



Hydrogeological Characterization of Leakage Water Flows in the Subsoil of Ouizert Dam, Algeria

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Abstract: Water leakage through dam foundations and abutments compromises both dam stability and useful storage capacity. The Ouizert Dam, located in north-western Algeria (Mascara Province), is a 60 m high earth-fill structure built on a heterogeneous geological basement of marls, sandstones, conglomerates and limestones, with a documented mean leakage of 10.42 hm³ yr⁻¹ through its left bank. The present study examined the origin and pathways of this leakage through a hydrogeological approach based on the correlation between the reservoir water level and that recorded in 14 piezometers installed on the left bank between 2009 and 2026. The analysis revealed a marked spatial differentiation of the hydraulic behaviour across the left bank: seven piezometers (P19, P20, P5, P12, P6, P10, P2) showed a very strong correlation with the reservoir level ($R^2 \geq 0.913$) and regression slopes close to or slightly exceeding unity, indicating direct hydraulic connection through the fractured rock mass; four piezometers (P14, P21, P3, P13) showed a good correlation ($R^2 = 0.653-0.797$); and three (P16, P1, P7) showed a weak or no correlation ($R^2 \leq 0.472$), suggesting hydraulically disconnected zones. The existence of two distinct flow regimes was confirmed statistically by segmented regression and a Chow test on monthly mean discharge ($F = 204.1$, $p < 0.001$), with the optimal breakpoint at 437.9 m NGA: a moderate Darcian regime below this level (slope = 25.9 L s⁻¹ m⁻¹) and a steeper enhanced-seepage regime above it (slope = 151.9 L s⁻¹ m⁻¹, about six times larger). The verified maximum leakage discharge of 1,967 L s⁻¹, recorded during the high-reservoir period of mid-2013, exceeds the peaks previously reported at the site and is consistent with an ongoing geomechanical evolution of the fractured rock mass. Long-term piezometric monitoring remains the most reliable tool for tracking leakage

development and for guiding remedial action.

Key words: Algeria, fractured rock, hydraulic connection, leakage, Ouizert Dam, piezometer.

Dams are important infrastructure for water resources management, providing water for irrigation, domestic and industrial uses, flood control, aquaculture, navigation and recreation (ICOLD, 2013). However, dam failure can have catastrophic consequences (Torabi Haghighi *et al.*, 2014). Among the various processes that compromise dam safety, water leakage through the foundations and abutments is one of the most common and the most difficult to control. It threatens the volume of water stored in the reservoir and, when persistent, raises serious concerns about the stability of the structure (Benfetta *et al.*, 2017).

Seepage rate is a key indicator of the structural behaviour of a dam, since it reflects physical changes in the body and the foundation of the structure (de Rubertis, 2018). The monitoring of seepage rate, uplift pressure and piezometric levels is therefore essential to assess long-term performance, particularly in dams founded on fractured rock masses (Hu *et al.*, 2018).

The Ouizert Dam, in north-western Algeria, sits on a heterogeneous basement of marls, sandstones, conglomerates and limestones. The fractured limestones and sandstones can form preferential pathways for water flow through the foundations and abutments, and so directly influence dam stability. The estimated permeability of the left bank corresponds to a leakage volume of $10.42 \text{ hm}^3 \text{ yr}^{-1}$ (Benfetta *et al.*, 2022). The phenomenon was first reported by Benfetta and Remini (2008) for the period 1986–2003 and updated by Benfetta *et al.* (2022) for 1989–2018.

The present study, extending the authors' own previous analysis (Benfetta and Remini, 2008; Benfetta *et al.*, 2022), draws on the longest continuous record available at the site (2009–2026, 17 years), incorporates three piezometers (P20, P21, P3) not analysed in the 2022 study, and provides the first formal statistical test of the hydraulic regime threshold using segmented regression and the Chow structural-break test. The objective was to identify the origin and the preferential pathways of the leakage recorded at the foundations and left bank of the Ouizert

Dam. The methodology follows that previously applied at Hammam-Grouz Dam (Toumi and Remini, 2006), Foug El Gherza Dam (Labadi and Achour, 2011) and Beni Haroun Dam (Chebbah and Kabour, 2023), all affected by similar leakage problems through fractured-rock foundations.

