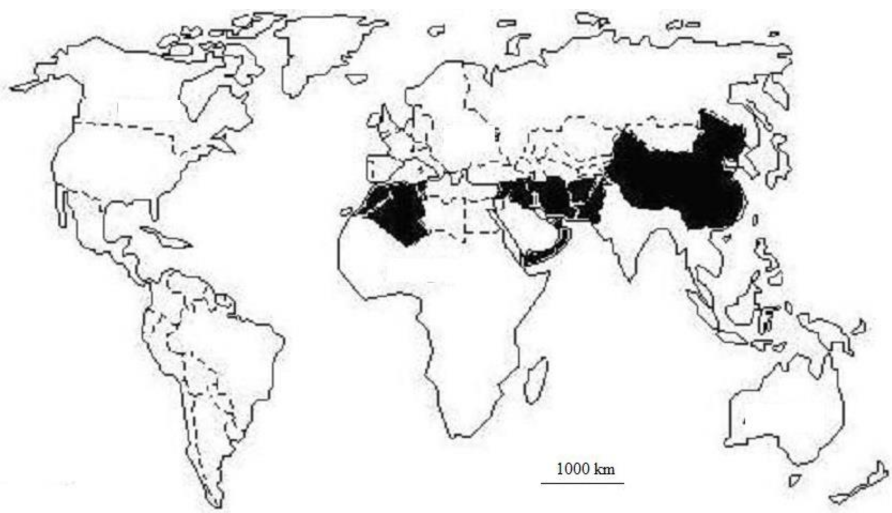


Figure 14: Countries that have foggaras in use (Remini et al, 2014c)

The role played by the foggara system in the water security of the oasis

If the water security of the oases of Touat, Gourara and Tidikelt has been ensured for more than 20 centuries despite an arid climate, it is due to the role of the foggara. This hydraulic system has been designed to adapt to dry environments that require rational water management. Thanks to the very gentle slope of the gallery, which only the oasis dwellers know the secret, the water flows slowly and continuously without disturbing the water table. To this end, the foggara system is made up of two main parts: upstream and downstream (Fig. 15). The gallery (with these 2 sections) occupies the upstream part, and the distribution network, which begins with Kasria lakbira, occupies the downstream part.

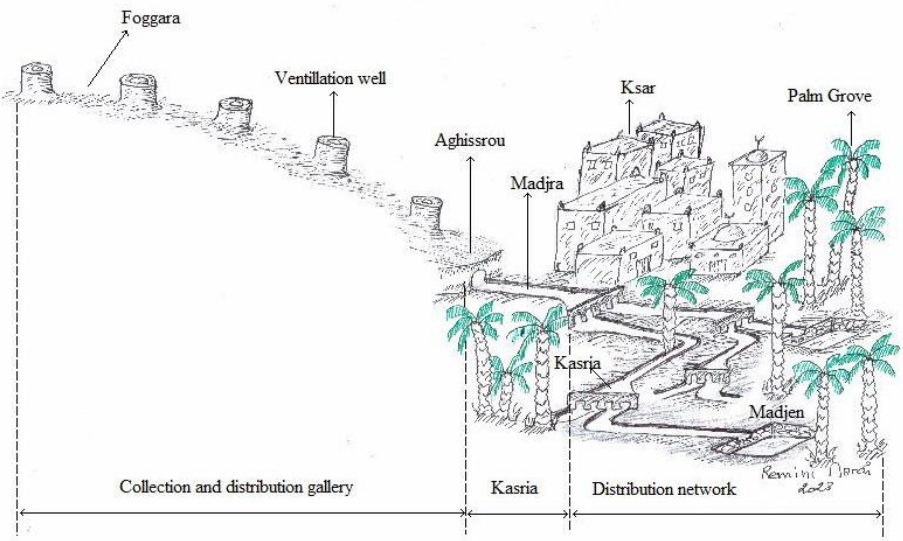


Figure 15: Diagram of the foggara system (Remini diagram, 2023)

The upstream part of the foggara

The upstream part of the foggara is made up of a gallery of several kilometers, which is divided into two parts that vary over time. The gallery can reach 20 km in length equipped with a multitude of ventilation shafts and can exceed 1000 ventilation shafts for a gallery longer than 7 km (Fig. 16). This tunnel is slightly inclined to form a gentle slope with a slope not exceeding 1/1000. This induces a gravitational river flow of water with a low velocity. Only from a practical point of view it is impossible to dig a gallery without the vertical shafts that allow the evacuation of the embankments and access of air and light into the tunnel. The digging of a gallery is completed once it enters the aquifer. The further upstream you go, the more water you will have, and the working conditions become very difficult because of the mud. In this case, the gallery is made up of two parts: draining and transport (Fig. 17).

Figure 16: Ventilation shaft of a Timimoun foggara (Photo. Remini, 2013)

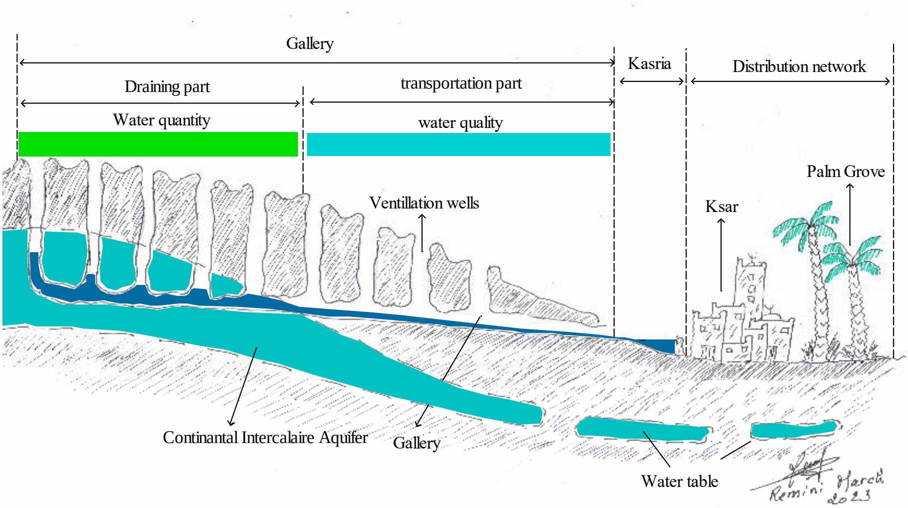


Figure 17: Probable diagram of the two parts of the gallery of a foggara (Diagram Remini, 2023)

The draining part is the part that continuously supplies the flow of water necessary for domestic supply and garden irrigation. This part represents the section of the gallery that was dug into the groundwater itself. It is this part that ensures the quantity of water from a foggara to supply the oasis (Fig. 18).

Figure 18: Draining part of the Tindouf foggara gallery (Remini and Abidi, 2019)

If you want to increase the flow of a foggara, all you have to do is increase the length of the draining part by digging a section upstream from the foggara. Otherwise, if there is a drawdown of the water table, part 1 decreases, and consequently, the flow of the foggara decreases. As we mentioned, the foggara is an evolving hydraulic structure (Remini, 2014) that was designed specifically to evolve over time. The oasis grows over time, which is explained by the population of ksar, which increases in parallel with the need for domestic water; thus, the irrigation of gardens multiplies. The foggara was initially designed with a single gallery of well-sized length to provide a flow capable of satisfying the water needs of the oasis. Over time, this flow becomes insufficient, and in this case, the foggara becomes unable to ensure the water security of the oasis. This new situation does not take enough time, and increasing the flow of the foggara becomes a priority. Called tarha; an additional section of gallery must be dug upstream of the foggara just after the mother well by adding an aeration shaft (Remini, 2016) (Fig. 19).

