The Durability of the Foggaras (Qanats) Vis-a-Vis the Natural and Human Constraints. A Case Study of Touat Area in Adrar, Algerian Sahara

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***Abstract*—In the world, the foggaras cover a geographical area which would go from China to the Central America and the South. In Algerian Sahara, foggaras are located in area of Touat, Gourara and Tidikelt.. They have four thousand kilometer (4000 km) underground draining galleries for collecting water table. They are confronted with several constraints, such as water quality and the lack of labor for the maintenance of the system. The land development by the irrigation under pressure involved the multiplication of drillings, whose proximity causes the draining of foggaras and their progressive disappearance. This work aims to better including understanding the system of operation of foggaras, in an increasingly competing environment, and to see how to surmount some of these constraints. We recommend, following this study, the precautions to be observed for the use of this water in irrigation, as well as solutions for the reduction of the working time and of the labor and to limit the interference of drillings on the foggaras.**

Keywords* —I *constraints; groundwater; foggaras; drillings. Sahara.

I. INTRODUCTION

The foggaras are a traditional system for collecting groundwater used for irrigation. In the world, they cover a geographical area which would go from China to the Central and South America. Their origin would be Iranian and go back to 3000 years [15]. According to [8], the investigations of [10] conducted in the valley of Soghun and the plain of Shah Maran-Daulatabad in Iran, have contributed substantially to the question of

the introduction of the qanats (foggaras) during the first millenium BC. The qanats were then propagated towards the west and the south of Iran [5]. They are called kanejring in China, qanats in Iran, Azerbaidjan, Afghanistan, Syria and along Jourdan. They are called sahzidji in Yemen and in Saudi Arabia, falaj in Oman,

khettara in Morocco, foggara in Algeria and Libya, kriga or n'goula in Tunisia [13]. They were introduced in Spain and in Morocco (Marrakech) by Omeyades, during the first centuries of Islam [14]. These systems were introduced after the Spanish conquest into the New World, mainly in Western Mexico under the name of galérias, at Atacama, in Peru and Nazca and Pica in Chile [5]. According to Hassani [6], in the Algerian Sahara, the foggaras have been introduced at the 11th century by "El Malik El Mansour", which would have dug the first at Tamentit to 15 km of Adrar. The development of an intensive agriculture in their geographical area, throughout the World, the rural migration and the absence of labor for the maintenance of the qanats, are one of the causes of their progressive disappearance. The Algerian Sahara, accounts for 84% of the entire surface of the country. It is characterized by weak precipitations (less than 100 mm/year), strong thermal amplitudes and by a vital need of mobilization of the water resources necessary to the agricultural and economic activities. Many zones of the Algerian Sahara are very rich in groundwater. That allowed in the areas of Touat, Gourara and Tidikelt, an important establishment of this traditional system of collecting groundwater for the irrigation in spite of the poor quality of these last. Over the past few decade we have witnessed, to a slow and progressive disappearance of this clever system. The 2004, census conducted by the National Agency of the Hydraulic Resources (NAHR), emphasized that over the 1400 foggaras of the area of Adrar; only 907 are still in activity. Each year, 1 to 2 foggaras are abandoned [12]. In the arid regions, this technique is a completely powerful means which has the advantage of providing continuous flows without any work of pumping out and any exploration: water runs out continuously by gravity from the higher zone of the watertable to the exit of the gallery. The counterpart is a certain wasting of water in period of weak use. Instead of sprinkling the grounds located upstream, the foggaras them serve the grounds located downstream, which are often the most saline grounds and poorest "sebkhas". The causes of their decline are especially of social, technique and environmental order. Among the social causes, the lack of maintenance due to problems of heritage between descendants of the same family and exploiting the same one foggara, the massive rural exodus of young people from small towns towards large urban

