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# LEAKAGE, EVAPORATION AND SEDIMENTATION AFFECTING WATER STORAGE IN ARID AREAS: CASE STUDIES OF THE FOUM EL GHERZA AND GARGAR DAMS, ALGERIA

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**ABSTRACT**

Most dams in arid areas face storage losses from leakage, sedimentation, and evaporation. We assessed these losses at the Gargar and Foum el Gherza dams in Algeria based on a long-term dataset supplemented by physicochemical analyses. Leakage and evaporation were the main loss pathways at the Foum el Gherza and Gargar dams, respectively. Estimated total losses were 46 $hm^3$ (about 98% of total capacity) and 166.8 $hm^3$ (about 37% of total capacity) at Foum el Gherza and Gargar dams, respectively. Water and capacity losses should be assessed at a case-by-case level to generate effective solutions for implementation in Algerian dams.

**Keywords:** dam leakage, arid areas, foum el Gherza dam, gargar dam, water losses, dam reservoir sedimentation, surface water evaporation.

## INTRODUCTION

Most dams are subject to a loss of capacity caused by some combination of the following three factors: structural or geological water leakages; sedimentation of the dam reservoir; and evaporation, which is particularly intense in arid regions. Algeria currently has more than 50 operational dams with a total capacity of 5 billion $m^3$, providing an annual volume of 2 billion $m^3$ of water for drinking, industry, and irrigation. Most Algerian dams have a lifespan of about 30 years; however, it is rare to abandon a dam so soon, especially when the reservoir holds water intended for irrigation or drinking.

Water leakages from dams result in considerable loss of valuable water resources and seriously threaten structural stability. While most dams in Algeria are threatened by leakage, losses particularly affect those that are situated in arid and semi-arid areas where economic development is closely linked to water availability. The Hammam Grouz dam, eastern Algeria, is subject to average leakage of around 50,000 $m^3$ $day^{-1}$ caused by implantation on a site with cracked hard rocks (such as limestones). Subsequent increase of hydrostatic pressure caused the deterioration of the rock massif alongside the deterioration of the structural waterproofing measures [3] [15]. In previous work [4], we estimated total average losses of 25 million $m^3$ $year^{-1}$ for the period 1988-2011. In some cases, leakage was so substantial that a collection system was put in place to recover water lost downstream and redirect it to farmland.

Dam sedimentation is the outcome of the natural process of erosion of the surrounding land and stream banks. Successive deposits of sediment cause reduction in reservoir capacity and affect water quality. This phenomenon is particularly prevalent in dry and semi-dry regions such as the Maghreb. Sedimentation is estimated to have caused annual losses of more than 50 million $m^3$ across Algerian hydrotechnical infrastructure [1] [2] [15]. The sedimentation of dams is one of the most dramatic consequences of hydraulic erosion; approximately 180 million tons of sediment are annually eroded from banks and hillsides into rivers in the North of Algeria [13]. The Sidi M'Hamed Benaouda dam, Relizane, received a sediment volume equal to 6.7 million $m^3$ $year^{-1}$ during the period 1995-2003 [1] [15]. In dry areas, high concentrations of fine particles have been recorded in wadis in flood periods, which are rapidly transported via overland flow to dam entrances [22]. These flood periods typically arise after a long drought (6-7 months), during which the dry ground is particularly favorable for erosion. The substantial reduction of water storage capacity is undoubtedly the most dramatic consequence of sedimentation; every year the level of sediment within the reservoir grows, causing considerable volume losses.

Algeria has been affected by a sustained dry period for more than 20 years. Reservoirs and lakes in arid areas are subject to intense evaporation due to high air temperatures (especially in the dry season), consistent solar radiation input, and strong, dry winds (especially in the autumn and spring). In Algeria, average annual evaporation losses from 39 large dams was 250 million $m^3$ $year^{-1}$, representing 6.5% of the total capacity [1] [8]. This evaporated quantity represents half of the volume consumed by irrigation, industry and as drinking water. The greatest levels of evaporation recorded in Algeria occur within the Saharan zone where the evaporated volume even exceeds the quantity of water intended for drinking water supply and irrigation [2]. This occurred between 1992 and 2002 at the Djorf Torba dam, commissioned in 1963, with a capacity of 350 million $m^3$. Losses reached 90 million $m^3$ in 1994, representing approximately twice the total volume required for consumption [1] [5]. The ANDT currently takes daily measurements of evaporation from 39 major dams with a total capacity of 3.8 billion $m^3$. The annual average over the period 1992–2002 was 250 million $m^3$ (6.5% of total

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capacity) with a range of 100-350 million $m^3$ [1] [15]. These data highlight a clear evaporation gradient: in the coastal zone (up to 50 km from the sea) annual evaporation is <0.5 $m^3$ $year^{-1}$, compared with a band 50-150 km from the coast, where it is 0.5–1 $m^3$ $year^{-1}$.

Earlier work has analyzed variations in reservoir volume as a function of losses by leakage, sedimentation and evaporation [1] [15]. However, until now, no detailed analysis of the ANDT data has been performed and there has been no recent assessment of the loss of capacity at the level of dams most threatened by leakage, sedimentation and evaporation. Our research group has identified 15 dams at which losses exceed 1 million $m^3$ $year^{-1}$. In six cases, leakage exceeds 5 million $m^3$ $year^{-1}$, including the Gargar and Foum el Gherza dams. These dams are extremely susceptible to leakage and a gradual reduction in their storage capacities has been observed over time. The Foum el Gherza dam provides irrigation for valuable palm plantations and thus water losses have a high potential economic threat. The Gargar dam is the third-largest in Algeria and is located in an arid zone where water resources are becoming increasingly scarce. The dam supplies water for the irrigation of 16,000 ha of the Lower Cheliff plains and supplies drinking water to the city of Oran and nearby towns and villages.

In this study, as an update to previous work [4], we examined water storage capacity losses at the Foum el Gherza and Gargar dams based on leakage, sedimentation and evaporation data from the ANDT. Furthermore, piezometer analyses were applied to better understand the leakages occurring at Foum el Gherza and provide recommendations for appropriate repairs. In light of our study concerning water leaks and capacity losses at these two Algerian dams, we can produce appropriate recommendations for solutions to these problems. It is necessary to handle the problem of water capacity losses case-by-case to produce targeted strategies to conserve water resources.

## METHODS

### Site descriptions

### Foum El Gherza

The Foum El-Gherza Dam is situated in the south of the Saharan Atlas (southeast Algeria), 18 km east of Biskra, and regulates the flow of the El Abiod River (Figure-1). It is an arch dam (126 m) with concrete abutments (60 m each) with an initial capacity of 47 million $m^3$. Its maximum height is 73 m. The dam was constructed during 1948–1950 on the most appropriate site in the region and became operational in 1952. The reservoir covers an area of 3 $km^2$ and has a capacity of 16.5 million $m^3$. This dam has great economic value in the region as it provides irrigation for over 300,000 date palms in the palm groves of Sidi Okba, Garta, Seriana, and Thouda [1] [15]. The dam has helped these regions to withstand drought for about 20 years and has allowed the agricultural development of the region [1].