Once the gallery cannot be extended due to a lack of groundwater, we must change direction. A branch of approximately ten meters can be added to the initial gallery. The digging is done from the old gallery. The flow of water drained by this branch, which depends on its length, must respond to the deficit recorded by the foggara. This branch is called kraa (Remini, 2016) (Fig. 20).

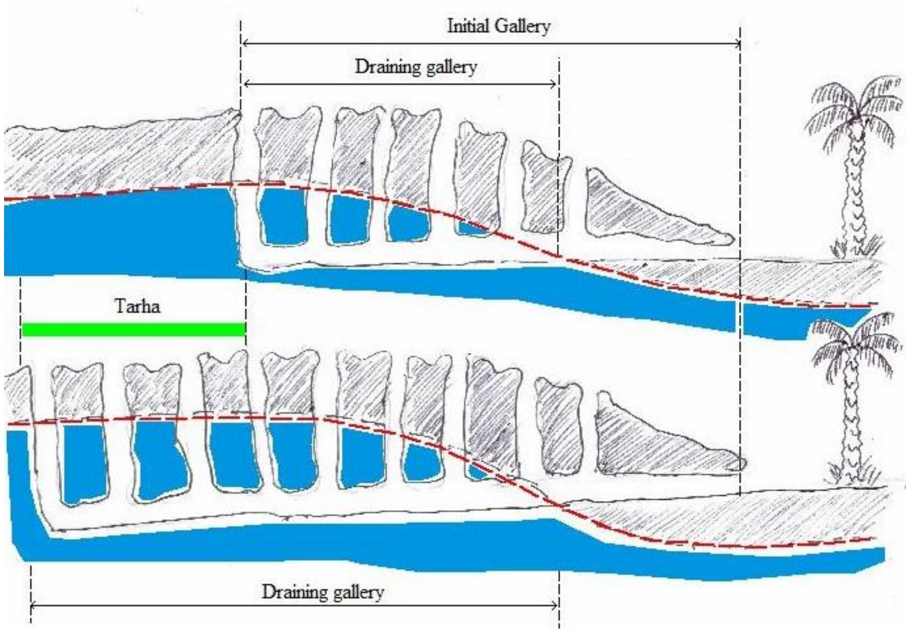


Figure 19: Extension of the gallery (draining part) called tarha (Remini, 2016)

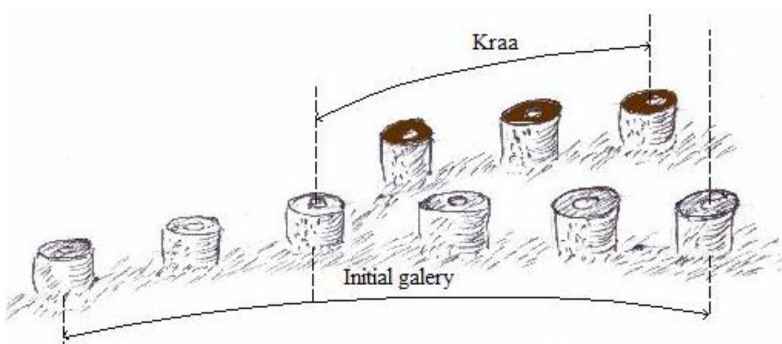


Figure 20: Diagram of a kraa added to the initial gallery of a foggara (Source: Remini, 2023)

Whether tarha or kraa, the length added to the main gallery depends on the water supply needs of the ksar or the irrigation of the palm grove. This was verified by the relation obtained between the flow rate of the foggara and the length of the draining gallery of the foggara of the oases of Touat and Gourara (Fig. 21(a and b)).

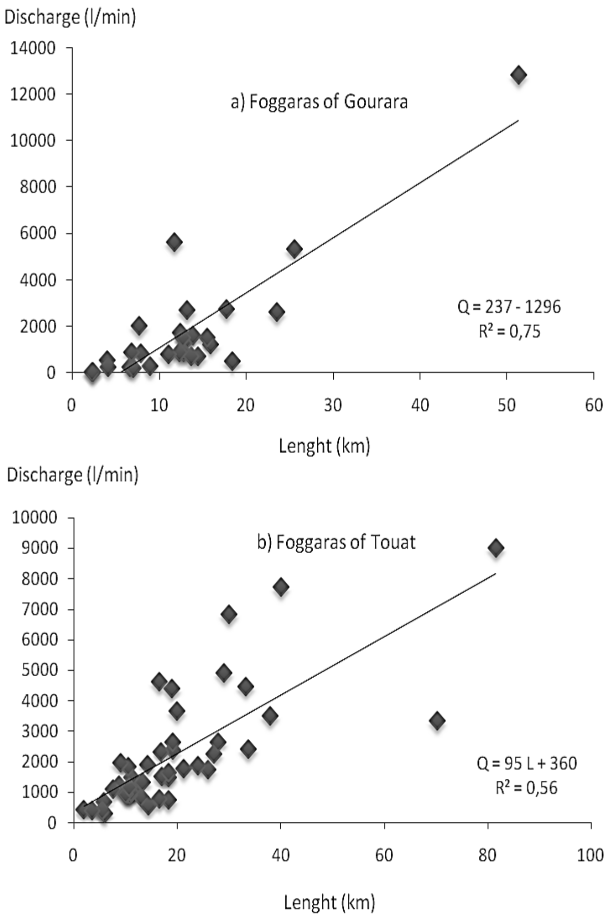
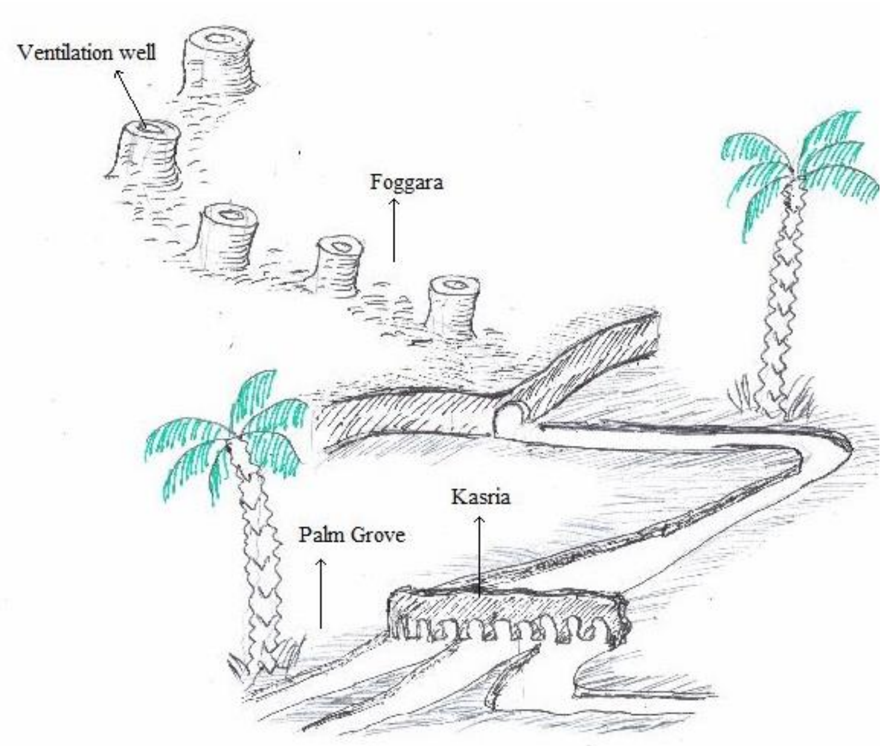