Materials and Methods

Study site

The Ouizert Dam is located on the Oued Sahouet, in Mascara Province (north-western Algeria), about 35 km south-west of the city of Mascara and 17 km south of Ain Fekan (Fig. 1). Its geographic coordinates are $X = 250.55$, $Y = 206.80$, $Z = 396.00$ NGA. The dam belongs to the larger Oued El Hammam basin ($\sim 14,389 \text{ km}^2$), which also hosts the Bouhanifia and Fergoug dams further downstream.

The Ouizert Dam is a 60-m high heterogeneous earth-fill structure with a designed storage capacity of about 100 hm^3 . The reservoir extends 10 km up the valley and receives a mean annual inflow of 45 hm^3 (Toran *et al.*, 1970). Impoundment began in 1989. The reservoir supplies $20 \text{ hm}^3 \text{ yr}^{-1}$ for drinking water (to Oran city and the Arzew industrial complex) and $12 \text{ hm}^3 \text{ yr}^{-1}$ for irrigation in the El Habra plain (about 20,000 ha), and provides regulated releases to the downstream Bouhanifia Dam (Benfetta *et al.*, 2022). However, the reservoir has never been filled to its design capacity, owing to persistent seepage through the left bank.

Geological setting: The dam site is underlain by a gently inclined ($5\text{--}10^\circ$) substratum composed of marls, sandstones, conglomerates, limestones, colluvium and alluvium. A limestone layer of about 5 m thickness is highly fissured and constitutes the main pathway for sub-surface water flow (Toran *et al.*, 1970). Two principal fracture systems were identified during the geological investigation: the first oriented quasi-parallel to the Oued Sahouet course, and the second quasi-perpendicular to the river and parallel to the dam axis. These fractures are best developed in the harder rocks (limestones, sandstones) and less so in the marly formations.

The geological map of the catchment (Fig. 2) shows that the basin is dominated by limestone formations, with significant outcrops of breccia and conglomerate near the dam site. Marly