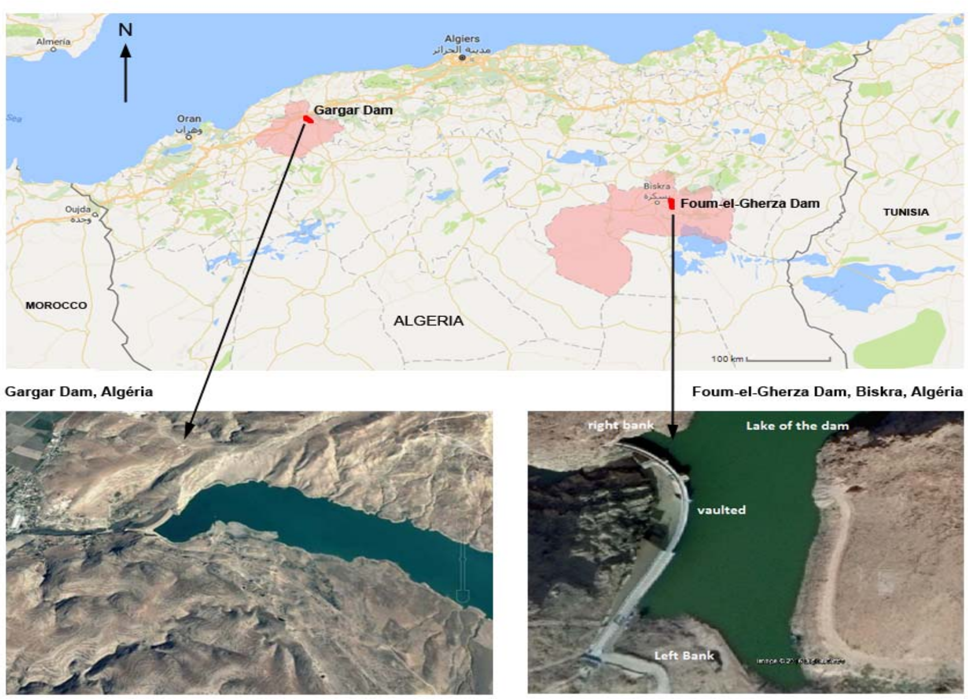


**Figure-1.** Location of the Foum el Gherza and Gargar dams with aerial photography of the two dams and their reservoir lakes. Map data: Google, DigitalGlobe, CNES/Airbus; source: own elaboration.

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Average annual leakage of 5 million $m^3$ has been estimated by the ANDT, with a peak of 20.7 million $m^3$ during 1980-1981 [2]. Much of these losses are due to the implantation site of this dam on crystalline limestone Maastrichtian rocks (Figure-2a) fractured to a depth of 80 m [10] [11] and lying above Campanian marl (Figure-2b) [11]. The watershed covers an area of 1300 $km^2$ with a perimeter of 200 km. On the cliffs on the right bank, downstream of the dam, significant discontinuities are visible (cracks and faults) and whose extension directions are almost parallel and perpendicular in the river. These discontinuities promote water losses from the reservoir. The aquifer system in this area consists of three layers: alluvial aquifer contained in alluvial deposits, Mio-Pliocene aquifer contained in the Tertiary and Saharan continental Quaternary formations, and limestone aquifers of the Senonian and Eocene sandstones that lose water naturally through springs [15] [19].

The average temperature in the area is 22.9°C. The average annual precipitation is 250 mm with high interannual variation (a range of 86-420 mm between 1950 and 2015). Precipitation is uncommon in the middle of autumn and early spring; rainstorms occur quite frequently in June and August but they are generally scarce. The short-term but heavy rainfall in the catchment area often leads to violent short-term floods during which the torrential river carries heavy sediment loads, leading to siltation in the dam reservoir.

Vegetation surrounding the reservoir is highly limited with continuous degradation of forest cover caused by human activities and fires. The steep slopes, the degraded vegetation and irregular heavy rainfall are major contributors to siltation and related capacity losses [2] [15].

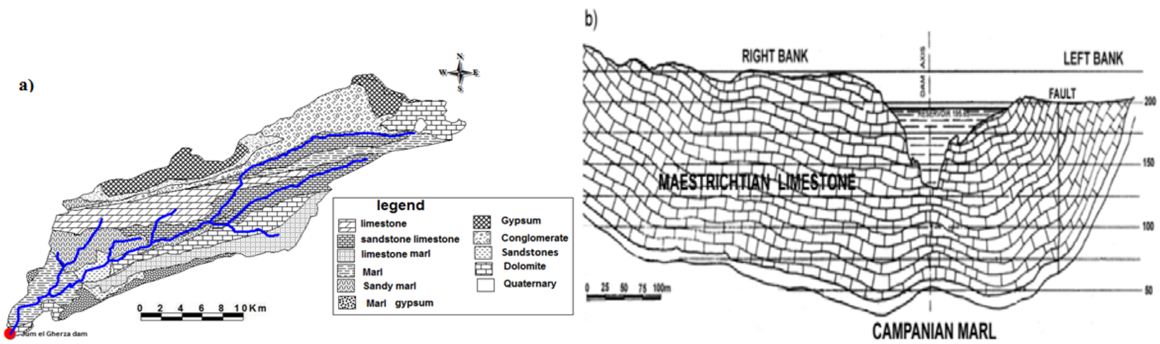


**Figure-2.** (a) Geological map of the watershed of the Foum el Gherza dam and (b) a geological cross section of the dam site; source: own elaboration, (ANDT 2010).

**Gargar**

The Gargar dam is a more recent and larger capacity dam (450 million $m^3$) than Foum El Gherza (Figure-1). The dam is located in Relizane province, 5 km southwest of the village of Oued Rhiou, in the Cheliff-Zahrez watershed. The study area forms part of the Rhiou river watershed, which covers an area of 2,900 $km^2$. Upstream, the valley expands around the village of El Alef to form a natural basin that is largely covered by limestone [3]. At the dam site, the Rhiou River cut a gorge into the limestone cliffs, producing appropriate topography. Although the first study for the construction of the dam was conducted in 1926, works on the dam were not completed until October 1988 and the reservoir was filled in November 1988 [3]. A gorge, carved into the crest of the limestone hills along the southern edge of the Cheliff plain, forms the dam site. Made of clay, the dam created a large reservoir designed to contain the highly seasonal flow of the Rhiou River, with annual average inflow of 185 $hm^3$. The dam's lifespan has been estimated at about 150 years [2].

The dam supplies water for the irrigation of 16,000 ha in the Lower Cheliff plains and supplies drinking water to the city of Oran and 15 other towns and villages in the Relizane and Mostaganem provinces. According to the National Water Plan, the Lower Cheliff irrigation perimeter is 50 $hm^3$ $year^{-1}$ and an average of 97, 000 $m^3$ $day^{-1}$ (35 $hm^3$ $year^{-1}$) is needed for drinking water supply. It is predicted that nine locations in Relizane province will require 13 $hm^3$ $year^{-1}$ [1] [2] [15].

Geologically, Tortonian marl is covered by a discontinuous limestone ridge of the same age (Figure-3). The river bed contains thick deposits of recent alluvium consisting of sand, gravel and pebbles, together with silt and clay. Excavation of the dam site [3] found that the alluvium extends to -115 m, -42 m at the coast and -38 m along the axis of the dam's river channel. There is evidence of large variations in the river level in the geological past. Karst features, though small, are frequently found on both the right and left banks of the river. Excavation of the spillway found funnel structures and underground channels filled with silt or clay as a result of dissolution. The upper area of the dam has extensive recent terraces of clay and silt. The mountainous slopes and ridges overlooking the gorge are smooth, showing that they were levelled by sediment transport when the sea level was much higher than the present day [21] [3].