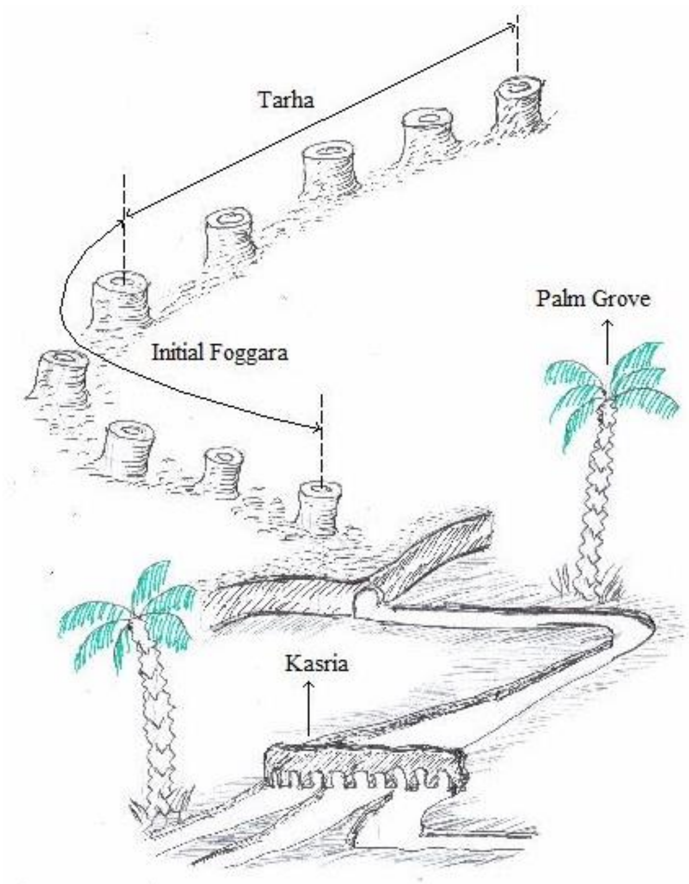
Figure 21: Relationship between flow and foggara length (Remini, 2016)

The tarha is a section of gallery of variable length depending on the quantity of water desired by the oasis (Fig. 22 (a, b and c)). Each time there is a water deficit at the level of the oasis, which results in the superiority of the water demand compared to the flow of the foggara ($Q_{foggara}<Q_{oasis}$), an addition of a section of gallery (tarha) imposes itself. The operation of the tarha does not stop in time; it is a particularity of the foggara and must be carried out each time the demand for water is greater than the contribution of the foggara. As soon as the upstream of the foggara can no longer drain the water, in this case, the extension of the mother (initial) gallery is stopped, and the tarha operation is over. As an example for an Albian foggara, once the foggara gallery reaches the limits of the Tademaït Plateau, the tarha operation is stopped. At this stage, we move on to the kraa operation, which is explained by the addition of a tributary or a branch. It is a section of gallery of approximately ten meters that is hollowed out from the mother gallery and takes another direction of 30° to 45° (Fig. 23). This work is the work of the water wizard. The

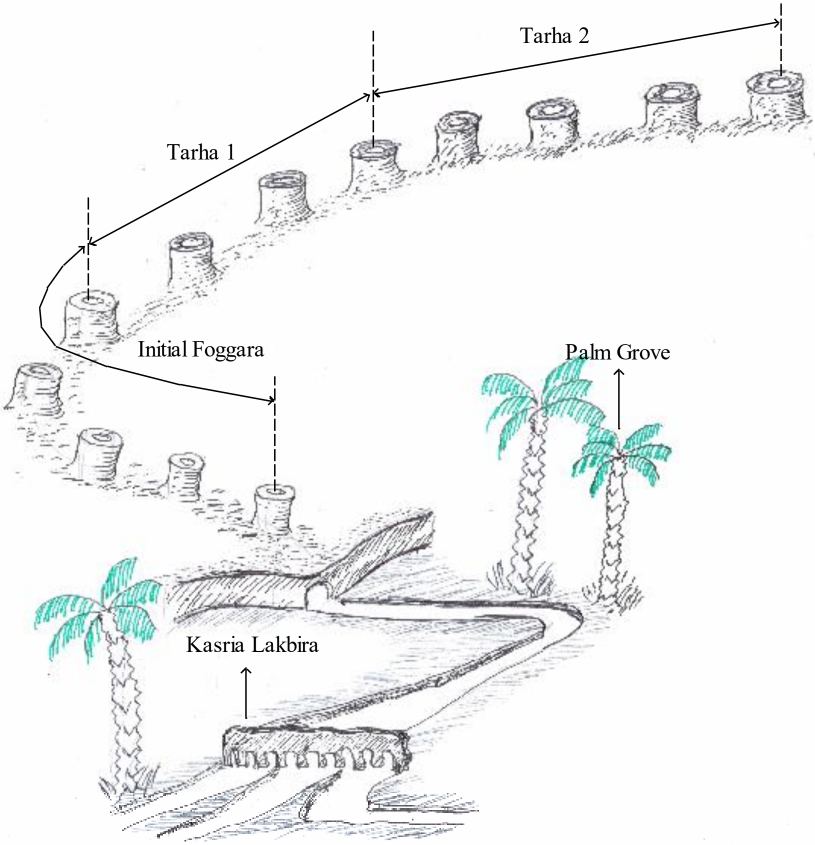
digging of this new branch stops as soon as the water table ends. Once we register a new water deficit at the level of the oasis, we dig a new kraa and so on until we reach several ramifications of galleries. Therefore, we go from a foggara with a single gallery to a foggara with a ramified network of galleries (Fig. 24). Indeed, the foggara is an evolving hydraulic structure. We can have an idea about the age of a foggara.



a) Initial Foggara



b) First operation of the tarha



c) Second operation of the tarha

Figure 22: Diagram of the extension of the drainage gallery (tarha) (Source: Remini, 2023)

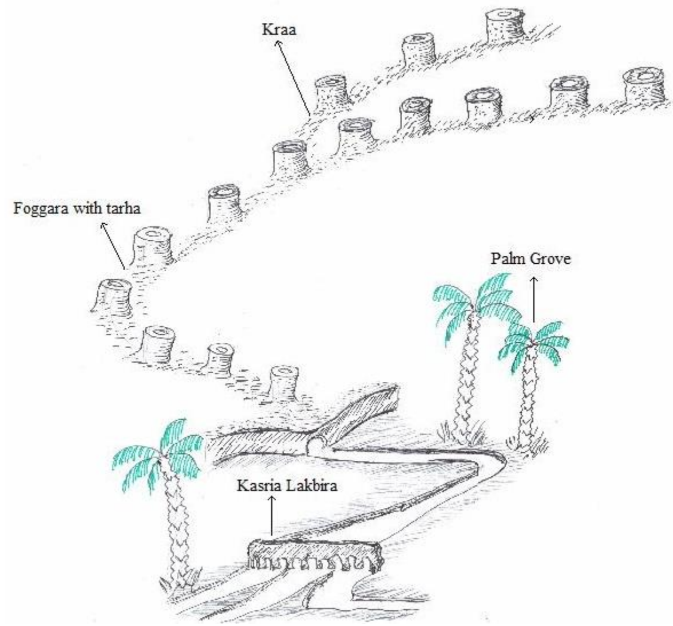


Figure 23: Foggara with the addition of a kraa (Source: Remini, 2023)

