DOI: 10.31577/ahs-2023-0024.01.0003

ACTA HYDROLOGICA
SLOVACA

Volume 24, No. 1, 2023, 14 – 23

Characterization of leakage water flows in the subsoil of Beni Haroun dam by hydrogeological approach

Lynda CHEBBAH*, Abdesselem KABOUR

Dams are designed and built to withstand severe destabilising conditions, including seepage problems, which are very often linked to localized discontinuity stress in the rock foundations, or in the banks. This situation allows water to take different circulation paths, and consequently jeopardizes the stability of the dam and reduces its useful capacity. The Beni Haroun dam, located in the North-Eastern part of Algeria on the Oued El-Kebir, with a water storage capacity of about 1 billion m^3, the dam is located on a Ypresian (Karst) limestone mass with an estimated annual leakage volume of 31.536 hm^3. The present work focuses on the identification of the water leakage origin in the Beni Haroun dam, using a hydrogeological approach, which consists in interpreting the correlation between the water level in the reservoir and that in the piezometers installed around the dam, for the period 2003 to 2021. The results revealed some interesting findings.

KEY WORDS: dam, leakage, piezometer, karst, Beni Haroun

Introduction

Dams are essential infrastructure for water supply and have served human societies for 5000 years (ICOLD, 2013). Dams are the cornerstone of water resources management by providing water for irrigation, domestic and industrial uses, flood control, aquaculture, navigation and recreation. However, the failure and breach of dams can have catastrophic results (Torabi Haghighi et al., 2014).

The problem of water leakage is very complex as it threatens the quantities of water accumulated in most dams around the world and causes concern about the stability of these structures especially if this problem persists (Benfetta et al., 2017).

Seepage rate is an important performance indicator of the dam structural behaviour, as it can provide insight into physical changes in the dam structure. The effect of seepage through the foundation area and banks on the dam safety has become a matter of concern for this reason, the prediction and analysis of recorded seepage data at dam sites is an essential operation in their monitoring tasks, to properly assess the situation and plan corrective actions (de Rubertis, 2018).

Leakage is recognised as having a direct impact on the dams safety. Therefore, it is important to monitor the uplift pressure and leakage rate to identify the risks, and the long-term behaviour of concrete dams and especially in the presence of cracks (Hu et al., 2017).

The Beni Haroun dam is built on limestone formations, which in itself presents a significant challenge to the construction and operation of this large dam. The water-soluble carbonate structure of this type of limestone can lead to the development of cracks and fractures that can eventually extend into conduits and even caves and grottos; a process known as karstification (Milanovic, 2017; Ford and Williams, 2007). As a result, water in a dam reservoir can easily seep through its foundations and banks and thus affect the stability of the dam. Seepage into the foundations of the Beni Haroun dam is estimated at $1 m^3 s^{-1}$, and on a yearly scale it loses 31.536 hm^3, which represents a fairly large volume (ANBT: Agence Nationale des barrages et transferts, 2002).

The objective of this case study is to detect the origin and path of the leakage recorded at the foundations and banks of the dam. This is done by a spatial and temporal piezometric analysis and also an analysis of the leakage rates in the different drainage points as a function of the water level in the lake.

Materials and methods

Presentation of the study site

The Béni-Haroun dam is located on the Oued El Kébir in the wilaya of Mila (East Algeria), (Fig. 1). It is fed by the Oued Rhumel and the Oued Endja (Fig. 2). It is part of the large Kebir-Rhumel basin with a surface area of 6595 km^2. This basin is naturally limited by the limits of

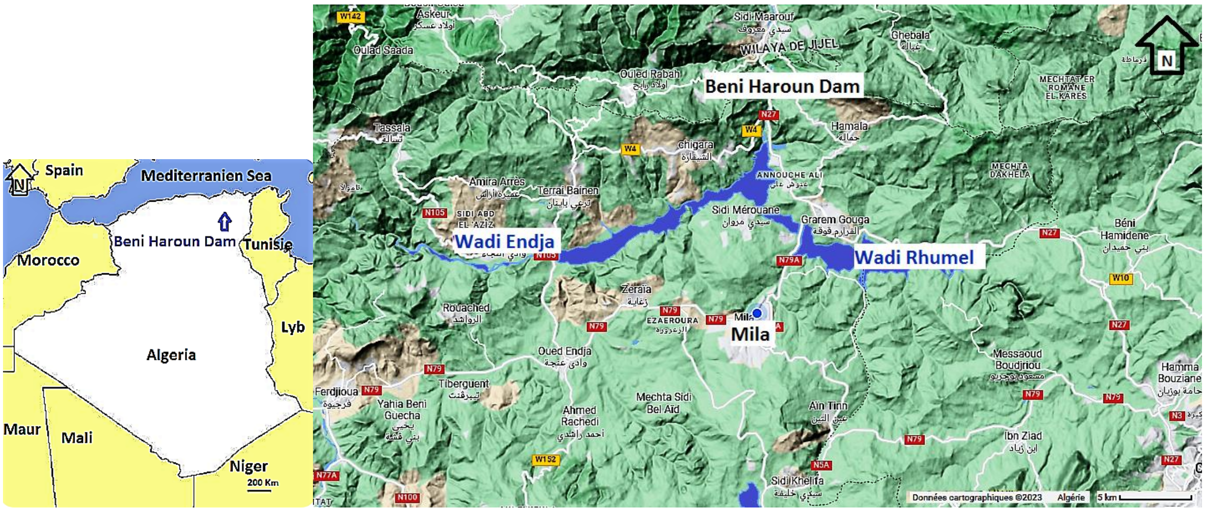


Fig. 1. Geographical location of the Beni Haroun dam (reservoir) (Chebbah and Kabour, 2018).