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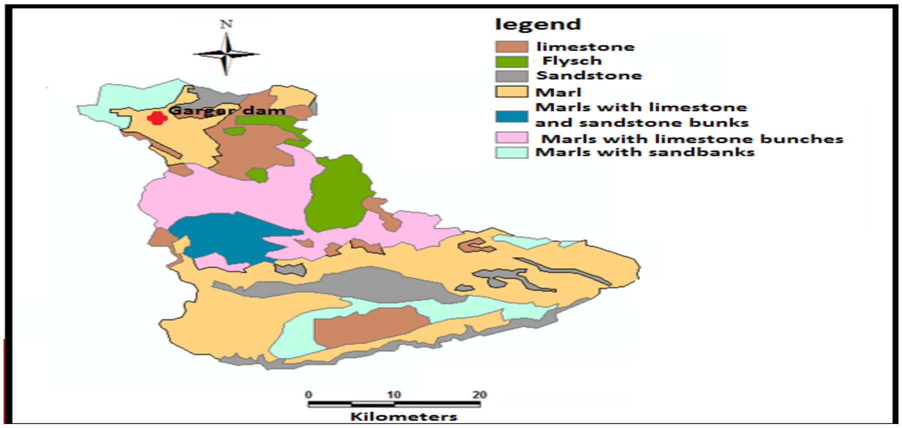


**Figure-3.** Geological map of the Gargar dam area; source: own elaboration.

There are two contrasting climates within the Gargar dam watershed. The upper basin is characterized by a rainy mountainous climate, with relatively low temperatures and heavy snow. The lower basin is characterized by a relatively warm, dry climate with high temperature variation. Average monthly temperature in 2006 ranged from 8.40 to 39.84°C with an annual average of 18.2°C. Annual average precipitation of 300 mm was recorded by the ANDT for 1990-2008 with a highly variable range of between 150 and 400 mm.

In contrast with the Saharan vegetation of Foum el Gherza, vegetation within the Gargar dam watershed is dominated by *Olea europaea*, *Quercus ilex*, and *Pinus halepensis*. *Thuja* spp. dominate to the west of the Rhiou river, but this highly resistant genus is subject to ongoing degradation due to human activities and forest fires [3] [15].

**ANDT Datasets**

Inflow data from 1950-2012 and leakage data from 1950-2010 were provided by the ANDT for the Foum el Gherza dam. Reservoir levels, leakage, sedimentation, and evaporation data for the Gargar dam were provided for the period 1988-2015. The chemical and physicochemical data were provided by the ANDT and the National Agency of Water Resources.

**Water leakage measurements**

Water leakage at both Foum el Gherza and Gargar dams were measured using measurements of daily leakage flows to produce an annual estimation of the leakage flow (in $hm^3$ by volume). To make these daily estimates of leakage, the ANDT used a tub of water and a chronometer to measure the time taken for the tub to fill, allowing an estimation of the leakage flow at each bank.

At Foum el Gherza, leaks were assessed at the output of a gallery by a weir V allowing a fairly accurate assessment of the flow. Sensing systems and measurements were also carried out on the left bank, a few hundred meters from the dam. It should be noted that the decrease of the flow of the leaks during the last decade was caused by measuring devices filling with mud released from the dam and is thus inaccurate [2]. An identical technique was used to measure the water leakage at Gargar. These assessments were made during the period 1950 to 2010 at Foum el Gherza and 1994-2015 at Gargar. To verify these estimates, an annual balance sheet was created by the ANDT for each dam, summarizing all water losses including exploitation of the dam reservoir, volume of mudding, volume of the water released, volume losses thorough drainage, the evaporated volume, and the siltation volume. The siltation volume and evaporated volume were estimated as described below. Based on evaluation of the inflows into the dam reservoir and the outflows and sedimentation, the agency estimated the annual volume of the dam leakages to verify the assessments made using the *in situ* water tub method [1] [2] [15].

**Sedimentation measurements**

An estimate of sediments conveyed by river flows and runoff in the basin of dams and evaluation is required to assess sediment volume. At Foum el Gherza, bathymetric surveys based on echo sounding techniques were established by the ANDT in 1952, 1967, 1975, and 1986 for regular monitoring of sedimentation, water height, and reservoir capacity. In June 2003, the Algerian Office of Education launched a study to evaluate the storage capacity and monitor sedimentation at the Gargar dam based on bathymetric and topographic surveys [1]. Depth profiles were established at 50 m intervals in the area 1,000 m from the dam, and at intervals of 100 m beyond this limit. The bathymetric survey, covering a total area of 1,319 ha, was carried out between 20 January and 10 February, 2004.

In all surveys, a study profile was pre-selected and a sounding line (deep water, precision approximately ±20 cm) or echo sounding device (low water heights) was used to assess the water depth from a boat. Based on the known initial profiles of the reservoir floor, the volume of accumulated sediment was estimated in each dam reservoir.

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**Evaporation measurements**

The hydric balance sheet method is based on the equality of inflows and the outflows of the volume of water in the dam, taking into consideration of the variation of storage. The evaporation in volume of water (VE, $m^3$) was determined by the following relation:

$$VE = VP + VS + VST - VQS - VQST \pm \Delta V, \qquad (1)$$

where VP is the precipitation volume, received by the dam, $m^3$; VS is the superficial volume of water entering the dam, $m^3$; VST is the underground volume of water entering the dam, (exfiltration), $m^3$; VQS is the evacuated volume of water, $m^3$; VQST is the underground volume of water leaving the dam, $m^3$; and $\pm\Delta V$ represents the storage fluctuations within the dam, $m^3$. This evaporation estimation method is little used because of the imprecision and because of the difficulty in measuring most of the components of Equation (1), especially the belowground inflow and outflow.

Therefore, assessments made using this method were supplemented by assessment using iron galvanized evaporation tubs (1-5 m diameter, 10-70 cm depth). These measurements were operated by the National Office of Meteorology (ONM) and National Agency of Hydraulic Resources (ANRH). This approach is similar to that of the hydric balance sheet but with the total absence of subterranean flows and infiltration losses. The simplified equation can be expressed as follows:

$$EBac = \Delta H \pm P, \qquad (2)$$

where EBac is the evaporation from the tub, mm; P is the precipitation falling in the tub, mm; and ΔH is the height difference of the water contained within the tub between two measures, mm. The conversion of the evaporation of the tub to the evaporation of the stretch of water is made by multiplication of the results by a coefficient (K) representing the tub material, type, size and weather conditions. In this study, K was taken to have a value of 0.7-0.8.

**Field measurements at Foum el Gherza**

To confirm and supplement the ANDT dataset, we measured the physicochemical parameters of water samples (pH, electrical conductivity (EC), and temperature) taken at different depths at the piezometers at Foum el Gherza dam (Figure-4) during February and March of 2011 and December 2012. We also used a staff gauge to record water depth and a tub of water and chronometer to assess leakage and verify the estimates from the ANDT, which were shown to be accurate. The dam was at capacity and thus 4 of the 26 piezometers on each bank were available for measurement.