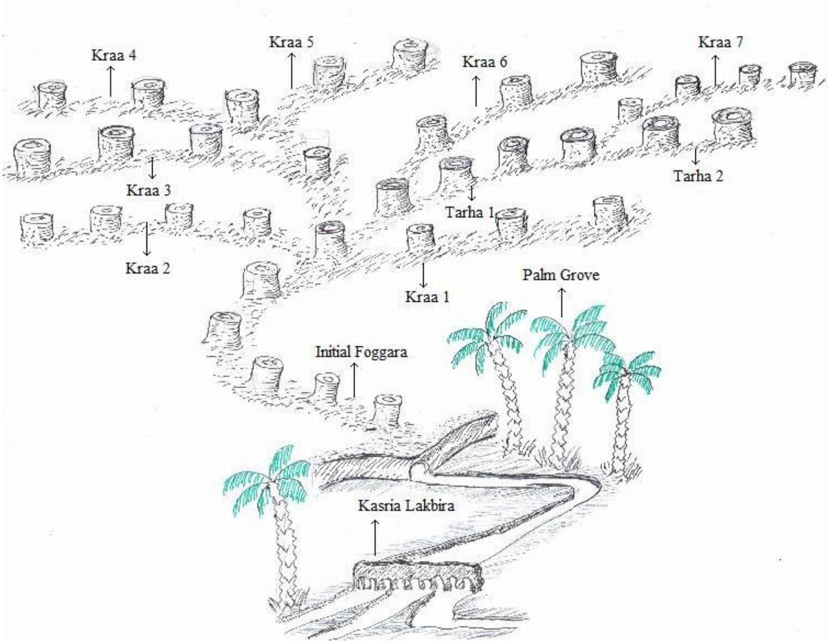


Figure 24: Foggara with a ramified network of galleries (Source: Remini, 2023)

On the other hand, the transport part conveys water from the groundwater table to the ground surface (Fig. 25). The most important thing is that this part of the gallery gives the drained water all the necessary elements so that it becomes very good quality water at the outlet of the gallery. Part 2 of the gallery is intended for the transport of water from the foggara to reach the surface of the ground and the gardens. This heterogeneous natural tunnel whose bottom and banks are made up of different types of rocks allows the water along its journey to gain better quality. Indeed, with a very gentle slope of the bed not exceeding 1/1000, the water flows slowly with a speed of less than 1 m/s and allows it to hug the different types of rock over a length of several kilometers. Arriving at the surface of the ground, the water of the oasis is of very good quality.

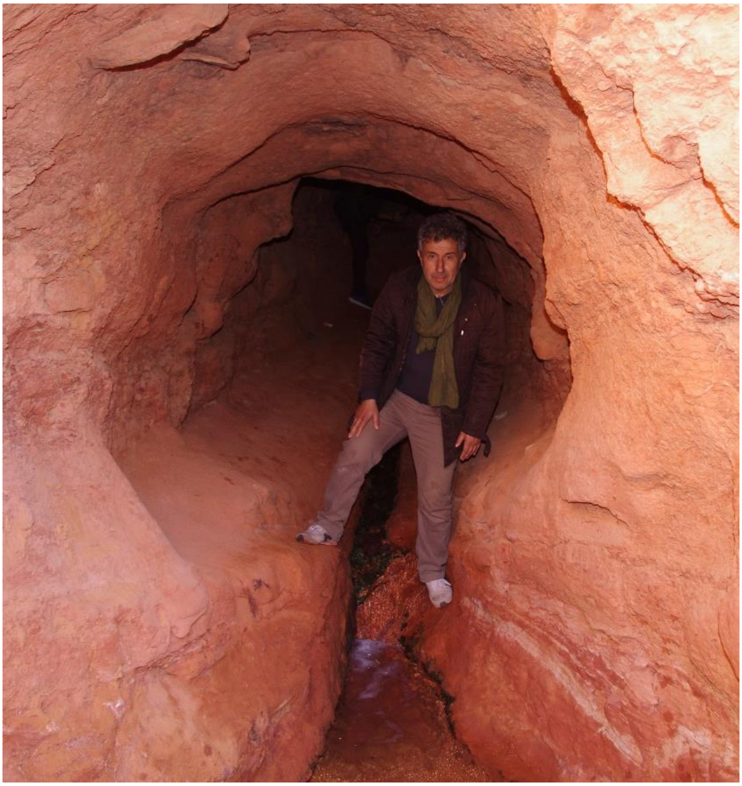


Figure 25: Transport part of the gallery of foggara of the Timimoun Oasis (Photo. Remini, 2019)

The gallery captures good-quality groundwater in the first phase, and then this water flows into the transport channel of several kilometers with a very gentle slope not exceeding 1/1000. Only the waters of the foggaras can thus have a good quality. This is due to the exceptional flow of rainwater carried out in the basement. Rainwater runoff descends several meters into the subsoil, allowing rainwater to flow slowly through the cracks in the rocks and the voids existing between the different particles. Once it reaches the aquifer, the water is already saturated with mineral salts. In the second phase, this water flows in a gallery of several kilometers of low slope with a low speed not exceeding 1 m/s. This still allows this water to gain other mineral salts by marrying several types of rocks. Once the water has reached the surface of the soil, the water can only be of excellent quality (Fig. 26). In addition, the water from the foggara flows continuously, so the water does not stagnate. The madjens fill up every 24 hours. The stock of foggara water in the madjens does not exceed 24 hours.

Figure 26: The population of Adrar is fed daily by the waters of the foggaras (Photo. February 2023)

The distribution network part

The kasria; a basin of triangular geometric shape that ends at the base in a dividing comb (partier) (Figs. 27 and 28). This work, invented in the regions of Touat, Gourara and Tidikelt, is located at the exit of Aghissrou at the highest point of the palm grove. It is at this kasria lakbira that the triangular network of foggara water distribution begins. It is at this structure that water is shared between the co-owners of the foggaras. The kasria is the heart of the system where we can observe the two domains: the technical and the social. In this place, the entire water sharing team gathers for each event of measurement of the flow rates of the water shares.