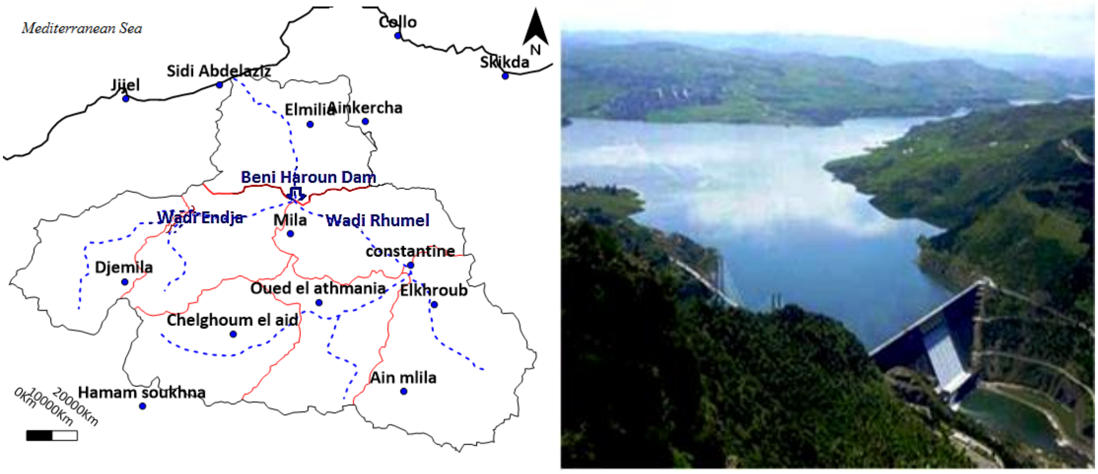


Fig. 2. Watershed and downstream view of Beni Haroun dam (Chebbah and Kabour, 2018).

the Kebir-Rhumel which are: to the North, the basins of the western Constantinois coast and the central Constantinois (BV n°03); to the South, the catchment area of the Constantinois high plateaux (BV n°07); to the West, the Soummam basin (BV n°15) and to the East the Seybouse basin (BV n°14) (Mebarki and Benabbes, 2008).

The structure is of the rectilinear weight type, in BCR (Roller Compacted Concrete) (Fig. 2), with a crest length of 710 m, levelled at elevation 216.3 m, an order height of 118 m above the foundations, and the direction of the axis of the dam is approximately North to South. The lake of the reservoir hugs the captured part of Oued El Kebir and the two valleys of Oued Rhumel and Oued Endja, on a surface of 39.29 km², that is to say nearly 4 000 ha. The rainfall-reservoir balance makes it possible to determine a net destocking by evaporation, equivalent to an average annual tranche of 350 mm. The reservoir can store 963 hm^3 of water, i.e. a useful volume of 732 hm^3, and can regulate an annual inflow of 435 hm^3, with a reserve of 1 billion m^3 of water reached on 12 February 2012. The dam was put into operation in 2003 (Mebarki and Benabbes, 2008).

Geological complexity and constraints

The Beni Haroun area is part of the Tellian domain and is mainly occupied by Paleogene formations (Vila, 1980), which start with the black Paleocene marls, easily friable to silty from colluvial deposits, and sometimes with traces of calcite filling clogging the joints. These Paleocene marls are overlain by Lutheran limestones and marls. The Beni Haroun dam is directly founded on the Ypres limestone (Fig. 3 and 4) (ANBT, 1999). The Ypresian limestone is characterised by the presence of spheroidal to elliptical black flint nodules, the thickness of this series is approximately 100 m (Vila, 1980). In the field, the rock is characterised by beds of

decimetric to metric thickness, it is dark grey to black with a micrite texture (fine grain). The Ypresian limestone is hard to very hard and weather resistant, because some layers are dolomitic or even siliceous, while the other layers contain black flint (ANBT, 2002).
Examination of the drill cores recovered during the investigation phase revealed some traces of karst dissolution in this limestone bedrock; these traces of karst developed mainly along certain sub-vertical joints. The opening of the karstified zones could reach 30 to 50 cm. However, during construction, all karst problems were treated by grouting (Fig. 5) (ANBT, 2002).
With regard to the subsurface studies, the Beni Haroun dam site was investigated in two phases using 32 boreholes reaching a maximum depth of 124 m. The first 20 boreholes were drilled during the first phase (1984) by Harza Engineering, and during the second phase in 1997, the remaining 12 boreholes were drilled by Tractebel. The borehole logs were used to draw geological cross-sections (Fig. 4) (Kebab et al., 2021).
The local geology is part of a complex tectonic context of thrusting and faults or detachments, characterised by plastic deformations (folding) and brittle deformations (faults, fractures) of the lithological units of the site. These units are schematically made up of a competent limestone base (with rigid – brittle – behaviour) from100 m to 150 m thick, framed by two incompetent marl series (with plastic – folded – tectonised – behaviour) (Fig. 3 and 4) (Mebarki and Benabbes, 2008).
This basic tectonic architecture, already complex in

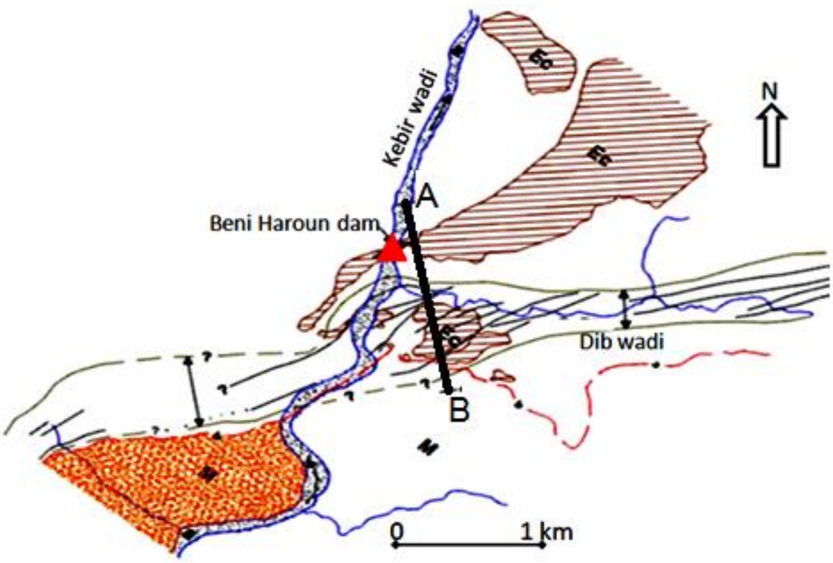


Fig. 3. Geological map of the site (Harza, 1984).