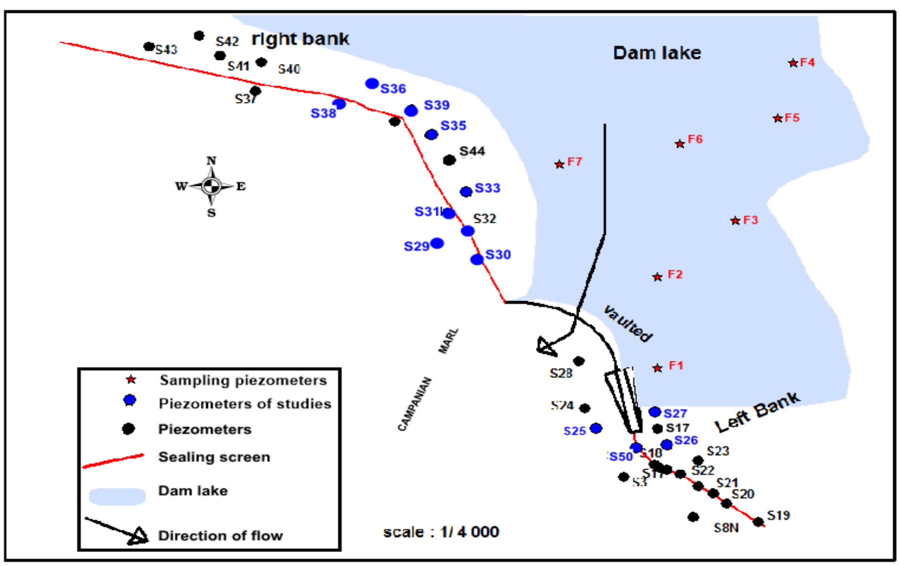


**Figure-4.** Map of the Foum el Gherza dam indicating the arrangement of piezometers and lake water sampling position(s); source: own elaboration.

On each sampling day, we took 15 to 20 samples at each piezometer and measured pH, temperature and EC in situ using a combined pH probe and conductivity meter. The water level was measured using a standard electric water level meter, which sounds when the electrodes touch the water level in the monitoring well. We also sampled groundwater from seven boreholes located in the immediate vicinity to establish possible interconnections. The water samples were taken in clean flasks, rinsed with distilled water then stored and transported in the dark in an ice box. Samples were placed into flasks and hermetically closed without introducing air bubbles. Samples were preserved in a refrigerator in the dark at 3-5°C. Samples were processed as soon as possible after flask closure.

The chemical analyses were conducted at the laboratory of the ANRH. Analysis was conducted for $Ca^{2+}$ and $Mg^{2+}$ (complexometric titration), $Na^+$ and $K^+$ (flame spectrophotometry), $Cl^-$ (colorimetry, 470 nm), $SO_4^{2-}$

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(precipitation with $BaCl_2$, followed by turbidometry), $HCO_3^-$ (reaction with mineral acid and measurement of $CO_2$ release), and $NO_3^-$ (colorimetryin a UV photometer, 440 µm). The EC at 25°C and the dry residue were also recorded.

## DATA ANALYSIS

Linear regression analysis was used to assess the relationships between leakage flows and reservoir volume or lake water height. All data were processed using Microsoft Excel 2016 for Windows (Microsoft, WA, US).

## RESULTS AND DISCUSSIONS

### River inflows and reservoir volumes

There was extremely high variability in the annual flow of the El Abiod River into the Foum el Gherza reservoir with annual inflow average for 1950-2012 estimated at 22.19 $hm^3$ $year^{-1}$ (Figure-5a). Floods of the El Abiod River, which can be violent and sudden, are associated with heavy precipitation from local storms in summer or Saharan depressions in spring and often again in autumn. Accordingly, solids transported by the river are not generated continuously but are related to floods, with high levels in October and December. At the Gargar reservoir, inflows from the Rhiou river were similarly variable with peak levels of inflow of over 150 $hm^3$ punctuated by years in which inflow was less than 20 $hm^3$ (Figure-5b). Annual inflow average during the period 1990-2009 was estimated at 72.58 $hm^3$ $year^{-1}$ [4].

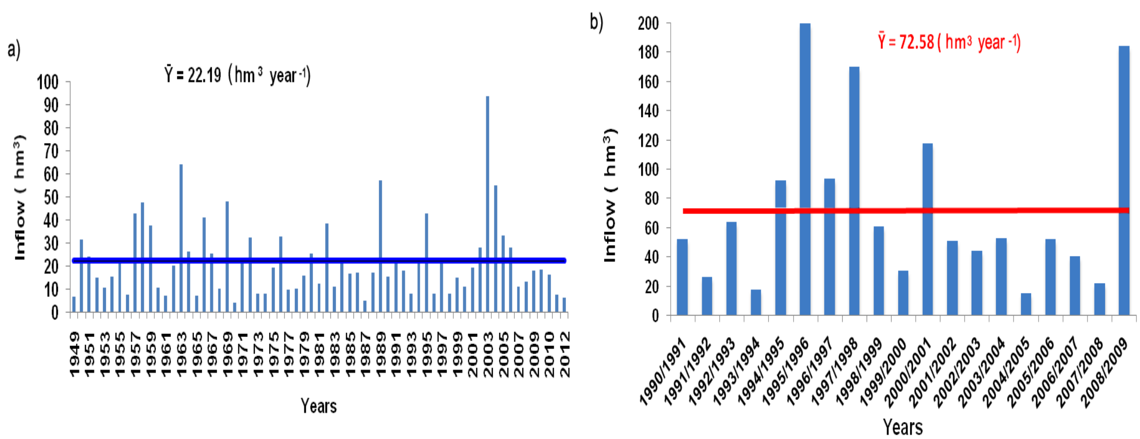


**Figure-5.** Variation of inflows over time in (a) the El Abiod River at Foum el Gherza and (b) the Rhiou river at Gargar (horizontal lines indicate the annual average over the same period); source: own study.

Figure-6a shows the variation of the reservoir volume of Foum el Gherza dam over time. There is a clear decrease in reservoir volume with time; the volume was initially about 46.84 $hm^3$ in 1950/1951 and decreased considerably to 1.49 $hm^3$ in 2009/2010. This decrease may be explained by water leakages threatening the useful capacity of the dam and also by the recurrent drought affecting Algeria in recent years. Figure-6b shows the variation of the reservoir volume of the Gargar dam from 2004-2008. Overall, the volume has decreased from over 100 $hm^3$ in the 1990s to 20-30 $hm^3$ between 2007 and 2012. The recovery of capacity after 2012 may be attributed to the exceptional increase in precipitation in recent years [5].

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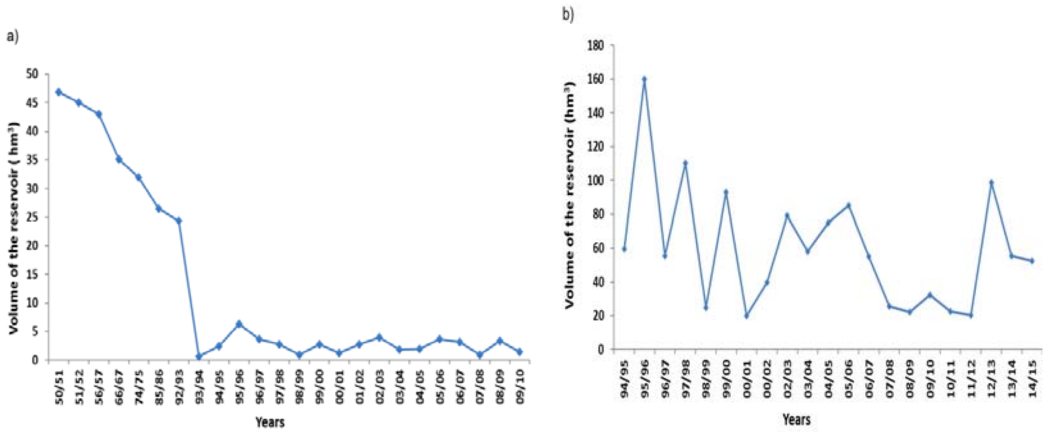


**Figure-6.** Variation of the reservoir volume over time at the (a) Foum el Gherza and (b) Gargar dams; source: own study.