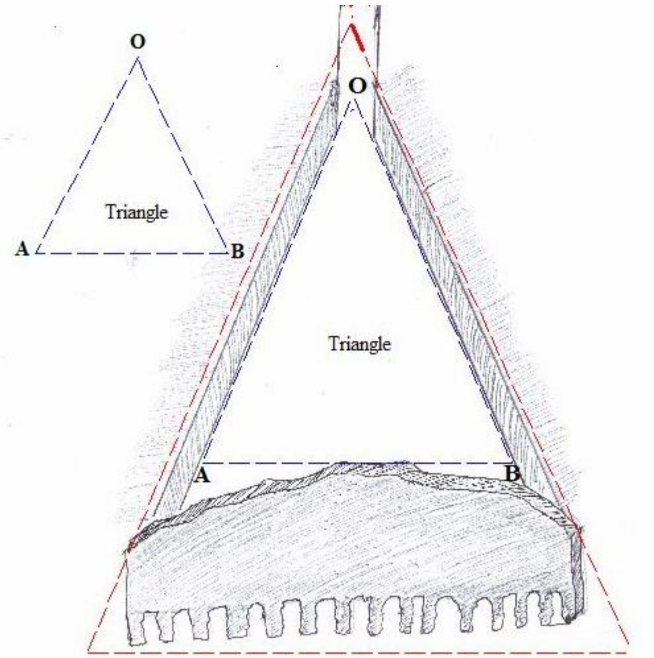


Figure 27: Diagram of a kasria, a triangular basin equipped at its base with a divider (Diagram Remini, 2023)

Figure 28: Kasria lakbira of a triangular-shaped foggara of the oasis of Guentour (Photo. Remini, 2019)

As we mentioned, volumetric foggara, which is only found in Algeria and more particularly in the oases of Touat, Gourara and Tidikelt and Ahaggar, has an original distribution network. We preferred to call it a triangular network. Two distribution networks are currently used to supply drinking water. These are meshed and ramified networks (Fig. 29(a and b)). The distribution network of volumetric foggara is triangular and is a deduction from kasria, which also takes the geometric shape of a triangle (Remini and Ghachi, 2021) (Fig. 30). Such a network adapts better to the arid environment than the other networks, meshed and ramified, since it is designed in such a way that the flow of the foggara at the entrance to the kasria is divided into several stages to finally reach the lowest flow. This can only be done by a triangular network. All the hydraulic structures of the network are dimensioned, taking into account the triangular network.

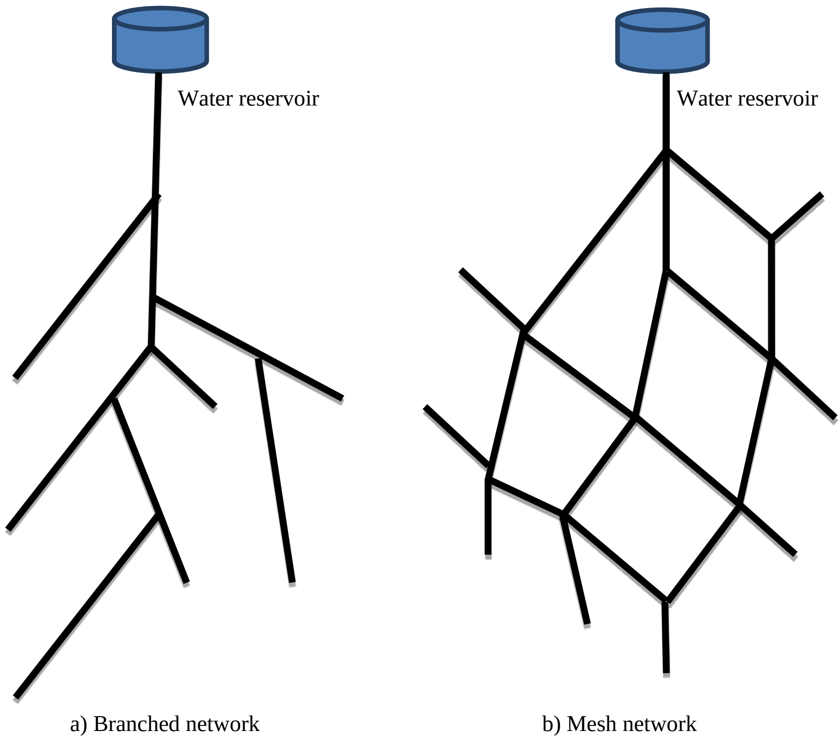


Figure 29: Types of distribution networks (Diagram Remini, 2023)

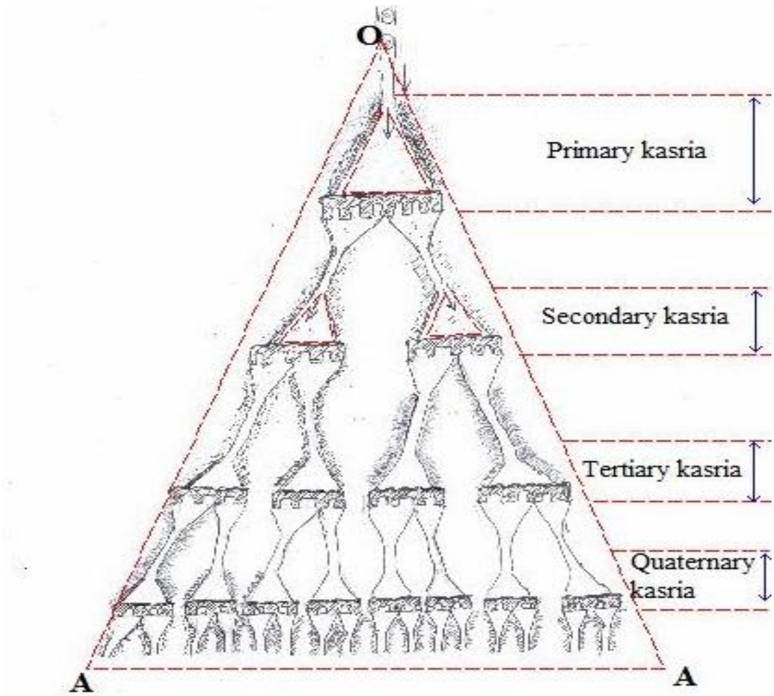


Figure 30: Triangular-shaped distribution network (Diagram Remini, 2023)

The dimensions of these structures are related to the flow rates. At each step concerning the division of the flow, the structures (kasria, seguia and madjen) are sized according to the new flow values. Therefore, the flow stored in the madjen for 24 hours is intended to irrigate a garden area that is proportional to this flow value. Therefore, in a triangular network, everything is dimensioned in a decreasing way from the top of the triangle, which corresponds to the entry of the water flow Q in the kasria lakbira, to the base of the triangle, which corresponds to the border of the palm grove with the sebkha (Fig. 31). We see in Figure 32 the decrease in the shape of the hydraulic structures constituting the distribution network. It is interesting to note the ingenuity of this system that lies in the rational use of water. For example, the kasria lakbira, which corresponds to the beginning of the watershed of a foggara, is quite large and ends at the end (last division) with a micro kasria (Fig. 33a, b and c). The same applies to the seguias, which begin sharing after the large-sized kasria lakbira ends at the end of the network with micro seguias, which can ensure the flow of a trickle of water (Fig. 32). The same applies to the madjens, which are sized according to the flow allocated to each co-owner (Fig. 32). Whatever the dimensions of the madjen, the filling of the latter takes place in 24 hours.