centers, and the non-transfer of the activity to the young generation. The progressive disappearance of "kial el ma" and the "chouhouds" (People in charge of the distribution of water shares resulting from foggara, and solving conflicts or disagreements between irrigants). Among the technical causes: *(i)* collapse and the landslides in the foggaras which cross the cities, caused by the installation and traffic exploited by the population; *(ii)* the complexity of cleaning with large scales of muds and the deposit of silts in the galleries, to maintain the flow of the foggaras stationary; that requires skilled and experienced labour force [12]; *(iii)* Water losses by infiltration, estimated between 10% and 20% of the drained total flow, in the gallery of collection of water, located at the downstream of the drainage gallery [2]; *(iv)* The facility of acquisition of the water well drillings using pumping systems, contrary to the foggaras. The exploitation of water by pumping, involves strong folding backs since the Sixties, installation date of the first major drilling in the area of Adrar. The difficulties of coexistence between the traditional system and the modern processes of water collecting (drillings) are sources of problems and conflicts which are likely to even put in danger the existence of foggaras [11]. Among the environmental causes, the collapse of foggaras following the floods resulting of believed from the wadis. Thus three foggaras crumbled in the town of Timimoun following the floods of 2003 [12]. The stranding remains also a thorny problem, because any sand wind has as consequences the stopping of the flues ventilating of the galleries of foggaras, the filling of the "kasriates" (device of distribution of engage water shares resulting from foggaras) and of the irrigation channels of distribution of water. The silting and obstruction of the galleries by the roots of the plants "Terza" [12]. The current stake is to guarantee the durability of this traditional system. It will be necessary to better know the effects induced by water quality used; to determine the profile of foggaras to improve their performances and to reduce the losses by percolation which occur in the part known as inactive by calling upon modern technologies of water conveyance; to reduce the care and maintenance of the galleries; to find solutions to limit the effect of folding back caused by the proximity of drillings. To analyze these aspects, we chose some foggaras located in the area of Touat which we used as case of study.

II. MATERIAL AND METHODS

A. Material

Touat is located at Adrar, region in the central Sahara of Algeria country, located at sixteen hundred kilometers (1600 km) to the South West of Algiers. It extends on a surface from 455395 km², on the western south edge of a vast unit called the Aquiferous System of the Septentrional Sahara (ASSS) which covers Algeria (700000 km²) Tunisia (80000 km²) and Lybia (250000 km²). Being given the conditions of the sahara climate, these aquiferous formations are slightly fed [1]: approximately 1 billion $m^3.an^{-1}$ on the whole, infiltrated primarily starting from the piémonts of the Saharian Atlas in Algeria, Dahar and Djebel Nenfoussa in Tunisia and Libya and starting from the direct infiltration of water of precipitations. The theoretical total reserve of the Continental Intercalaireaquifer (CI), according to the NAHR [9] is estimated at 6.10^{13} m^3. The examination of the topography of the area of Adrar shows that all foggaras are located in the periphery of the plate of Tademaït (Fig. 1). The use of this clever system of drainage, developed with the favor of the existence of topographic and especially hydrogeologic conditions which are: the presence of shallow groundwater tables with static level between 13 and 30 m and can reach 200 m on the level of the plate of Tademaït in drillings of Ain Belbel and the existence of a natural depression [2]. We estimate at approximately 4000 km (half in Touat) the overall length of the drains of this existing type in the whole of the Algerian Sahara. The totality of the oases of Touat irrigated by this system covers a surface of 4000 ha [9]. For better including the effect induced by some of the constraints than we presented, three important parameters were the subject of analyzes: the water quality exits of foggaras, the knowledge of their profile and the interference of

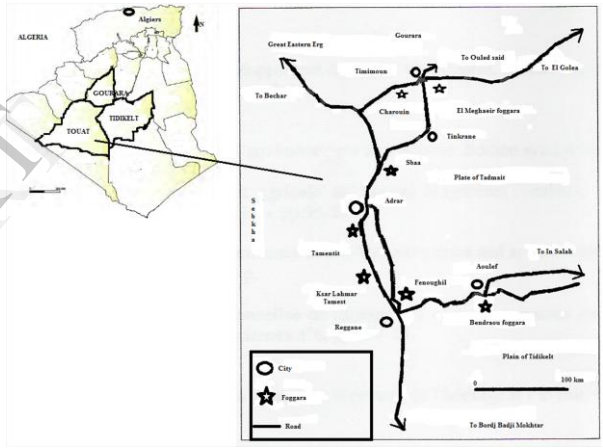

Figure 1. Map of the Adrar study area showing location of the selected sampled localities.

drillings on foggaras. The foggaras and all the measurements covered in this study are located in the oases of Machraa, Tinkram, Aoulef, Charouine and Ait Youcef (Fig. 1).

B. Methods

B.1. Foggaras water quality. Water resulting from two principal groundwater aquifer (CI) and Terminal Complex (TC) which feed the foggaras, are of poor quality. Ten samplings, were made on water feeding the foggaras of Ait Youcef, Machraa and Tinkrane, located in the palm plantation of Ikkis (Fennoughil) at 70 km at the south of Adrar, on the axis Adrar-Reggane, and in those of Aoulef (southern of Adrar, between Reggane and In Salah) and Charouine (80 km in the north of Adrar, between Adrar and Timimoun; (Fig. 1). The goal is to know the contents of calcium, magnesium, potassium and pH. The analyzes were carried out at the laboratories of the Adrar NAHR (2011).