**Water losses through leakages**

In this section, we consider the variations in total volume of leakage and leakage flow and their associations with variations in volume and lake water level of the two reservoirs. In Figure-7a, we present the variation of the volume of leakage at Foum el Gherza over time for hydrological years from 1950 to 2010. Just after the dam filling in 1952, leakages started to appear immediately downstream of the dam (1.6 million $m^3$ in 1952/53 and 2.0 million $m^3$ for the next two years). Construction was then resumed between 1954 and 1957 including reinforcement of the hydraulic works and the injection of a grouting curtain. Large leakages of 10.44 and 8.71 $hm^3$ occurred in 1959/1960 and 1989/1990 because of the deterioration of the grouting curtain and the increased precipitation during those years. These increases in leaks suggest that the waterproofing effect of the grouting curtain is no longer effective, allowing further deterioration in the underlying massif and foundations of the dam. However, reduction of precipitation led to a corresponding decrease in water leakage in later years [5] [20].

In Figure-8a, we consider leakage according to flow rate. Water leakage flow increased from 56 L $s^{-1}$ in 1993 to 180-190 L $s^{-1}$ in 1996; however, the reduction of the water volume in the reservoir caused substantial decreases in leakage flow, reaching 20 L $s^{-1}$ by March 1994 and 10 L $s^{-1}$ by August 1997. The total flow increased steadily after 1994 and later reached record values exceeding 180 L $s^{-1}$. The decrease or increase of leakage flow primarily occurs according to the progressive reduction or gradual increase in the volume of water in the reservoir. We identified a clear positive relationship between the leakage flow and reservoir volume at Foum el Gherza ($R^2$ = 0.89), with lower leakage flow occurring at times of low reservoir volume during reduced precipitation. Moreover, we identified a positive relationship ($R^2$ = 0.99) between total water leakages and the lake water level, due to the high hydrostatic pressure exerted by the reservoir water on the bottom and the banks of the dam [7].

To further identify the source of the leakages at Foum el Gherza, we assessed leakage flow from the two banks separately. The leakage rate on the right bank gallery was greater than the left bank at the same water level (192.4 or 194.3 m). For example, in the left bank, 14.5 and 16 L $s^{-1}$ was recorded at water level of 192.4 and 194.3 m, respectively, whereas in the right bank, leakages were estimated at 39.0 and 57.3 L $s^{-1}$, respectively (data not presented). Seepage occurred in both banks. The leakages on the left bank were relatively low and were collected within a small irrigation channel which follows the riverbed towards the irrigated areas. On the right bank, leakage occurred via a two-row network of drains within the irrigation gallery. The larger leakage flows on the right bank than the left bank may be caused by the more degraded state of the geological layers in the right bank than in the left bank. This is examined further in the next section.

The average annual loss of water through leakage at the Gargar dam was 0.3 $hm^3$ $year^{-1}$. Figure-7b shows leakage volume estimated by the ANDT for the period 1994-2015 and highlights significant variation over time with leakage volumes peaking in 1997–1999 because of increased precipitation.

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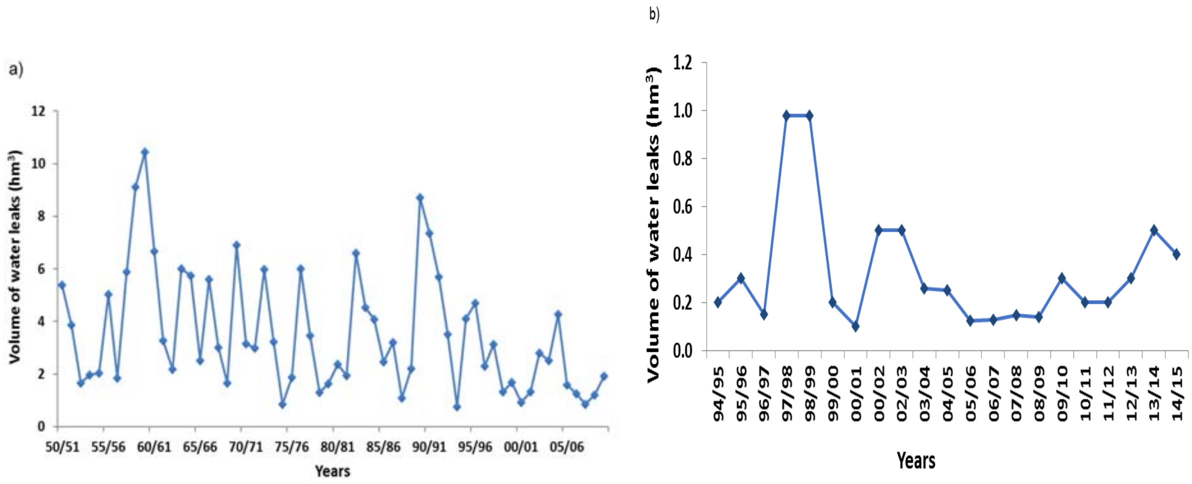


**Figure-7.** Total annual leakage calculated for the (a) Foum el Gherza and (b) Gargar dams; source: own study.

Figure-8b indicates leakages in terms of flow rate. Maximum leakage of 8.5 L $s^{-1}$ was recorded in February 2004, reaching 12 L $s^{-1}$ in May 2004. Levels subsequently decreased due to falling water levels in the reservoir, reaching 2.18 L $s^{-1}$ in January 2008 [2]. We further assessed leakage flow from the two banks separately. Flow rate through the left bank exceeded 4.3 L $s^{-1}$ in February 2004, reaching 5.98 L $s^{-1}$ in May 2004. The flow rate subsequently decreased, due to the reduction in the volume of water in the reservoir, reaching 0.81 L $s^{-1}$ in January 2006. The flow rate through the right bank exceeded 4.6 L $s^{-1}$ in February 2004, reaching the same value as the right bank (5.98 L $s^{-1}$) in May 2004. Like the left bank, the reduction in the volume of water in the reservoir led to a considerable decrease in the flow rate, reaching 2.25 L $s^{-1}$ in November 2006. The upstream body of water at the foot of the dam is separated from the basin by a cofferdam. Although leaks were observed in the joints of the injection and drainage galleries of both banks, they were greater in the right bank. This is because the right bank is in contact with the reservoir, while the left bank is in contact with the body of water located upstream of the dam. Leakage in the two galleries increases as a function of reservoir level increase and decreases due to sealing after a long period. Some leaks are sealed by the adhesion of molten limestone [1] [2].

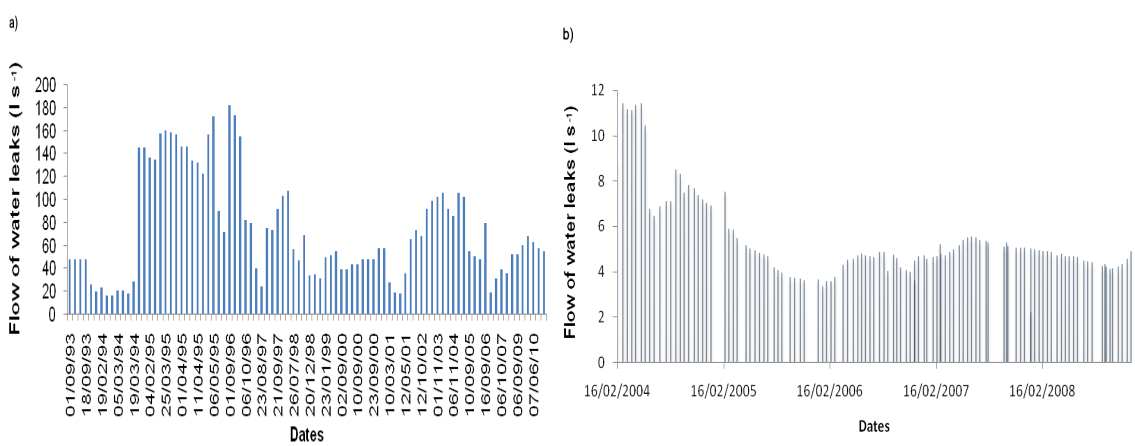


**Figure-8.** Variation of leakage flow rate over time calculated for the (a) Foum el Gherza and (b) Gargar dams; source: own study.