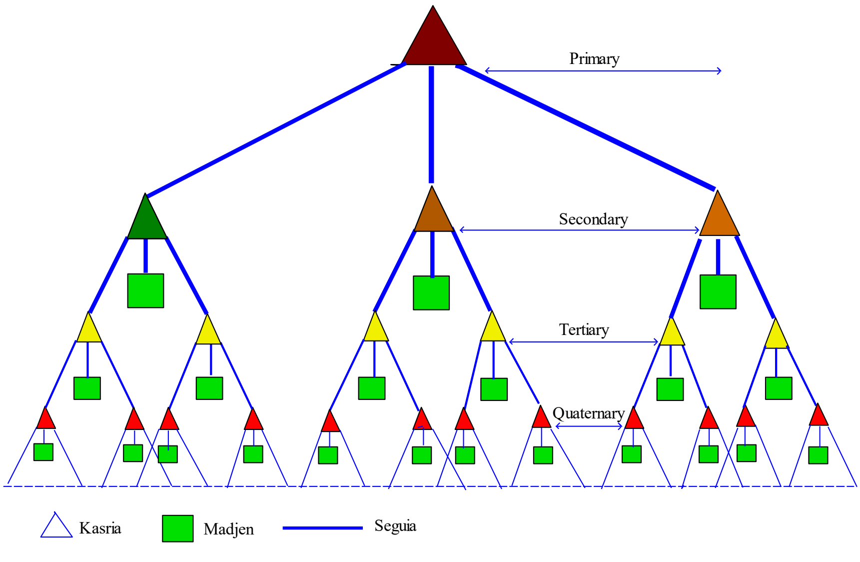


Figure 31: Triangular network of a volumetric foggara (Diagram Remini, 2023)

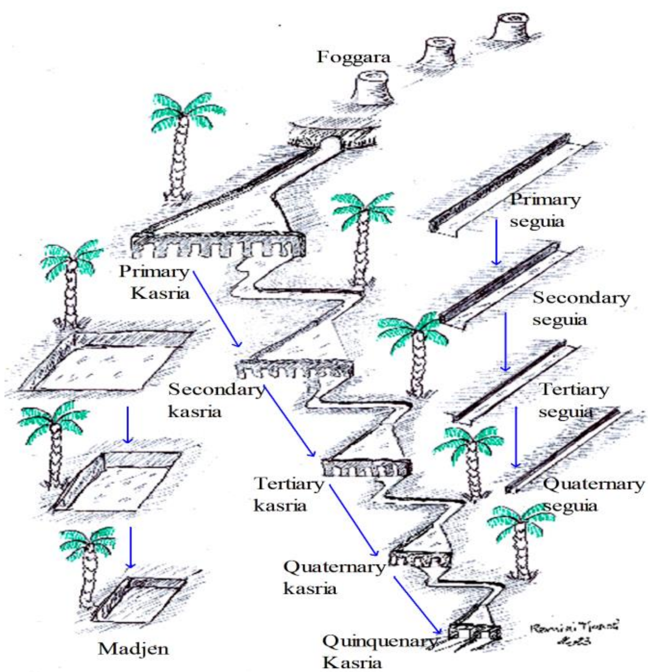


Figure 32: The decrease in kasria from the top to the base of the triangle (Remini, 2023a, Remini, 2023b)

a) Mega kasria of a foggara in the Augrout oasis (Photo. Remini, 2014)

b) Micro kasria in an oasis of Timimoun (Photo. Remini, 2019)

c) Micro kasria in an oasis of Timimoun (Photo. Remini, 2019)

Figure 33: The triangular division of the kasria

The madjens are basins of different volumes that are sized according to the flow rate of each co-owner. Each madjen ensures the irrigation of an area of the palm grove without excess or deficit of water. Figure 34 (a and b) represents the irrigation flow as a function of the area of the gardens. The recent data are not representative since the boreholes have influenced irrigation by foggaras. For this reason, we used the old data since irrigation was carried out only by the foggara system at that time. It is interesting to note the existence of a linear law between the irrigation flow rate and the irrigated area. This proves the effectiveness of the triangular network, and therefore, we can say that it is proof that the foggara ensures the water security of the oases.

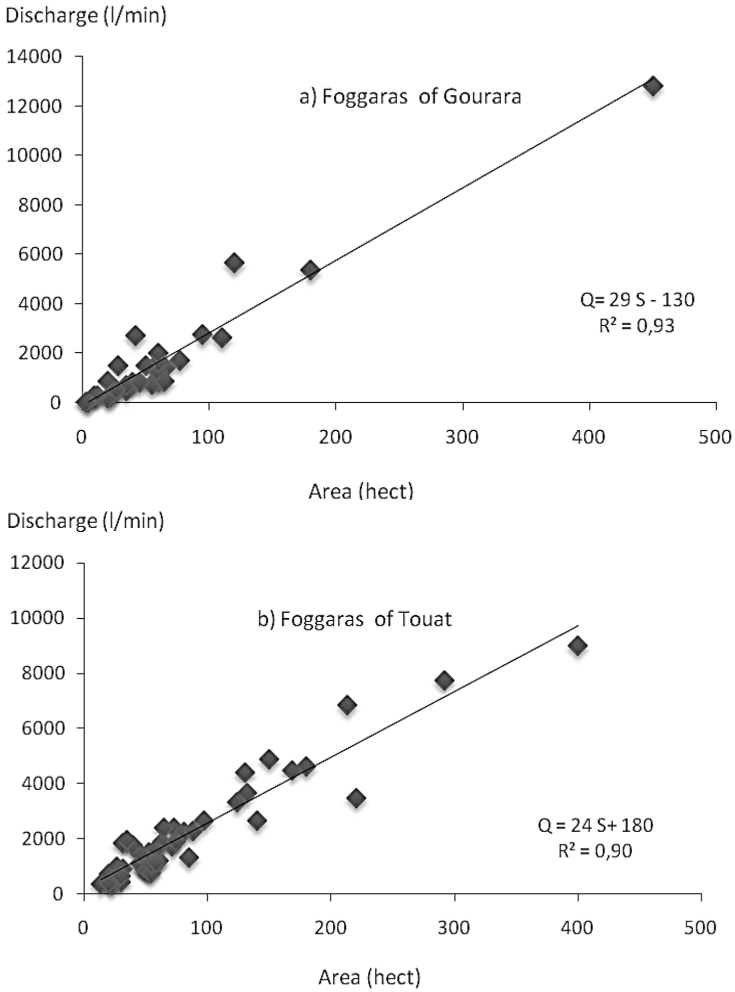


Figure 34: Relationship between irrigation flow and irrigated area in the oases of Touat and Gourara (Remini, 2011)

The two parts of the foggara, namely, the gallery and the distribution network, evolve over time according to the water demand for irrigation and the supply of ksar. Therefore, at the beginning, the foggara system is composed of a gallery and a triangular distribution network; it is a young foggara (Fig. 35). As the foggara is an evolving hydraulic system, the initial gallery of the foggara increases in length in the first stage following the growth of the drainage section. Then, in a second step, several branches of galleries are added to the main gallery to obtain a branched network of galleries. Similarly, the triangular network expands over time following the arrival of new co-owners; it is an old foggara (Fig. 36).