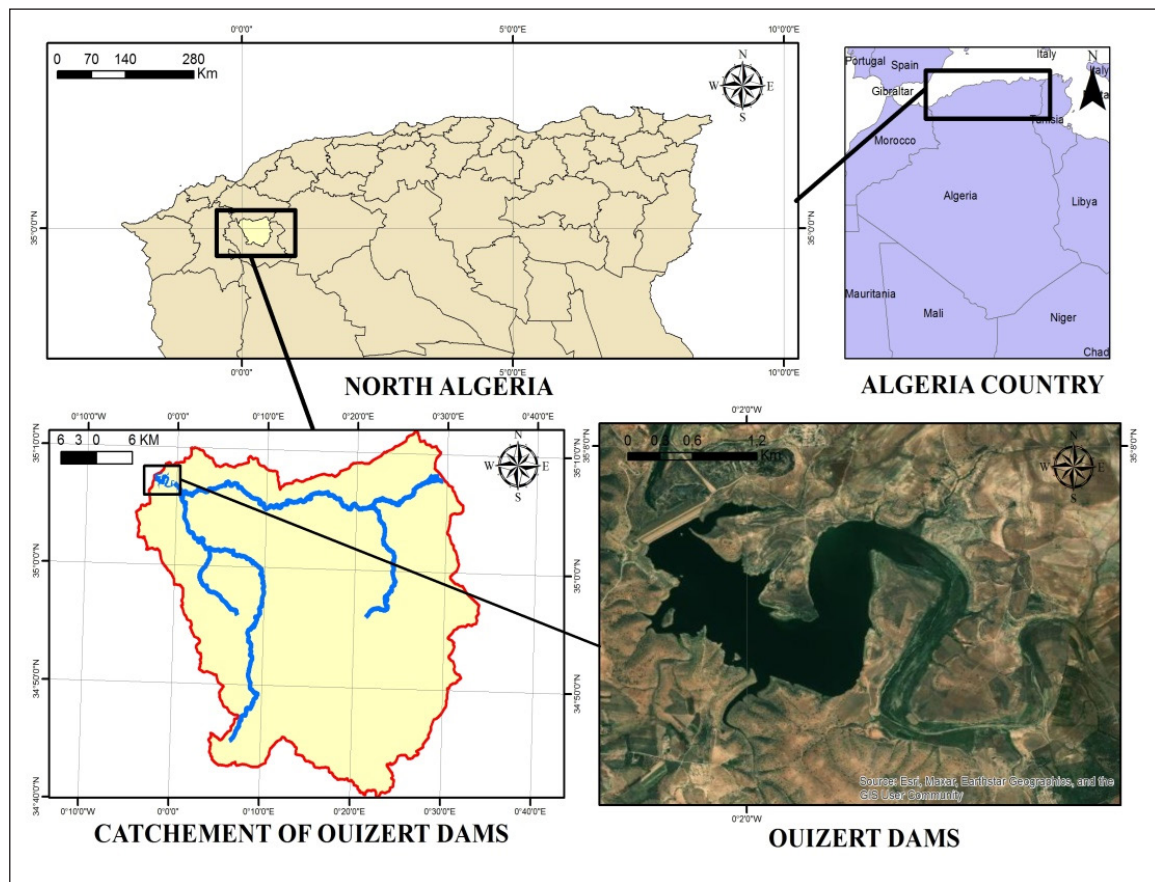


Fig. 1. Geographic location of the Ouizert Dam (Mascara, Algeria). Top-left: position of Mascara Province in northern Algeria. Top-right: location of Algeria in northern Africa. Bottom-left: catchment area of the Ouizert Dam (Wadi El Hammam basin). Bottom-right: satellite view of the Ouizert reservoir.

limestone occurs around the reservoir, while shale, schist and undifferentiated volcanic rocks outcrop in the central-eastern part of the basin. The combination of carbonate and clastic lithologies, together with the fracture pattern at the dam site, accounts for the permeability and the persistent leakage observed on the left bank.

The left bank of the dam shows visible discontinuities (fissures and faults) that create preferential seepage pathways from the reservoir towards the downstream artesian spring zone. Earlier work based on temperature and conductivity profiling within the piezometers identified two coexisting flows: a vertical downward flow with steady values, and a more horizontal flow originating from the reservoir, with lower conductivity (Benfetta *et al.*, 2022). The latter is the focus of the present study, since it carries reservoir water through the fractured rock mass to the downstream spring.

Piezometric network and data analysis: A network of 14 piezometers (P1, P2, P3, P5, P6, P7, P10, P12, P13, P14, P16, P19, P20, P21) was installed around the dam, mainly on the left bank, at distances ranging from approximately 150 m to 1,800 m from the dam axis (Fig. 3a). The piezometric record used here covers the period 2009-2026 and represents the longest continuous data series available at the site. Reservoir level and leakage discharge were recorded daily over 1989-2026, whereas the piezometric levels were read at a median interval of about one month (28 days). All reservoir and piezometric levels are referenced to the same datum, the Nivellement Général de l'Algérie (NGA), and expressed in metres NGA.

For each piezometer, a linear regression was fitted between the water level recorded in the piezometer and the corresponding reservoir level. The strength of the hydraulic connection was evaluated through the coefficient of determination (R^2); the local