Similar to Foum el Gherza, we found a clear positive relationship between the total leakage and reservoir volume at the Gargar dam ($R^2$ = 0.89), with lower values of leakage flow occurring at times of low reservoir volume during reduced precipitation. Moreover, leakage flow rate decreased as a function of reservoir volume ($R^2$ = 0.72). There was also a clear positive relationship between total leakage volume and the reservoir level ($R^2$ = 0.98) and between variation in flow rate and reservoir level for all hydrological years ($R^2$ = 0.72). Moreover, flow rates gradually increased to a reservoir level of 98 m, beyond which there was a more rapid increase (data not presented). This could be because flow is governed by Darcy's law and depends on the permeability of the massif at reservoir levels up to 98 m. Above 98 m, underground flows no longer follow this law and instead pass through highly permeable layers or faults. This increase was particularly remarkable for the hydrological years 2004-2005 and 2005-2006. Increasing hydrostatic pressure due to the progressive increase in the reservoir level caused a considerable decrease in load, resulting in the deterioration of the rock massif, which translated into major cracks [1] [2].

Gargar dam is positioned on fairly complex and faulted fractured hard rock with limestone outcrops for some distance each side of the dam's supports and relatively impenetrable marls on the reservoir basin. Lugeon limestone tests were carried out before the project commenced [21] [3] and low values (impermeable strata) were observed despite fractures, faults and micro karst features, characterized by secondary porosity, in some areas (Figure-2). Close to the surface, these cracks are often filled with clay; however, at depth, they remain open until reaching the Campanian marls. This impermeability and the length of flow paths suggest low seepage losses. Although the groundwater level is low, it barely rises above the level of the river. Some water was absorbed into the soil during the establishment of the new groundwater regime. An extension to the grouting curtain of approximately 150 m on each wing could help to locate any other karst areas that could potentially cause leakage if percolation areas developed along pathways in downstream areas [21] [3].

Additional test points would enhance the reliability of leakage measures and make it possible to differentiate leaks in the various galleries (injection, drainage and access). It is also important to observe the progress of cracks, which could expand under pressure if the reservoir level rises [2]. This could be solved by the construction of a screen under the dam at the left and right banks.

**Physicochemical assessment of dam leakages at Foum el Gherza**

Measurements of pH, EC, and temperature enable us to establish the relation between the various bodies of water to determine their hydraulic connection and direction of flow within the piezometer and consequently at the level of the rock massif. In Figure-11, we present the EC and temperature for the accessible piezometers.

The temperature and EC profiles indicate the presence of vertical and horizontal flows. The vertical flows are represented by the approximately constant temperature and EC values. The oblique flows, almost horizontal from the reservoir, are indicated by the lower EC values and homogeneous temperature values [19]. This is an indicator of the degraded state of the geological layers of both banks. The temperature and the EC vary with depth according to the geothermal gradient and geological layers, which further confirms the degradation due to water leak evolution by infiltration [17] [20]. The moderate values of EC (~1000 µS $cm^{-1}$) indicate high mineralization; however, EC decreased with depth towards the Maastrichtian limestone groundwater. This salinity is mainly of geological origin (primary salinity) but could be enhanced by overexploitation. The high mineralization of underground waters of Foum el Gherza dam presents a considerable risk of salinization and belowground water pollution.

The Piper diagram (Figure-12) based on the hydrochemical analysis of the water samples indicates chlorinated calcic superficial groundwater (groundwater and Mio-Pliocene) and copper sulfate calcic deeper groundwater (lower Eocene and Maastrichtian). The dominant anions were chlorides and sulfates and the dominant cations were sodium, calcium and magnesium [17]. The chemical signature shows no relation between boreholes and surface water.

The mineral characteristics of groundwater within Phreatic, Mio-Pliocene and lower Eocene formations were generally poor, with values sometimes not corresponding to drinking water standards [18]. However, groundwaters within Maastrichtian limestones have more acceptable mineral physicochemical qualities.

**Capacity losses through sedimentation**

The Foum el Gherza dam is located in a Saharan region where the river system is torrential and floods are violent, and carries a large amount of solid material from denuded slopes. From 1950 to 1992, ~25 million $m^3$ of silt was deposited in the reservoir, with an annual average of 0.60 $hm^3$ silting causing siltation of 54% [1]. Currently, the dam is silted to about 65% [1]. For example, the average total solids concentration in the year 1979-1980 was 32 g $L^{-1}$ [21] indicating that the Foum El Gherza dam reservoir is subject to strong sedimentation from erosion of the paying pond. We noticed a clear evolution of sedimentation over time according to the height of water in the reservoir of the dam. Continued dredging is imperative given the importance of the dam for irrigation of palm groves. The first dredging operation began in 2005 and lasted 24 months, removing 4 million $m^3$ of sediment. A further alternative, given the advanced sedimentation at Foum el Gherza, is to add height to the dike of the dam to achieve additional volume.

At the Gargar dam, the sedimentation volume was 112.5 $hm^3$ from 1988-2008 with a forecast annual average of 4.6 $hm^3$. In 2008, sediment represented approximately 25% of the dam's initial capacity [4]. By 2015, this volume had increased to 144.7 $hm^3$. Periodic bathymetric surveys are required to assess sedimentation within a dam reservoir. Surveys taken during the first or second year of reservoir exploitation are important indicators of the degree of sedimentation and allow the selection of appropriate reduction strategies. However, at Gargar, the first survey was undertaken in 2004, 15 years after exploitation commenced. Taking its initial capacity as a reference, the reservoir had lost about 91.72 $hm^3$ of its capacity by March 2004 (approximately 20.4%) according to the Algerian Office of Education survey in June 2003. This corresponds to an average loss of about 6,114,600 $m^3$ $year^{-1}$. Its current volume is about 358.28 $hm^3$. Based on the 27% rate of filling of the reservoir in 2014, the Gargar

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dam would be abandoned in 2060 if desilting activities are not taken in the short and medium term [1] [2].

There are several methods that can be applied to reduce the sedimentation problem. A settling pond can be constructed to allow the sediment to settle before reaching the reservoir. This approach was taken at Boughezoul dam and reduced sedimentation by 24% [2]. The causes of sedimentation can be tackled by stabilizing surrounding land through reforestation such as planting of long-stalked vegetation in wadis, stepping of land, and development of gullies. When sedimentation reaches >50%, dredging is likely to be the ultimate solution extend the life of the dam reservoir [1]. Dredging of dam reservoirs has been practiced on several dams during the history of Algerian hydraulics. Unfortunately, despite the considerable sedimentation problem at both Foum el Gherza and Gargar, the dams have received only intermittent dredging. A planned program of bathymetric survey and dredging operations would be beneficial to both dams. Finally, the capacity of the reservoir could be increased by increasing the height of the dam perimeter and thus replacing the lost volume. This was realized at the Hamiz, K' sob, and Zardézas dams with height increases of between 7 and 45 m leading to volume increases of 23 to 31 $hm^3$ [2]. However, like dredging, this can only be considered a short-term management of the situation rather than addressing the cause, and should thus be conducted alongside measures to reduce slope erosion.