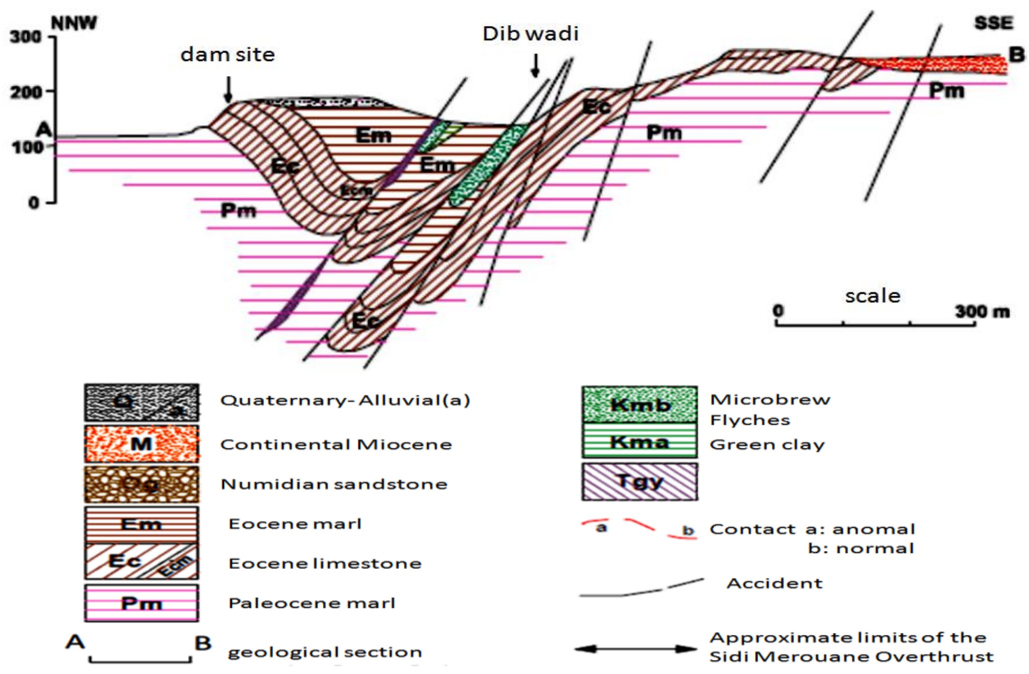


Fig. 4. Geological cross section in the Beni Haroun dam site (Harza, 1984).

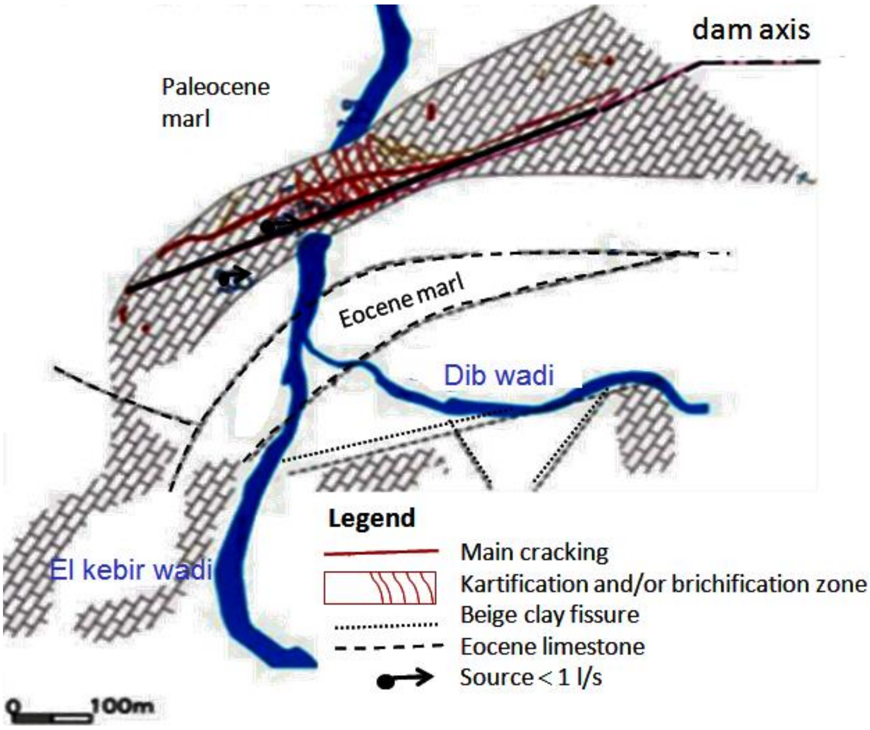


Fig. 5. Location of the karst aquifer (ANBT, 1999).

itself, is complicated by the presence of faults with a strong north-north-west plunge (shear zones) and North-South fractures (observed in the dam foundation). There is every reason to believe that these are traction fractures linked to the torsion of the limestone banks mentioned. (Fig. 4) (ANBT, 2007).

The limestones have a synclinal structure, the dam being entirely founded on its northern flank. Along the left bank of the reservoir, extend into a boat shape, the limestone banks have a sub-vertical or even slightly upward plunge (towards the interior of the slope), and are therefore subject to mowing (or rocking of the heads of the layers). This gravitational phenomenon results in a progressive dislocation of the rock, until it develops into an instability of the settlement, rockfall or landslide type, such as that observed just upstream of the dam (mirador landslide). These phenomena of superficial stretching of the rock mass are accompanied by an opening of the fracture systems, and therefore by a strong increase in permeability (Fig. 4) (Kebab et al., 2021).