B.2. The knowledge of the profile of the foggaras. The collecting of the water of the surface zone of the groundwater aquifer by the foggara, is assured at the upstream of the gallery by drainance on the level of section DF, water is then transported towards the exit by the means of the section downstream AD where losses occur by percolation (Fig. 2). The determination of the profile of the foggaras requires the estimate length of the 2 parts, draining (DF) and inactive (AD) that makes it possible to locate the importance of the inactive part. The inactive part of the foggara is the seat of water escapes per infiltration, which decreases by as much the collected flow. The foggara which was the subject of measurements is that of Ait Youcef at Ksar Lahmar (Fig. 1). It was necessary to make an inventory of all the wells of the foggara over all its length by GPS; the layout of the piezometric chart; the depth of the gallery of the foggara, measured with a probe. What makes it possible to carry out the approximate layout of the profile of the gallery and that of the curve of depression of the groundwater aquifer. The intersection of the 2 curves constitutes the zone which shares the two parts of the foggara (draining and inactive).

B.3. The interference drillings-foggara. The exploitation of water by pumping, involves strong folding backs on the level of the groundwater aquifer. The foggara is certainly influenced by pumping since drilling. When several drillings and foggaras pump the water of the same groundwater aquifer, their zones of call (of action) will superimpose themselves and consequently create an interference between the works and which will modify the characters of the zone of call (extension) and thus the fictitious radius of each of them. To explain this problem of interferences we have applied the approach to the foggara of Machraa in the area of Ikkis. The expression which was used in the study for determination of cut of the works of collecting is the Theis well function (1). It is supposed that their limits of application exist. Generally the formula is used in the mode of not-balance and the conditions for application are those of the test of well: laminar flow and homogeneous isotropic medium; complete well, i.e. collecting all the thickness of the aquifer, reaching the substratum and strainer on all its height; well correctly developed and equipped; piezometric surface subhorizontale; flow of constant pumping.

Moreover the hydrodynamic type of aquifer, bases calculations, must answer the three following characteristics: confined groundwater aquifer; with impermeable substratum and roof.

The expression of Theis, [3] applicable to all the devices of testing station is:

$$s = \frac{Q}{4\pi T}\int_u^{\infty}\frac{e^{-u}}{u}du \text{ For } \frac{Q}{4\pi T}W(u) \text{ With } u = \frac{x^2}{4Tt}S \quad (1)$$

The term W (u) is a decreasing integral exponential function of type $-E_i$ (-u). It is the function of the well (Well function) given by tables.

$$w(u) = -0.577216 - \log u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4.!} + \cdots$$

The calculation of the variable (u) was made for the various periods of pumping: 1 day, 1 month and 6 months (frequencies of pumping of drillings).

The significance of the symbols is the following one:

S: folding back measured in a piezometer in m;

Q: flow of constant pumping in m^3/s;

T: transmissivity in m^2/s

S: coefficient of storage without dimension

t: time passed at one moment given since the beginning of pumping in s;

u: variable of integration without unit

x: out distance piezometer with the axis of the wells in m;

Note: in our case, x is the distance between drilling considered (foggara) and the drilling which influences. The distance between selected drilling and foggara is very variable because each part of the drainage gallery constitutes a point of collecting. To solve this problem, in the study was taken the distance between the drilling and the two extreme points of the drainage gallery (P1 at the end F and P2 at the end D; Fig. 2) provided that the length of the latter is equal to half the overall length of foggara. The cut will be calculated on the level of these two points and in this way it is possible to consider the influence of pumping in drilling and on foggara and to see whether this influence is partial or total.

The hydrodynamic parameters used are:

T average = 1.938 10^{-3} (calculated starting from the test results of pumping); S = 10^{-3} [2].

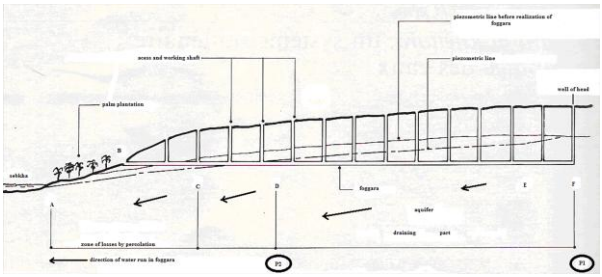

Figure 2. The *operating principle* of a *foggara*

Table.1. Physico-Chemical characteristics (mean and range values) of foggaras water sample for the all localities.