**Water losses through evaporation**

Figure-9a shows the evaporation losses provided by the ADNT for the Foum el Gherza dam. The evaporation losses ranged from 0.98 to 6.64 $hm^3$ $year^{-1}$ and the annual average value was approximately 3.8 $hm^3$. The volume lost by the evaporation of the lake and the leaks through banks is similar to that required for the irrigation of date palms (~10 $hm^3$ $year^{-1}$). In 1998/1999, a particularly dry year, the evaporated volume (5 $hm^3$) was twice that intended for irrigation that year.

The analyses presented here are based on operational data provided by the ADNT for the period 1989-2015 [2] [6]. Figure-9b shows losses due to evaporation at Gargar dam. These range from 5-32.2 $hm^3$ $year^{-1}$, with an annual average of 21.6 $hm^3$ $year^{-1}$ [8] [2]. Evaporation is an important issue at Gargar, considering the geographical situation and, particularly, the large surface area of the dam reservoir. At the Gargar dam, the evaporation level has typically remained above the water requirement for irrigation during the exploitation period.

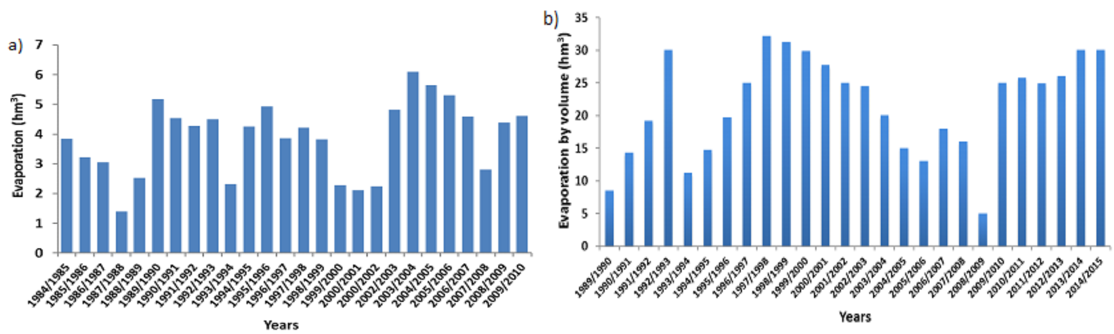


**Figure-9.** Variation of evaporation over time at the (a) Foum el Gherza and (b) Gargar dams; source: own study.

There are several possible approaches to reducing evaporation from dam reservoirs. For example, the surface of the water exposed to the sun can be reduced by floating wax covers (85% polyethylene with microscopic pearls) or other reflective surfaces that change the characteristics of the water surface, reflecting sunlight and reducing evaporation [9]. Fatty acids, amines and ketone bodies can be used to produce a thin coating layer on the water surface and have been shown to have no negative environmental or water quality impacts [15] [17]. Finally, evaporation is more effective under windy conditions. Vegetative and non-vegetative windbreaks can be effective; however, vegetative windbreaks contribute to evaporation through evapotranspiration. Crow (1963) showed that in small reservoirs, non-vegetative windbreaks reduced evaporation by 9% under average wind speed of 4.5 m $s^{-1}$. More research is required to assess windbreaks and other evaporation reduction methods for large reservoirs in arid areas.

## ASSESSMENT OF TOTAL LOSS PROPORTIONS FROM BOTH DAMS

Most dams are strongly threatened by water leakage, excessive sedimentation, and intense evaporation. This phenomenon has become a major threat for hydrotechnical infrastructure, both at the level of reduced useful capacity and decreased structural condition of the dam. Therefore, it is important to assess the overall losses of reservoir capacity to sedimentation and the losses to leakage and evaporation. We estimated these losses as follows (without taking into account losses from the bottom outlet):

$$Lv = Iv + Ev + Dv, \quad (3)$$

where Lv is the total volume loss, Iv is the infiltrated volume, Ev is the evaporated volume, and Dv is the dead volume (all units are $hm^3$ $year^{-1}$).

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The total losses of water and capacity of each dam based on the calculation from Equation (3) and the ANDT data are expressed in Figure-10. The Foum el Gherza dam has lost a volume estimated at 25 million $m^3$ over 42 years from sedimentation, with a water leakage average annual volume estimated at 3.49 $hm^3$ and an annual evaporation volume of 3.38 $hm^3$. We thus estimated the total losses of volume at 32 $hm^3$ for 1992 (about 68% of the total capacity of the dam). We estimate the losses volume in 2016 as follows: average water leakage annual volume is 3.49 $hm^3$, annual volume average of evaporation is 3.38 $hm^3$, and sedimentation volume is 39.6 $hm^3$ in 2016. The total volume of losses was estimated at 46 $hm^3$ (about 98% of the total capacity of the dam). Table-1 shows these losses as a proportion of total losses for the period 1950-2016. We conclude that water leakage and sedimentation are the most important factors that lead to water losses and reduce the capacity of the Foum el Gherza Dam. Thus, it is necessary to control these problems to reduce water losses. Leakage increases with reservoir level over time and these losses are high and strongly affect the total losses of the dam. Losses from sedimentation are less important than those from leakage and evaporation at this dam. The volume lost by the evaporation of the lake and the leaks through banks are similar to those required for the irrigation of date palms [6]. The leakage situation is critical in Foum el Gherza and may threaten the structural stability of the dam. However, because of the geological complexity of the site, more experiments are required to better understand and better address the leakage phenomena. The problem of Foum el Gherza dam is almost certainly due to the poor choice of the site despite the good original maintenance [2] [6].

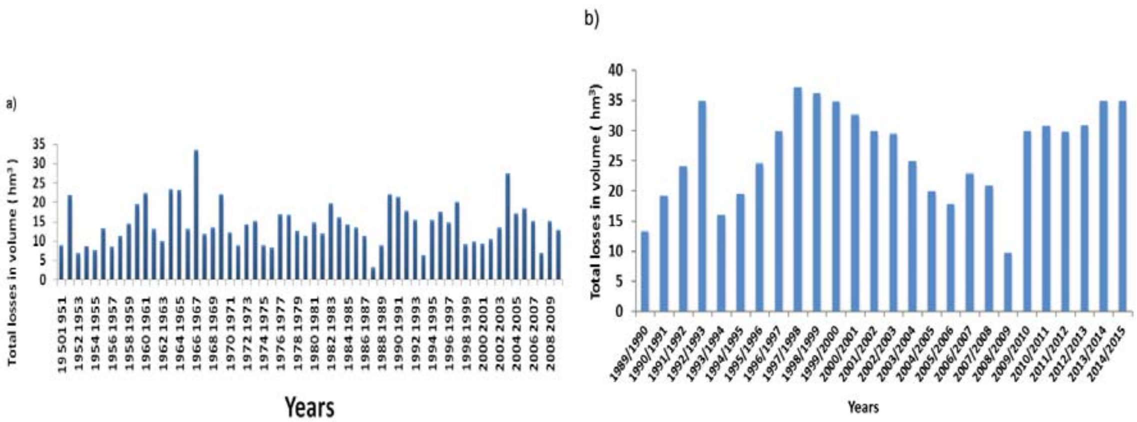


**Figure-10.** Variation of total losses in volume over time at the a) Foum el Gherza and b) Gargar dams; source: own study.