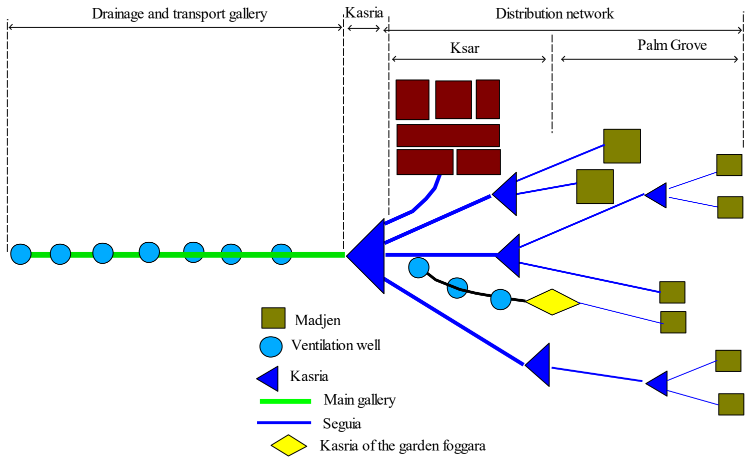


Figure 35: Diagram of a network of a young foggara (Diagram Remini, 2023)

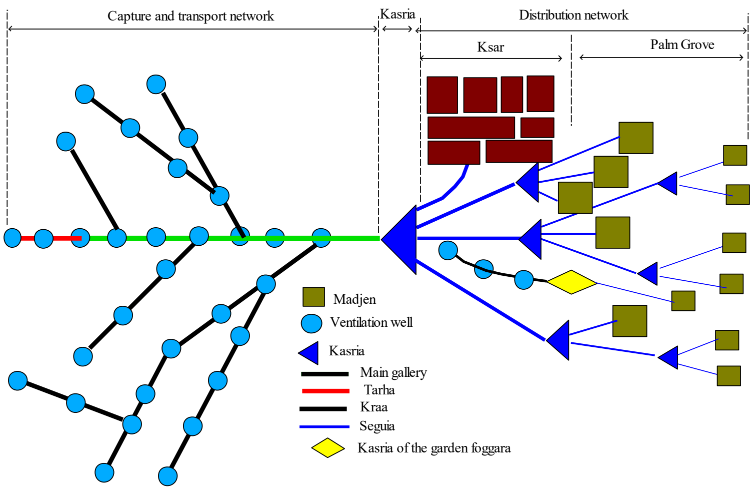


Figure 36: Diagram of a network of an old foggara (Diagram Remini, 2023)

During our 2008 visit to the oases of Timimoun, we discovered for the first time small foggaras in gardens of a hundred meters that we named garden foggara (Remini et al., 2015). After investigations, it turns out that these mini foggaras generally belong to a single family capturing water from the infiltration of the classic foggara to reuse it in irrigation (Figs. 37 and 38). This confirms that no water loss is tolerated at the oasis level. In arid regions, water regains its value.

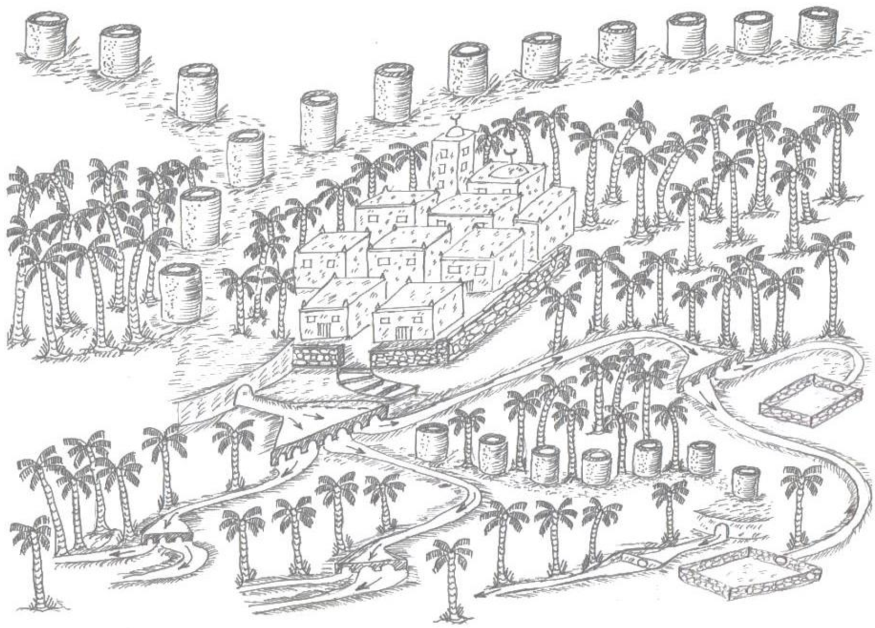


Figure 37: Diagram of a Garden foggara (Remini, 2022)

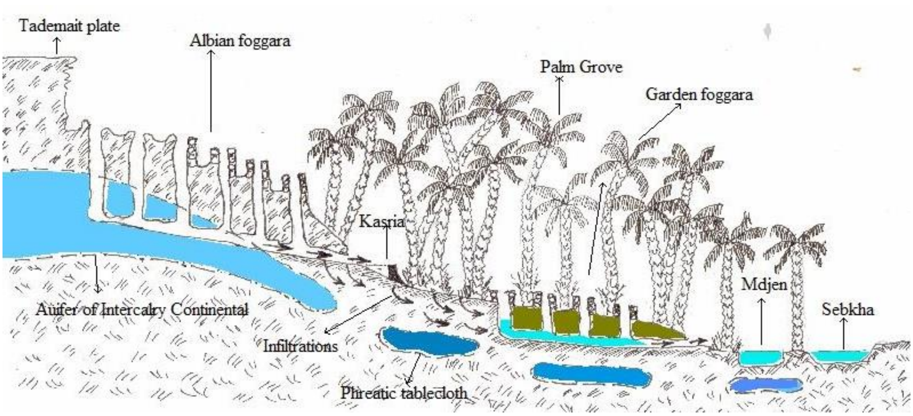


Figure 38: Diagram of a longitudinal section of Garden foggara (Remini, 2022)

The kial el ma

The kial el ma is the genius of this hydraulic system, which deals with the sharing of water between the owners of the foggara (Fig. 39). All measurements of the flow of the foggara and the quantity of water of each subscriber are the work of the kial el ma. Called hallafa in the oases of Tidikelt and louh in the oases of Timimoun (Remini, 2019; Remini and Ghachi, 2019). A flow meter has been invented, and it is within the reach of kial el ma. All transactions and gauging operations are recorded in a register called Zemmam, a confidential document that remains with kial el ma. Everything is noted by kial el ma with the dates and the calculation steps. Laws and regulations have been established by the Djemaa (the council of elders), which oversees the proper functioning of the foggara system. El Hassab is the calculator or the mathematician of the oasis. It accompanies the kial el ma in these hydrometric and water sharing operations. It is he who takes care of the calculation of all transaction operations. In some oases, this function is attributed to the kial el ma.

Figure 39: The kial el ma of the Gourara oasis (Photo. 2008) (Remini, 2019; Remini and Ghachi, 2019)

The hallafa

This is the foggara flow meter, and it is based on the theory of flows through orifices. At the level of the oases of Touat and Gourara, a flat rectangular plate pierced by holes of different sizes. It is called hallafa in Touat and louh in Gourara (Fig. 40). However, in the oases of Tidikelt, the hallafa takes the form of a rectangular cylindrical wall

Figure 40: Quantification of foggara flows and water shares in the oases of Timimoun (Photo. Remini, 2008)

According to the technical bibliography, the flow rate through an orifice is given by the relationship $Q = S_0 \sqrt{2gh}$, which is the work of Torricelli. This relation was obtained in 1638 (Carlier, 1972). However, in 1732, after the discovery of head losses, Bernoulli established the relation of the flow: $Q=C_d S_0 \sqrt{2gh}$ (Carlier, 1972). By applying the flow rate relationship while fixing the water height h by a benchmark. It is quite simply sufficient during a gauging operation to establish a permanent flow when the level reaches the mark fixed on the copper plate. This steady state is obtained by closing and opening the orifices with the clay paste. Once the free surface stabilized around the marker, we counted the number of open holes. Each opening corresponds to the unit of measurement called habba, which corresponds to the flow obtained by the relationship $Q=C_d S_0 \sqrt{2gh}$. In each oasis, there is a hallafa that was designed for 2 or 3 foggaras of this oasis. Such a difference is expressed by the choice of the reference point of the water level in the hallafa, which is expressed by the height h in relation to the flow. An experimental study was conducted to measure the flow of a foggara through a triangular weir and the hallafa (Figs. 41 and 42). The results obtained indicate the same values, which proves the effectiveness of hallafa.