The marls surrounding the limestones have similar or comparable characteristics from a hydrogeological point of view. From a geo-mechanical point of view, however, the Paleocene marls, being more calcareous, have more favourable characteristics than the Eocene marls.

Results and discussions

Leakage problem

The Beni Haroun dam showed an "original" deficiency during its first impoundment, December 2003 – January 2004, resulting from particular and complex geological conditions. It is about important leaks in the left wing and abnormally high pressures in this part of the structure (under pressure). This problem, immediately identified by ANBT, and its consulting engineer, who had designed the structure, was analysed in detail (the dam is equipped with an efficient monitoring system) and led to the definition of judicious reinforcement measures: extension of the waterproofing curtain and drainage in the foundation (Benchabane, 2015).

Piezometry

Whatever the type of dam, its foundations and supports are subject to pressures due to the flow of water through the rock. These can be quantified locally using piezometers.

Piezometry is very useful in determining faulty areas in the banks and foundation of the dam. The variation of the piezometric level and the lake level over time allows to deduce the anomalies that occur in the area crossed by the piezometer (Labadi and Achour, 2011).

The piezometers installed in the Beni Haroun dam site show a piezometric control of the reservoir lake in relation to the limestone aquifer on the left and right banks and in the syncline (Fig. 6).

In order to show the influence of the lake shoreline on the water level in the piezometers we plot the piezometer shoreline against the lake shoreline. The good correlation indicates that there is a strong water circulation between the represented piezometers and the lake. On the other hand, the steepness of the regression line indicates the permeability of the area between the lake and the piezometer (Toumi and Remini, 2006).

Monitoring data from the piezometers over the period (2003–2021) have clearly shown the performance of the various seepage control measures (Fig. 7).

Right bank

The water level in the piezometers located in the right bank (piezometers, POI 1, POIII 1, POIII 2, POIII 3, POIV 1) (Fig. 6) showed a good correlation (R^2 between 0.557 and 0.608) with the water level in the reservoir (Fig. 7), from the graphs (Fig. 7) we notice an average correlation between the studied parameters, and also that the slope of the regression lines undergo an increase for all the concerned piezometers which indicates a strong water circulation which is due either to the entrainment of the clogging materials by the flow created by the hydraulic load, or to the chemical dissolution of the components of the rock mass (Toumi and Remini, 2018). But for the piezometers (PUIT 124 RD3, PUIT 124 RD4, POIV 2, PO II 3, POI 2) we have a weak correlation (R^2<0.304), which allows us to see that there is no water circulation between the lake and the piezometers, and that the slopes of the regression lines undergo a rather increasing variation, which indicates the existence of water circulation under the effect of simple cracks and deterioration of the layers crossed by the piezometers**.**

Left bank

For the piezometers located on the left bank, a strong correlation is recorded (PO RG A2 and PORG A1) (R^2>0.9); for the piezometers located upstream of the dam axis, a good correlation is observed for PO VII 1 (R^2=0.582), for PUITS 124 RG 2 (R^2=0.529) and for PO VI 1 (R^2=0.952).
For the rest of the piezometers (POV 1, POV 2, POVII 2, POVI 2, PO 124 RG 1), a very weak correlation (R^2<0.4) between the parameters presented is noted, which informs us of the absence of water circulation in the zones located between the lake and these piezometers (Fig. 7).
On the basis of the data observed, we have noted that the various works undertaken have enabled a significant reduction in the under-pressures of the dam. On the other hand, we can say that the dam in these conditions is in full safety except that in the event of a strong flood, the under-pressures can increase in this case, it is necessary to increase the pumping capacity of the drainage pumps.