Elements	Minimal value	Maximum value	Average	Standard deviation
pH	7.19	8.13	7.85	0.17
CE (ms/cm at 25°C)	2.04	11.46	4.73	2.09
Ca me l^{-1}	4.2	41.75	8.14	7.01
Mg me l^{-1}	0.66	29.16	11.70	5.16
Na me l^{-1}	9.56	71.73	25.70	14.04
K me l^{-1}	0.51	12.30	2.03	2.68
SAR	3.72	20.01	8.29	4.09

III. RESULTS

A. Description of foggaras water quality

In table 1, a synthesis of the results of analysis is presented, including the values maximum, minimum, as well as the mean value of the water samples taken in 33 foggaras quoted, for the analyzed factors at Adrar NAHR in 2011. The results emphasize that 82% of the water samples have a pH higher than 8. For sodium, 75% have contents which surplus 10 me/l. 70% of water have contents higher than 4 me/l for calcium. For magnesium, 56% of the samples have values higher than 5 me/l. For potassium 94% of the values are higher than 0.51 me/l. Almost all water has a mineralization lower than 2000 mg/l.

B. The profile of foggaras

Here, we reported only the results of the Ait Youcef (Ksar Lahmar) foggaras. The length of draining part (DF) is about 1500 m accounting for 52.64% of the total length, with a slope of 5.47 10^{-4}. However, the length of inactive part (AD) is about 1350 m accounting for 47.36% with a slope of 9.52 10^{-4} (Fig. 2). The lengths of the two parts are rather close; this is the most frequently encountered case.

C. The interference drilling-foggara

The results of calculations show that the influence of drillings on the values of folding back on the level of the drainage gallery results in: with the upstream on the level of the point P1 (s=2.17 m), with the downstream on the level of the point P2 (s=1.40 m). The median value of the slope in the drainage gallery (DF) is of I=0.547 10^{-3} and the median value of the slope in the inactive gallery (AD) is of I=9.52 10^{-3} (Fig. 2).

IV. DISCUSSION AND CONCLUSION

In this investigation we have enumerated the principal's difficulties and constraints with-which foggaras are subject, and make their maintenance more difficult. For the constraints which we had analyzed, above many solutions can be proposed to improve operation of foggaras. The use of water, of poor quality, present risks of alkalinization. According to the pH and alkalinity, hardness higher than 200 mg/l of $CaCO_3$ can cause layers of sediment. Water of the area of Charouine is hard; the values obtained in foggara of Tinkrame ranged from 300 mg/l of $CaCO_3$ to 2410 mg/l. In the Aoulef area, hardness ranged from (300 and 810) mg/l. Among analyzed water, 75% are currently used in the irrigation of the cultures and are of poor quality according to the diagram of Riverside (US Salinity Laboratory Staff, 1954) and can present risks of alkalinization. The use of this type of water in agriculture requires some care such as the choice of textures, the addition of amounts of scrubbing to the needs for the cultures and the systematic practice of the drainage. However in all these zones irrigated by this water, the drainage is not a known practice. The multiplication of drillings for irrigation associated with extensive and intensive application of fertilizers for cultures, whose effects on the water table, in the area, are not yet well identified. This impact is not negligible. Reference [7] highlights the impact of the excessive use of fertilizer in the zones of collecting of the qanats of Shahrood (Iran), where median values of the nitrate concentration are among 14.5 mg/l and those out of phosphate of 0.105 mg/l. High values of the concentration out of Ca (36 to 54) mg/l, Mg (14 to 39) mg/l, pH (7.97 to 8.41) and the fact that hardness exceeds the limits recommended highlight the influence of carbonates on the composition of subterranean water.

Concerning the profile of foggaras, the measurements carried out at Ait Youcef (Ksar Lahmar), the results of the inventory of the Adrar NAHR (2004) consolidate which has made it possible to better know this system of collecting and to say that indeed consists of two different parts but generally of the same length foggara it: upstream a part known as activates (draining) which penetrates in the water table and a part downstream (inactive) seat of important escapes by infiltration, which makes it possible to transfer water towards the gardens. The slope of the inactive part is generally higher than that of the draining part. The length of the two parts of foggara is conditioned by only one parameter, which is the topography of the area and only measurements on ground make it possible to fix the real length of each part. The downstream part, inactive section AD of foggara, constitutes a transitory zone connecting the draining zone, section DF, and the irrigated palm plantation. Its variable length is proportional with the folding back of the surface of the drained sheet of water. When drained water crosses this section, a part is lost by infiltration. The quantity thus lost by infiltration is all the more important as the length of the inactive section is large. The proofing of this part constitutes the only solution which makes it possible to recover the volume of water lost

by infiltration. Knowing with precision the length of the inactive part of foggara, one could, to improve the flows of exit, to plan to install in the inactive galleries of the PVC conduits (diameter from 150 to 200 mm). The losses by percolation (10 to 20) %, thanks to the installation of these conduits, would be thus completely eliminated. They would have there no more also, of problems of care and maintenance in these galleries which generally account for (40 to 50) % of the totality length of the galleries of foggara and which could even be embanked. In addition, the risks of collapse of these inactive galleries, especially in urban areas, due to the vibrations of the ground caused by the passage of the vehicles, would be eliminated.