Figure 41: Operation of measuring the flow of the foggara of El Meghier by the louh (Photo. Remini 2007)

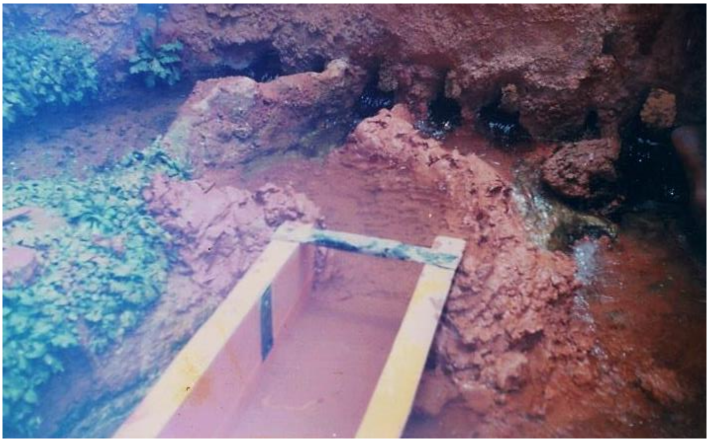


Figure 42: Operation of measuring the flow of the foggara of El Meghier by the triangular spillway (Photo. Remini 2007)

What we can draw as a conclusion in this study is that the hallafa, the ancestral flow meter, was scientifically designed using the flow rate law of orifice flows long before being established by the works of Torricelli (1668) and Bernoulli (1732) since the foggara was made more than 10 centuries ago.

The oasis people invented their own units of measurement using the number 24 as a base. This choice was justified by dividing it by all the numbers, namely, 1, 2, 3, 4, 6, 8, 12 and 24, to the submultiples of the units. (Table 1).

Table 1: Submultiples of the unit of measurement for volumetric foggaras (The habba z'rig) (Remini and Ghachi, 2019; Remini, 2019)

Fraction of the habba	Submultiples		
	Number of kirat	Number of Kirat-El-Kirat	Number of kirat–El-kirat-El-kirat
1/24	1	24	576
1/12	2	48	1152
1/8	3	72	1728
1/6	4	96	2304
¼	6	144	3456
1/3	8	192	4608
½	12	288	6912
2/3	16	384	9216
1	24	576	13824

Exploitation of all water sources

The discovery of the foggara completely changed life in the oases. The success of the foggara in the regions of Touat, Gourara and Tidikelt has favored its export to other oases of Algeria, such as Saoura (Remini and Rezoug, 2018; Remini et al, 2010) and Ahaggar (Remini and al, 2014b; Remini 2022). Approximately 52 countries on all continents of the planet except the Australian continent (Remini et al, 2014c) have benefited from the implementation of this particular work. However, to take advantage of all the water sources available in each environment, the oasis dwellers adapted the foggara of Touat, which was supposed to exploit the Continental Intercalary aquifer to all the types of water sources existing in the Sahara. This is how we identified 9 types of foggaras (Table 2) (Remini, 2022).

These results indicate that the oasis dwellers have exploited all the water sources. Only the garden foggara; a small foggara, which is located inside the palm grove. It is intended to exploit the leaking waters of the foggaras of the Erg or the Albian, which infiltrate into the basement. This explains the rational exploitation adopted by oasis dwellers to ensure the water security of the oasis.

Table 2: Types of foggaras (Remini, 2022)

N°	Types of foggara	Water source exploited
1	Albien foggara	Aquifer of Intercalary Continental
2	Erg foggara	Tablecloth of the Erg
3	Wadi foggara	Inferoflux Tablecloth
4	Ain foggara	Natural water source
5	Ouakda foggara	Water table
6	Garden foggara	Infiltration waters
7	Kenadsa foggara	The mountain tablecloth
8	Foggara de Mzab	Flood waters
9	Ziban foggara	Natural water source

CONCLUSION

The foggara is not a simple hydraulic structure, as it has been described by several authors in the technical bibliography, but the foggara is rather a hydraulic system that consists of an upstream part consisting of an underground gallery and equipped with a multitude of ventilation shafts. The downstream part is represented by the distribution network, which begins with the kasria lakbira, a triangular basin that receives all the groundwater from the gallery, which will then be shared and distributed by kasrias and seguias of different sizes (Fig. 14).

There are seven essential elements that form the foggara system, all of which contribute to the rational management of water; therefore, this ingenious system ensures the water security of the oasis. The slightest mistake in a hostile arid region risks causing poor water management, and consequently, desertification remains the only way out.

The rational management of water in oases must be taken as an example for any study on water security. Indeed, foggara has ensured the water and even food security of oases during the last 20 centuries. The oasis remains one of the oldest regions on the planet that successfully achieves water and food security through foggara. Whether in quantity or quality, it has supplied the oasis with drinking water and irrigation without excess and without deficit. Thanks to oasis genius and know-how, the foggara remains the only hydraulic system that can provide continuous water in quantity and quality in a hostile region such as the Sahara while protecting and preserving the environment. This is the result of the operation of this hydraulic system. Made up two parts. The upstream part is composed of an equipped gallery and a multitude of aeration wells that ensure the quantity and quality of the water. The second part represents the distribution and sharing network different from other existing networks, such as branched and meshed networks. This triangular-shaped network begins with Kasria lakbira and ends with the smallest possible flow. The triangular network is the ideal network that adapts to the arid climate since it reflects the rational management of water in the oasis.

All water sources used included the Continental Intercalary aquifer, the Erg aquifer, the Inferoflux aquifer, the groundwater aquifer and natural water sources. However, what caught our attention is the existence of small foggaras (garden foggaras) in the palm groves. It is a mini foggara with a length of 100 to 200 meters, which is dug in the middle of the gardens to draw the water infiltrated from the foggaras of the Albian or the Erg. This well justifies the inestimable value of water in the oases. The foggara adequately ensures the water security of the oases.

NOMENCLATURE

Delou: A goatskin pocket attached to a rope from a well

El Hassab: The Calculator

Foggara: Horizontal well

Hallafa or Louh: Rectangular or cylindrical plate in copper perforated by different openings

Kraa: Gallery branch attached to the main gallery

Ksar: City of peasants

Seguia: Canal

Ksaria: Triangular basin whose base is a divider.

Kasria Lakbira: Great Kasria

Kial El Ma: Water measurer

Madjen: Storage basin

Traha: Extension of the foggara gallery

Zemmam: Kial El Ma register

ACKNOWLEDGMENTS

Thanks to more than 20 years of work in the oases of the Algerian Sahara, I discovered an exceptional population. I have never had any problems with accommodation or catering. In contrast, I learned a lot about hydraulics, architecture and agronomy. The ksourians are very intelligent people. I take advantage through this paper to thank all this population of ksours from the bottom of my heart. I would also like to thank the foggara; it is thanks to her that I discovered the most beautiful country on the planet. I love you my Algeria. May God protect Algeria.

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