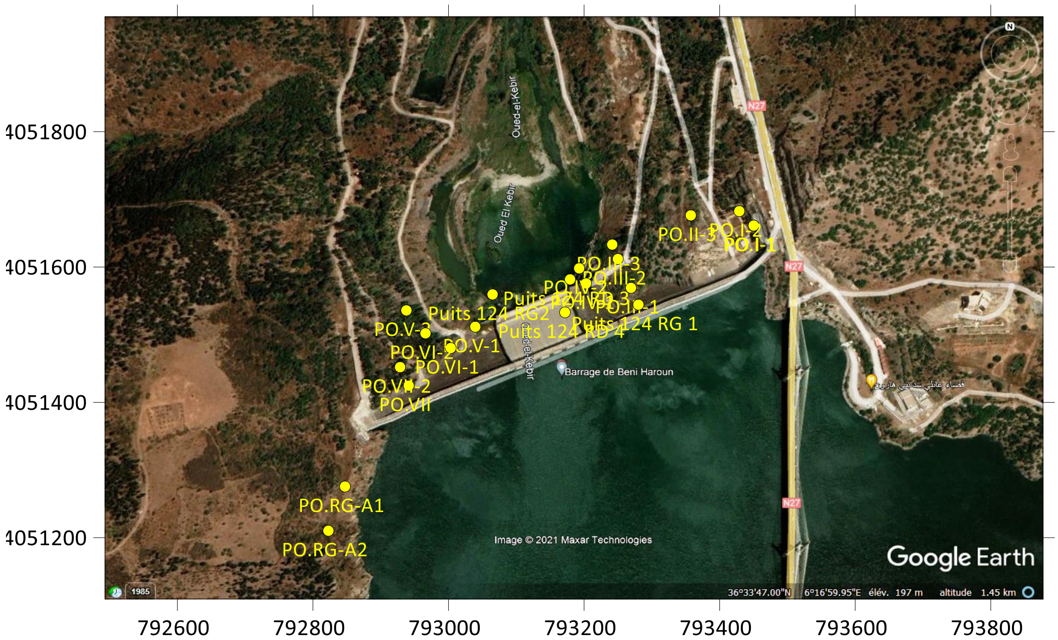
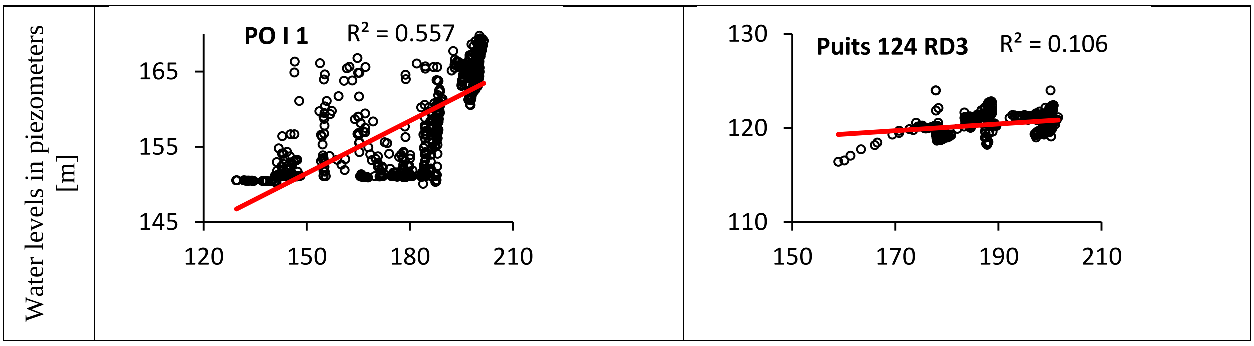
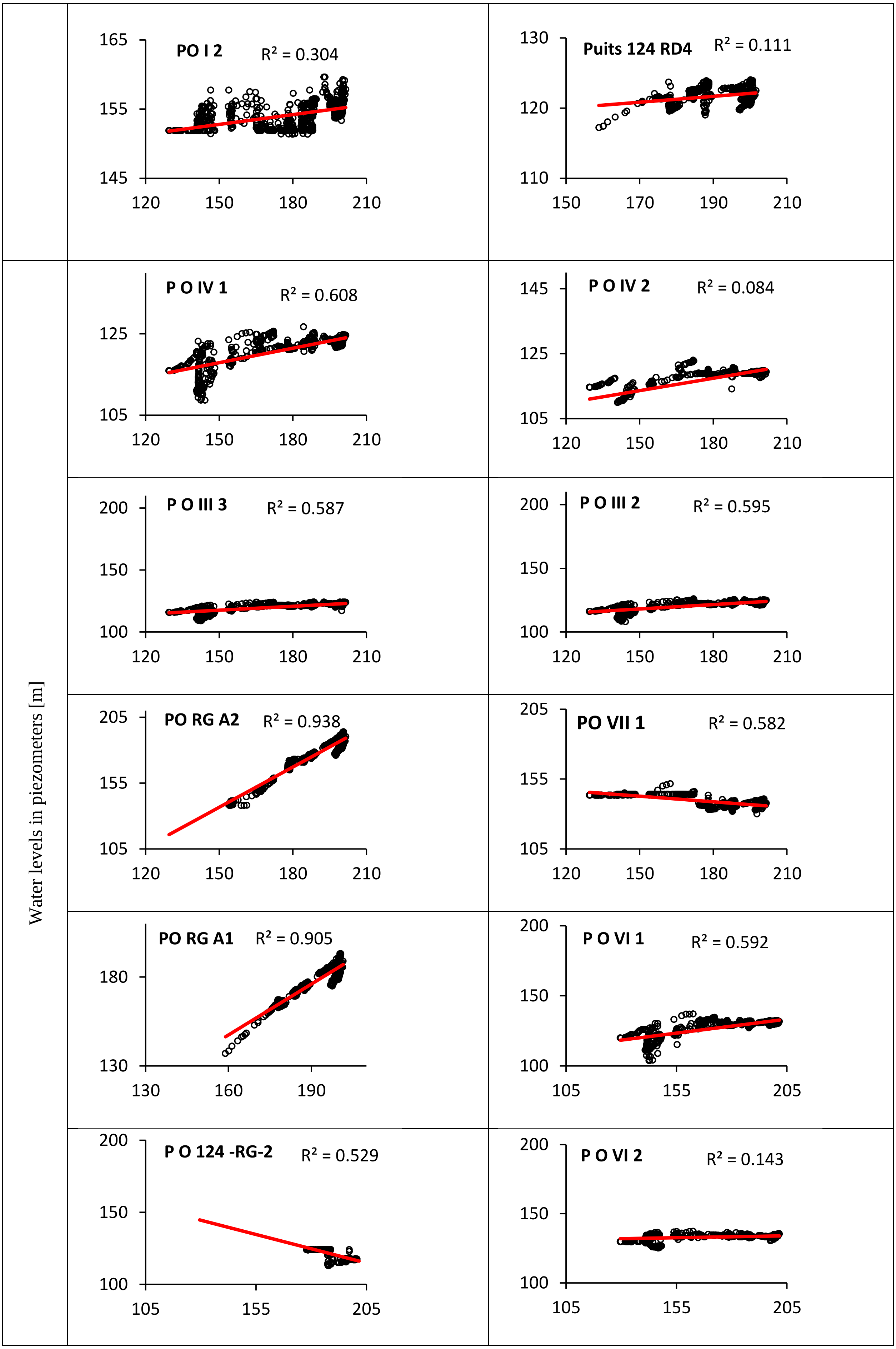


Fig. 6. *Location of piezometers around the Beni Haroun dam.*




Water levels in piezometers [m]
PO I 2
R² = 0.304
Puits 124 RD4
R² = 0.111
P O IV 1
R² = 0.608
P O IV 2
R² = 0.084
P O III 3
R² = 0.587
P O III 2
R² = 0.595
PO RG A2
R² = 0.938
PO VII 1
R² = 0.582
PO RG A1
R² = 0.905
P O VI 1
R² = 0.592
P O 124 -RG-2
R² = 0.529
P O VI 2
R² = 0.143