The advent of drillings and their multiplication, to meet the requirements out of water for irrigation in this area for the Sahara, are likely to precipitate the disappearance of the mode of foggara. They drain water of groundwater aquifer of CI. The water resources of this system are not renewable. Each extracted volume influences total volume, which results in the continuous folding back of the static level of the groundwater aquifer. According to model ASSS, in the area of Adrar where the groundwater aquifer of CI is free on a broad surface, the piezometric fall observed between 1950 and 2000 were from (5 to 20) m in 20 years in Gourara; (3 to 28) m in (30 to 35) years in Touat and (5 to 10) m in (30 to 35) years in Tidikelt. The measurements taken on the influence of drilling close to foggara of Machraa in the area of Ikkis show that there exists a real danger of draining of the latter. To rehabilitate this will foggara with the traditional methods, the farmers have only two solutions (Fig.2):

First solution, to look further into the bed of the gallery of foggara between P1 and P2 from 1.4 to 2.17 m. One will keep a homogeneous slope of $I=0.547\ 10^{-3}$. Since P2 until emergence foggara, to have a value of h ($1.4\ m \leq h \geq 0\ m$). The slope between these two points will remain $I=9.52\ 10^{-3}$. The result of this process is the displacement of the ″kasria″ (comb), towards the downstream of the palm plantation. I.e. one will prolong the part downstream of the foggara (AD) of 147 m, thus one increases the rate of loss of the water drained by linear infiltration in the inactive zone not draining ranging between the end downstream gallery drainage and the exit of water towards outside (between D and A).

The second solution, to upstream prolong the gallery drainage (DF) by keeping a homogeneous slope about $I=5.47\ 10^{-4}$. To reach the folded back level of the sheet of water, it is necessary to dig a new drainage gallery; its overall length will be approximately 3967 m. Let us note that the advance of the part draining upstream in the case of foggara of Machraa will complicate the current location, because it will be under the influence of the zone of call of the drillings located in the fields of collecting of Ksar Titaf. The most adequate solution in this situation is the reorganization of the field of collecting of the area of Tamest where Ksar Titaf is.

The low flow which characterizes the majority of foggaras of the area of Ikkis, ranging between (1 and 3) l/s [12], returns primarily to the nature of the geological formations which contain groundwater aquifer. The geological cuts on the drillings carried out in the area, show that this groundwater aquifer is consisted alternations of argillaceous sandstone and clays red and sandstone. The average permeability of this groundwater aquifer is of $1.686.10^{-5}$ $m.s^{-1}$. In the field of collecting of foggaras, it varies between (3.2 and $1.5\ 10^{-5}$) $m.s^{-1}$ [2]. Generally these values characterize not very permeable formations [9].

According to Remini [12] the services of hydraulics of Timimoun, estimated the ray of influence of drillings at 1.7 km, likely to cause a lowering of the water level in foggaras which would be in this zone. Compared to the problems of interferences involving of the folding backs of groundwater aquifer, it is possible to correct the flows of pumping of drillings which have an influence on foggaras, that would make it possible to reduce or eliminate this phenomenon of interference. In the medium term, it would be a question of digitizing the topographic charts on which will be localized the foggaras, their underground grids and their flows. That would make it possible to be able to decide at the time of the establishment of new drillings, of the sites which would not cause phenomena of interferences drillings-foggaras and drillings-drillings [2].

Currently, it is difficult to proceed to the realization of news foggaras, because of the lack of qualified labor and of the cost of the operation. The maintenance actions are rare. One can however quote some cases of maintenance of foggaras, as in Ksar Kali (Timimoun) where the population is an example for the others oases, the foggara it of Ifan bara was rehabilitated there in 2002 and that of Ksar Aghlab in 2004 [12]. The foggaras of Amehri and Bamoussa at Ouled Aissa, area of Timimoun, also profited from an operation of rehabilitation for the replacement of the concrete irrigation channels by PVC conduits 160 mm in diameter [4].

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