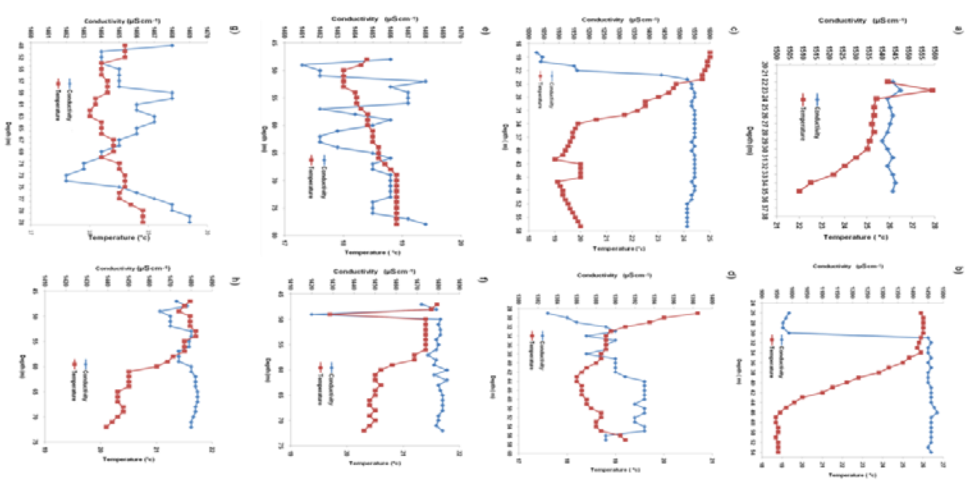

**Figure-11.** Electrical conductivity and temperature profiles for selected piezometers on the left and right banks of the Foum el Gherza dam; a) LB-S25, b) LB-S26, c) LB-27, d) LB-S50, e) RB-S35, f) RB-S33, g) RB-S30, and h) RB-S38; source: own study.

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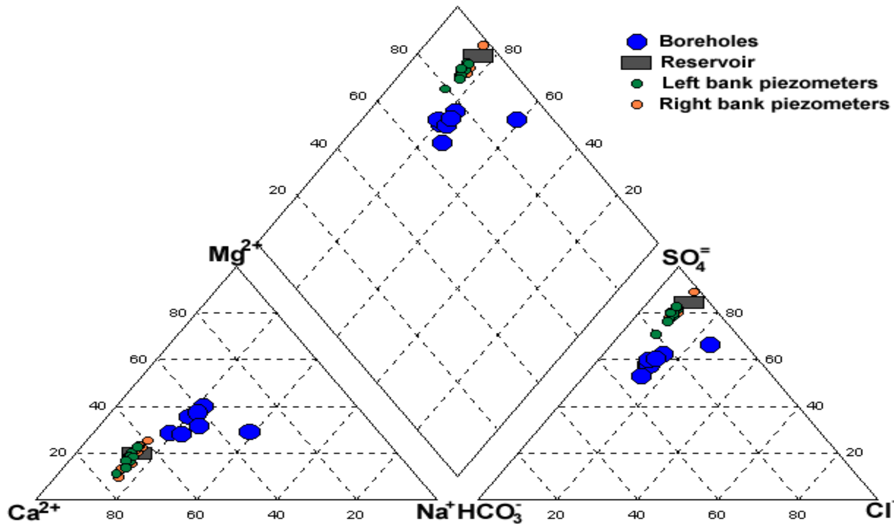


**Figure-12.** Piper diagram to indicate the hydrochemical facies of water from the Foum El Gherza dam reservoir; source: own study.

**Table-1.** Total losses by sector at the Foum el Gherza and Gargar dams (source:own study).

| | **Remaining volume** (%) | **Volume loss to leakage** (%) | **Volume loss by sedimentation** (%) | **Volume loss to evaporation** (%) |
|---|---|---|---|---|
| | | | | |
| Foum el Gherza | < 1 | 47 | 8 | 45 |
| | | | | |
| Gargar | 32 | < 1 | 20 | 48 |
| | | | | |

At Gargar dam, not only have losses increased over time but the problem is ongoing, and the situation is deteriorating. Based on data from the bathymetric survey conducted in 2004 [2], the dam has lost 92 million $m^3$ of water over a period of 15 years. This is due to excessive sedimentation, leakage (annual average 0.3 $hm^3$) and evaporation (annual average 21.6 $hm^3$). Total losses for 2004 were estimated at 113.9 $hm^3$, which represents about 25.31% of total capacity. Taking 2015 as the baseline, current losses are estimated as an average inter-annual leakage of 0.5 $hm^3$, average inter-annual evaporation of 21.6 $hm^3$, and estimated sedimentation of 144.7 $hm^3$. This makes a total loss of 166.8 $hm^3$, representing about 37% of the dam's total capacity. Table-1 shows these losses as a proportion of total losses for the period 1988-2015, and it is clear that evaporation is the major cause of losses from this dam, which is likely to be due to the large surface area of the dam reservoir.

Leakage, sedimentation and evaporation have reduced the capacity of the Gargar dam and threaten the dam's future. Our findings confirm the presence of leaks in both banks downstream of the dam, exacerbated by the presence of cracks. Leaks are especially worrying as flow rate continues to increase due to the deterioration of certain impermeable zones caused, in turn, by hydraulic erosion or chemical corrosion. Our study established that the origin of these leaks is a lack of impermeability at the point where the reservoir meets the groundwater. Therefore, the proposed solution consists of improving the impermeability of both banks with a curtain injection. In addition, losses due to sedimentation and evaporation are considerable at this dam. It is therefore crucial to address the losses of storage capacity in order to minimize environmental damage and ensure that the project remains financially viable.

## CONCLUSIONS

Both the Foum El Gherza and Gargar dams are subject to an accelerated loss of capacity from enhanced sedimentation, intense evaporation and substantial leaks, and are representative of difficulties facing dams across Algeria. Already the Foum El Gherza dam can no longer guarantee the necessary quantities of drinking water and irrigation. This study has indicated that the two dams are threatened by water losses and that the lost volume is increasing over time because of the drought conditions and the deterioration of the waterproof structures of the dam by hydraulic or chemical corrosion. Furthermore, water leaks may be attributed to the continuity of circulation between the reservoir and the groundwater, causing

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substantial reduction in structural leak prevention. In light of our study, we can suggest the following recommendations.

It is necessary to first solve the problem of the water leaks that cause considerable economic and resource losses and present a threat to the stability of many Algerian dams. Such issues typically originate from the positioning of the dams in areas that are geologically favorable to leakage and unfavorable to storage. The second problem is often the choice of the type of the dam, particularly for older dams such as Foum el Gherza. It is necessary to reduce volume losses by infiltration through the dam banks until an acceptable level is reached to safeguard the stability of the structure. The next priority is to take measures to fight dam sedimentation and also reduce losses by evaporation. It is therefore necessary to consider monitoring approaches for siltation and evaporation to increase the storage capacity of the dam, reduce economic losses, and avoid considerable damage to the environment.

Several other Algerian dams are affected by water leaks. Of these 15 are seriously threatened because with losses exceeding 1 million $m^3$ each year. Further studies are planned in our research group to assess water losses from these dams. The positioning and type of new dams must take the flow of the potential leaks and their variations in time into account. Therefore, leakage flow should be more accurately assessed at current sites using tracer methods to ensure sufficient data for preventative applications in future dam construction projects. An exploratory study of the problem of water leaks and their repercussions on the dam is also of primary importance. Moreover, the establishment of a forecast map of the evaporation based on relations between the evaporation and the surface of lakes allows would be valuable for any potential dam project or dam in operation. It is necessary to continue to handle the problem of water leaks at a case-by-case level to generate effective solutions to the problem of water and capacity losses in Algerian dam reservoirs.

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