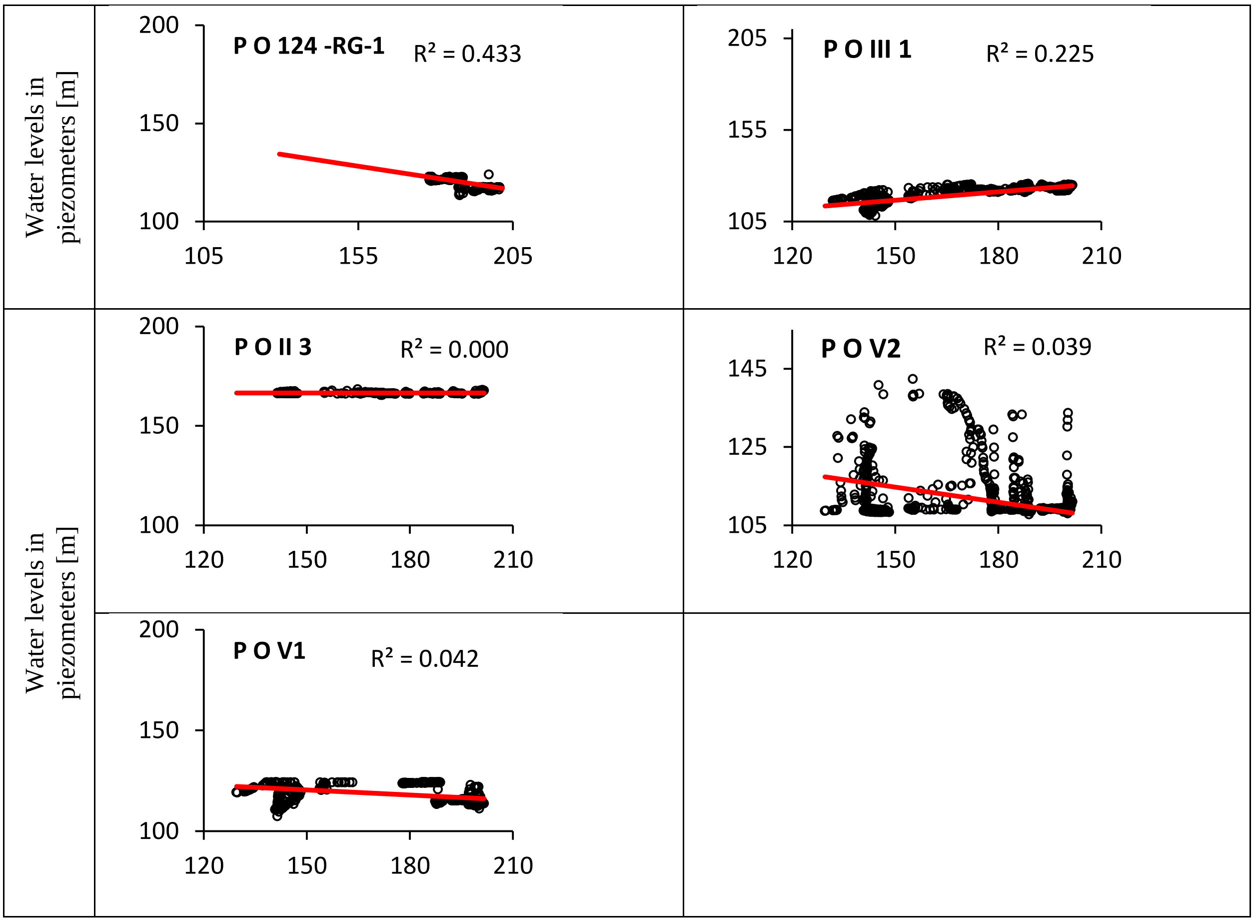


Fig. 7. Correlation between the water level observed in the reservoir and that of the piezometers around the Beni Haroun dam (2003–2021).

Spatial evolution

Piezometry during the construction of the dam

The synclinal structure has a steep western termination, marked by the limestone outcrops on the left bank. Gravity flow has been able to exploit submeridian discontinuities in these limestones to bypass the marly core of the syncline (Fig. 8) (ANBT, 1999). Circulations are fed in a concentrated way under the alluvium of the left bank. They follow two types of drainage axes: firstly, the contact between the limestone wall and the Paleocene black marl to the northwest; secondly, the network of breccias and fracture discontinuities, which jointly direct the gravity flows towards the spring area of the dam site (ANBT, 2007; Benchabane, 2015).
The installation of the dam caused the karst aquifer discharge threshold to rise from 105 m, the approximate altitude of the talweg, to more than 200 m, the approximate altitude of the dam's scouring sills (ANBT, 2007).
The hydraulic gradient was increased to 60–70 m and the spillway was moved to the left bank, on the natural path of the gravity flows that bypass the marl core of the syncline, by reusing the drainage axes abandoned during the digging of the cluse (ANBT, 2007).
The flow pattern in the limestones implies a long pathway, confirmed by a delay of at least 50 days, and on average about 100 days, between the temperature cycles in the reservoir and those observed downstream on the left bank. (Benchabane, 2015).

Piezometry after the implementation of the dam

There is a slow flow from south to north along the dam from a level of 135 m to 115 m (Fig. 9). On the right bank the flow direction is East-West towards the river. From the piezometric data, it can be seen that, even if the water level in the reservoir increases, the water level in most of the piezometers does not move, except for small disturbances during the rainy seasons (Fig. 9). In piezometers POI1 and POI2 a different response is observed, i.e. the water level is higher than in the other piezometers, and the level rises at the time of flooding, which means that there is a relationship with rainfall and that infiltration is rapid in limited areas. On the left bank, the curves are tight with a South East-North West flow direction, which indicates the existence of a rapid flow from a water table (fissured limestone) and the lake water. A hydraulic gradient likely to maintain underground circulation between the lake and the downstream side of the dam, which is expressed preferentially on the left bank. This bank presents a remarkable differentiation compared to the right bank, this difference is located at the level of the piezometers PORG A1, PORG A42 where the water level in these piezometers evolves with that of the water level of the dam, this means the existence of a direct dam-groundwater relationship.