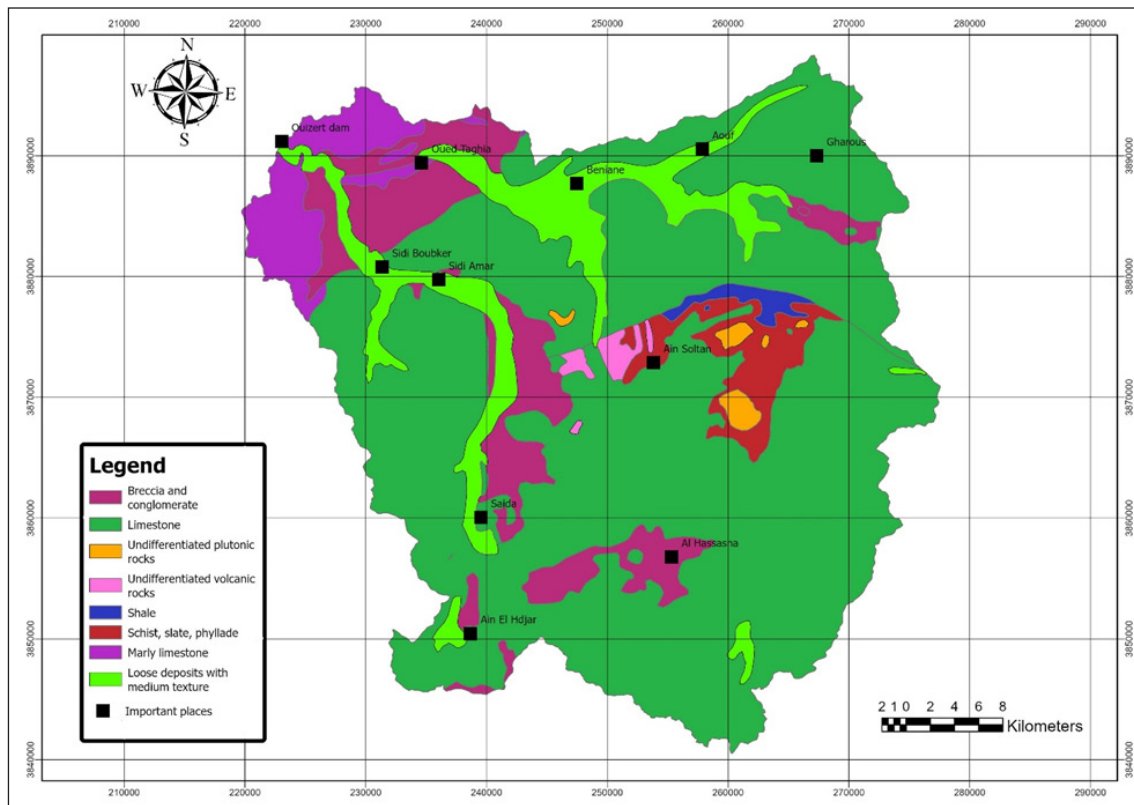


Fig. 2. Geological map of the Ouizert Dam catchment area. The main lithologies are limestone (green), breccia and conglomerate (purple), marly limestone (magenta), and loose deposits with medium texture (light green).

permeability of the rock mass between the reservoir and the piezometer was assessed through the slope of the regression line, with values close to or exceeding unity indicating

a near-direct hydraulic response (Toumi and Remini, 2006). Rainfall, seasonal recharge and lateral groundwater inflows were not modelled explicitly, reservoir level being the

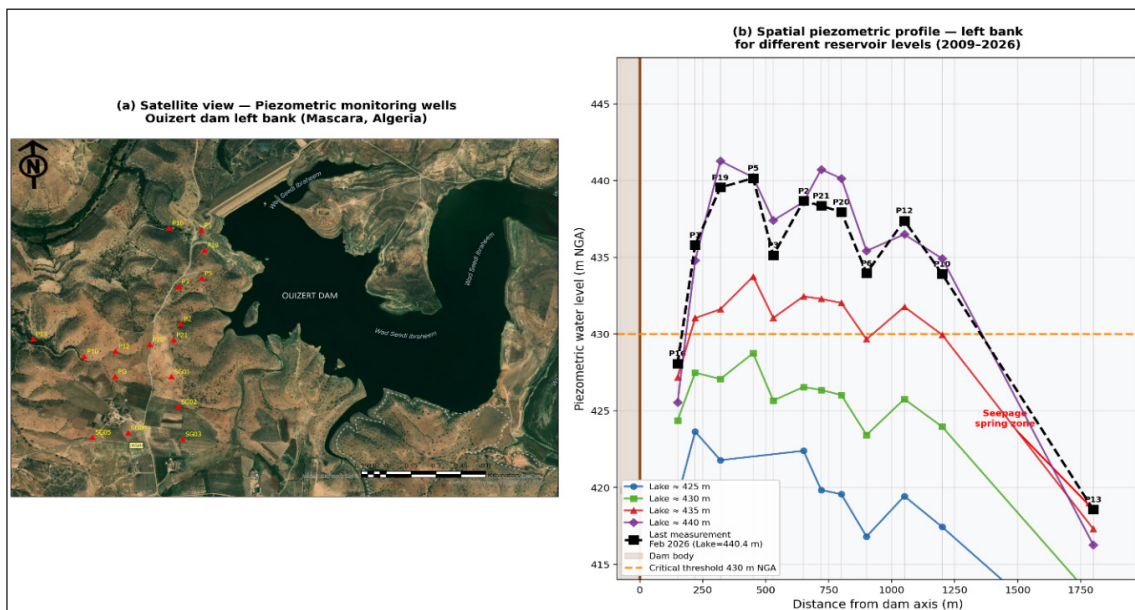


Fig. 3. (a) Location of the piezometers around the Ouizert Dam (left bank), with their approximate distances from the dam axis; (b) spatial piezometric profile along the left bank of the Ouizert Dam for different reservoir levels (2009-2026).

dominant control on the piezometric response; these factors, together with the operational measurement uncertainty (piezometric levels read to the centimetre and leakage obtained by volumetric gauging), probably account for part of the residual scatter.

Outliers were identified and removed using a Z-score criterion applied to the regression residuals: observations whose standardised residual exceeded $\pm 2.5 \sigma$ were excluded. This threshold was chosen as a conservative balance between sensitivity (retaining genuine extreme hydraulic events) and robustness (excluding erroneous or technically defective readings). For each piezometer, the final sample size after cleaning is reported in Table 1. Across the 14 piezometers, the proportion of removed points ranged from 0% to 4.8%, confirming that the cleaning had a minor effect on the regression statistics.

The strength of piezometric correlation was classified using explicit R^2 thresholds adopted as an internal criterion for the present study, consistent with common interpretive bands for the strength of a correlation: very strong, $R^2 \geq 0.900$; good, $0.600 \leq R^2 < 0.900$; weak, $0.300 \leq R^2 < 0.600$; and very weak or no correlation, $R^2 < 0.300$. These thresholds were applied consistently across all 14 piezometers (Table 1).

The spatial hydraulic gradient along the left bank was estimated from simultaneous piezometric readings collected during the February 2026 campaign (reservoir level 440.35 m NGA). The gradient was computed between pairs of piezometers along the principal flow direction: from P5 (440.16 m NGA, ~350 m from the dam axis) to P13 (418.56 m NGA, ~1,800 m from the axis), giving a head loss of 21.60 m over about 1,450 m, *i.e.* 14.9 m km^{-1} at peak level. Values of 7–10 m km^{-1} cited in the text correspond to moderate-level campaigns (reservoir level 430–436 m NGA), computed from the same piezometer pair.

The leakage rate was analysed jointly with the reservoir level over 1989–2026, in order to identify the regime changes associated with the activation of preferential pathways at high reservoir levels.

Statistical test of the hydraulic regime threshold: The existence of two distinct flow regimes was tested using segmented linear regression (Muggeo, 2003) fitted to the monthly mean

leakage-reservoir level series ($n = 436$ months, 1989–2026). Monthly aggregation was adopted to suppress the strong day-to-day autocorrelation of the daily record, which would otherwise inflate the test statistic through pseudo-replication. The optimal breakpoint was estimated by minimising the total residual sum of squares across candidate break levels, implemented with the *pwlf* library (version 2.2.1) in Python 3.11. The significance of the structural break was assessed by the Chow test (Chow, 1960), which compares the residual sum of squares of the restricted (single-slope) model with that of the unrestricted (two-slope) model through an F-statistic. Segment-wise 95% confidence intervals for slopes and intercepts were computed from the standard errors of ordinary least-squares regression within each regime. The independence of the segmented-model residuals was examined with the Durbin-Watson statistic.

Results and Discussion

Leakage problem

Persistent leakage has been observed through the left bank since the impoundment of the Ouizert Dam in 1989. The right-bank seepage was sealed during construction by a grouting curtain, but the left-bank leakage has continued unabated for more than three decades. Two earlier studies documented this evolution: Benfetta and Remini (2008) reported a maximum leakage discharge of 930 L s^{-1} in October 1996, while Benfetta *et al.* (2022) recorded a peak of 940 L s^{-1} in December 2013. The mean inter-annual leakage volume is estimated at $10.42 \text{ hm}^3 \text{ yr}^{-1}$ (Benfetta *et al.*, 2022), a substantial loss for a reservoir of 100 hm^3 design capacity in an arid region.

Re-examination of the complete daily record (1989–2026) shows that the verified maximum daily discharge is approximately $1,967 \text{ L s}^{-1}$, sustained over roughly two months (May–July 2013) when the reservoir stood at about 444–445 m NGA (m above the Algerian national vertical datum). This exceeds the peaks reported by Benfetta and Remini (2008; 930 L s^{-1} , 1996) and the monthly value of 940 L s^{-1} reported for 2013 by Benfetta *et al.* (2022); the difference from the latter reflects the daily peak in the raw ANBT series versus the monthly aggregation used previously. Because leakage is governed primarily by reservoir level, its

maximum coincides with periods of maximum impoundment rather than increasing steadily through time. Even so, the rise from 930 L s⁻¹ in 1996 to about 1,967 L s⁻¹ in 2013 is consistent with a continuing geomechanical evolution of the fractured rock mass, in which peak discharge capacity increases as new fracture pathways are activated.