It is concluded that the piezometric observations on the left bank of the dam show that the permeability of these limestones is anisotropic, it is higher parallel than transversal to the layers, implying circulations parallel to the stratification. The under pressure of the dam is more developed on the left bank than on the right bank.

Leaks

It is clear that one of the major problems encountered when building a dam on fractured limestone soils is the sealing of the reservoir. The most important leakage from the reservoir corresponds to circulation through pre-existing natural drainage networks. The leakage rates are limit by the head losses that can occur throughout the limestone mass.

Conversely, for the same hydraulic load, flows can increase if there is a decrease in head losses following geometric and morphological modifications of the fractures. These modifications can have two origins; either erosion or entrainment of clogging materials, or chemical or mechanical erosion of the rock matrix (Labadi and Achour, 2011). The correlation of the seepage rates at the shoreline with the lake level (Fig. 10) clearly shows that the seepage rates increase strongly with the load and this for a lake level of about 178 m, for the left shore. For the right bank, the variation

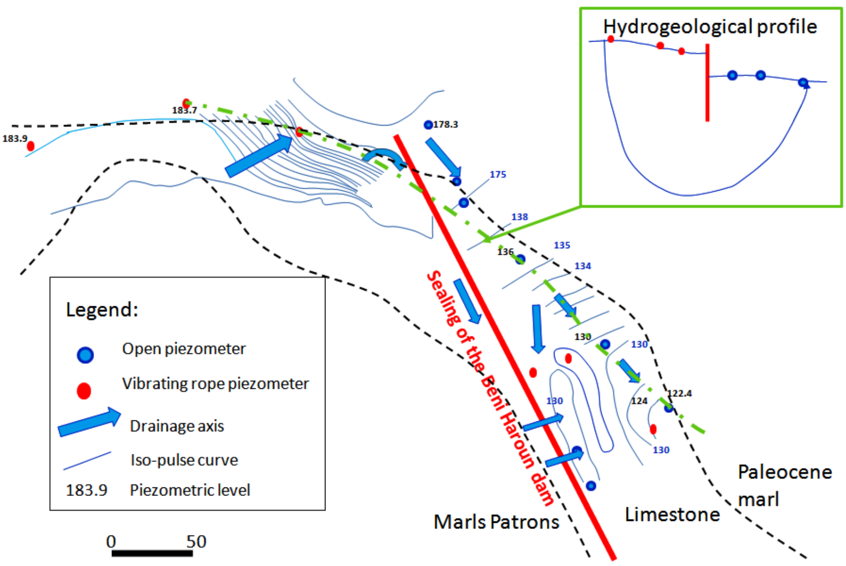


Fig. 8. Groundwater flow in the limestone aquifer during dam construction (ANBT, 1999; Benchabane, 2015).

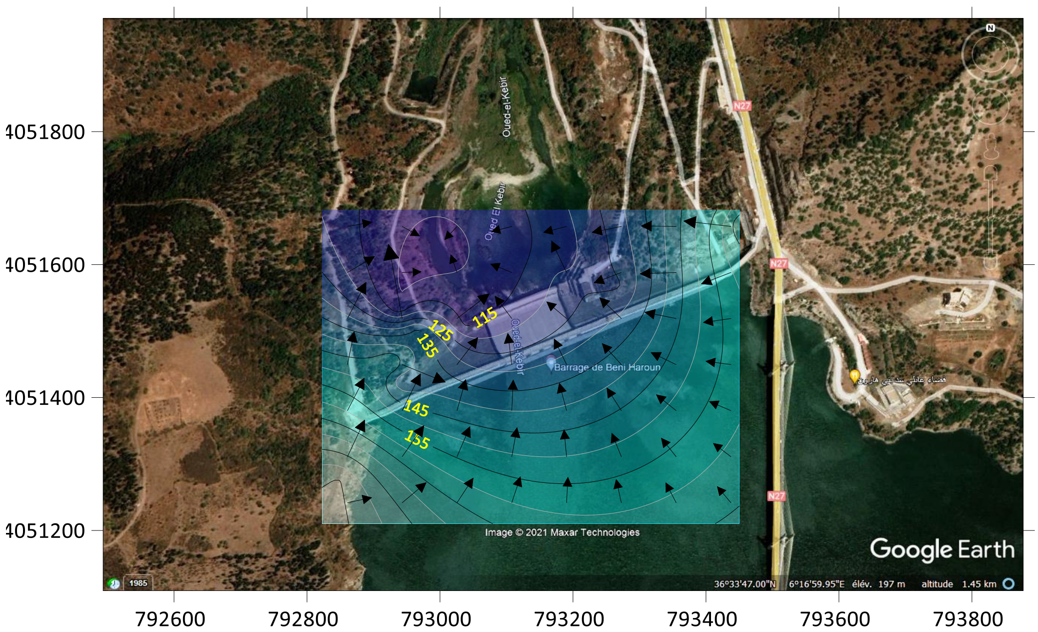


Fig. 9. Piezometry of Beni Haroun dam foundations (February 2019).

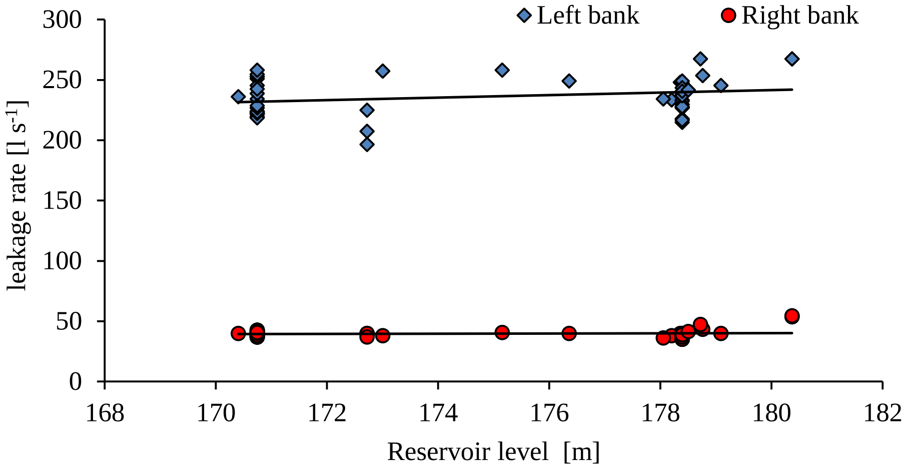


Fig. 10. Variation of leakage rates as a function of reservoir elevation.

of the lake level has no influence on the leakage rates on this bank, and they are stabilised around a value of 40 and 50 l s^{-1}.

It can also be seen that the leakage flows in the left bank are greater than those from the right bank, and there is no relationship between the leakage flows from the right bank and the left bank (Fig. 10).

Conclusion

The majority of dams around the world are confront with the problem of water leakage through the banks and foundations. The study of this phenomenon is of great importance, as it can endanger the stability of the dam and reduce its useful capacity.

The study of the relationship between the piezometric level and the water level of the reservoir allowed us to highlight the existence of a very pronounced relationship between the reservoir and the various piezometers. Thus, the following results were retained:

- The left bank is more cracked than the right bank.
- There are preferred directions of water flow within the limestone massif with a spatial variation in the degree of fissuring.
- The two banks have no relation to each other in terms of underground water circulation.

Based on these observations, we can say that actually we are in the presence of continuous flow channels in which the water will flow from upstream to downstream in a South East–North West direction for the left bank and East-West for the right bank.

References

ANBT (1999): Transfert de Beni Haroun. Rapport de Synthèse. Tractebel, Ingénierie, volume l. Alger.

ANBT (2002): Barrage de Beni Haroun sur L'oued Kebir. Monographie volume 1 Textes. Tractebel Engineering, 363 p.

ANBT (2007): Barrage de Beni Haroun (wilaya de Mila, Algérie). Rapport final de la compagne géophysique.

Benchabane, N. I. (2015): Relation barrage-nappes. Etude de cas barrage de Beni Haroun. Wilaya de Mila, Mémoire de Magister, Université de Constantine, Algérie, 113 p.

Benfetta, H., Achour, B., Ouadja, A. (2017): Les fuites d'eau dans les barrages dans le monde: quelques exemples Algériens. Larhyss Journal. 31, 195–218.

Chebbah, L., Kabour, A. (2018): Impact de la retenue d'un barrage sur le régime climatique local : cas de Béni Haroun (Est algérien). Geo-Eco-Trop, 42–1, 173–186.

ICOLD (International Commission on Large Dams) (2013): Historical review on ancient dams. Bulletin 143. International Commission on Large Dams, Paris, 68 p.

de Rubertis, K. (2018): Monitoring Dam Performance: Instrumentation and Measurements. Virginia. American society of civil engineers, 422 p.

Ford, D., Williams, P. W. (2007): Karst hydrogeology and geomorphology. Chichester, England, A Hoboken, NJ: John Wiley & Sons.

Harza Engineering Company (1984): Etude technico-économique conduisant au choix du site. November, Vol. 3, Annexe B- Géologie.

Hu, J., Ma, F., Wu, S. (2017): Comprehensive investigation of leakage problems for concrete gravity dams with penetrating cracks based on detection and monitoring data: A case study. Struct Control Health Monit. 25–4, 1–18

Kebab, H., Boumezbeur, A., Rivard, P. (2021): Rock mass properties and their suitability as a foundation for a rolled compacted concrete gravity dam: case study of Beni Haroun dam (Mila, NE Algeria), Bulletin of Engineering Geology and the Environment, 80, 1729–1743.

Labadi, A., Achour, S. (2011): Apport de l'analyse piézométrique dans l'étude des fuites du barrage voûte a assises calcaires de Foum El Gherza, Biskra, Algérie, courrier de savoir, 11, 25–32.

Mebarki, A., Benabbes, C. (2008): Le système Beni-Haroun (Oued Kebir-Rhumel, Algérie) aménagements hydrauliques et contraintes morpho-géologiques. Ann-geographies, 105. 37–51.

Milanovic, P. (2017): Water resources engineering in Karst. CRC Press. The Annual Meeting of International Commission on Large Dams July 3–7, Prague, Czech Republic PRAGUE.

Torabi Haghighi, A., Marttila, H., Kløve, B. (2014): Development of a new index to assess river regime impacts after dam construction. Global Planet Change, 122.186–196.

Toumi, A., Remini, B. (2006): La problématique des fuites

d'eau du barrage Hammam-Grouz (Algérie), Larhyss Journal, 05, 41–48.
Toumi, A., Remini,B. (2018): The problem of water in Beni Haroun Reservoir (Algeria). Jordan Journal of Civil Engineering, 12–3, 402–423.
Vila, J. M. (1980): La chaîne alpine d'Algérie Orientale et des confins Algéro-tunisiens. PhD thesis of Sciences, Univ. P & M. Curie, Paris VI, 665 p.

Lynda Chebbah, MCB, (*corresponding author, e-mail: cheblyn@yahoo.fr)
Abdesselem Kabour, MCA.
Department of Civil and hydraulic engineering
University Centre of AbdelhafidhBoussouf
Laboratory of Modeling and Socio-Economic Analysis in Water Science – MASESE Lab.
BP 25, Mila
Algeria