Piezometric correlation analysis: Piezometric monitoring is one of the standard tools for detecting preferential flow paths in dam foundations and abutments (Labadi and Achour, 2011). A high coefficient of determination between the piezometer and reservoir levels indicates strong hydraulic communication, whereas the slope of the regression line reflects the local permeability of the rock mass between them (Toumi and Remini, 2006). The piezometric data over 2009–2026 reveal a marked spatial differentiation of the hydraulic behaviour across the left bank (Fig. 4 and Table 1).

Strong correlations: A very strong correlation with the reservoir level was recorded for seven piezometers: P19 ($R^2 = 0.980$), P20 ($R^2 = 0.972$), P5 ($R^2 = 0.968$), P12 ($R^2 = 0.960$), P6 ($R^2 = 0.949$), P2 ($R^2 = 0.946$) and P10 ($R^2 = 0.913$). The regression slopes for these piezometers ranged from 0.967 to 1.130, close to or slightly exceeding unity.

A regression slope close to unity indicates that a 1-m rise in reservoir level produces an almost equal rise in the piezometric head at the well, consistent with an essentially unconfined, direct hydraulic connection through a highly permeable fractured medium. A slope marginally above unity (e.g. 1.076 at P19, 1.130 at P20) is, in every case, statistically indistinguishable from unity once the 95 % confidence interval and the residual scatter are taken into account, and these wells are therefore interpreted as being in near-perfect hydraulic equilibrium with the reservoir. Slopes that formally exceed one should not be read as a physical amplification of the head signal - in a steady-state configuration the piezometric head cannot persistently exceed the reservoir head that drives it - but rather as the combined effect of measurement error in the reservoir stage (regression dilution), a restricted stage range, and the large negative intercepts obtained for these wells (Toumi and Remini, 2018). Slopes well below unity (e.g. 0.532 at P13, 0.420 at P16) indicate partial hydraulic isolation, interpreted as lower local fracture permeability or residual effectiveness of the grouting curtain.

The high R^2 values at P19, P5, P12, P6 and P2 reflect the high local permeability of the fractured rock mass in their immediate environment. These wells lie within the densest fracture zone identified during the original

Table 1. Summary of piezometric correlation results for the 14 monitoring wells around the Ouizert Dam (2009–2026, after data cleaning). Distances from the dam axis are approximate. The 95% confidence intervals for R^2 were computed by Fisher's Z-transformation; those for the slopes are $\pm t(0.975, n-2) \times SE(\text{slope})$

Piezometer	Dist. from axis (m)	n	R^2	95% CI R^2	Slope	95% CI slope	Intercept	Classification
P19	~150	157	0.980	0.976–0.984	1.076	± 0.030	–35.28	Very strong
P20	~200	158	0.972	0.967–0.977	1.130	± 0.037	–60.00	Very strong
P5	~350	121	0.968	0.960–0.975	1.003	± 0.037	–2.07	Very strong
P12	~300	158	0.960	0.953–0.967	1.087	± 0.042	–42.01	Very strong
P6	~250	157	0.949	0.941–0.957	1.024	± 0.044	–17.63	Very strong
P2	~400	99	0.946	0.933–0.958	1.038	± 0.057	–18.93	Very strong
P10	~450	157	0.913	0.900–0.925	0.967	± 0.052	7.12	Very strong
P14	~600	159	0.797	0.762–0.831	0.762	± 0.060	96.38	Good
P21	~500	158	0.702	0.658–0.744	1.178	± 0.104	–79.96	Good
P13	1,800	159	0.656	0.607–0.703	0.532	± 0.054	183.18	Good
P3	530	79	0.653	0.580–0.721	0.782	± 0.101	91.28	Good
P16	~700	155	0.472	0.391–0.550	0.420	± 0.060	242.59	Weak
P1	~800	141	0.154	0.083–0.226	0.516	± 0.138	205.76	Very weak / none
P7	~900	47	0.054	0.000–0.168	–0.481	± 0.348	660.98	Very weak / none

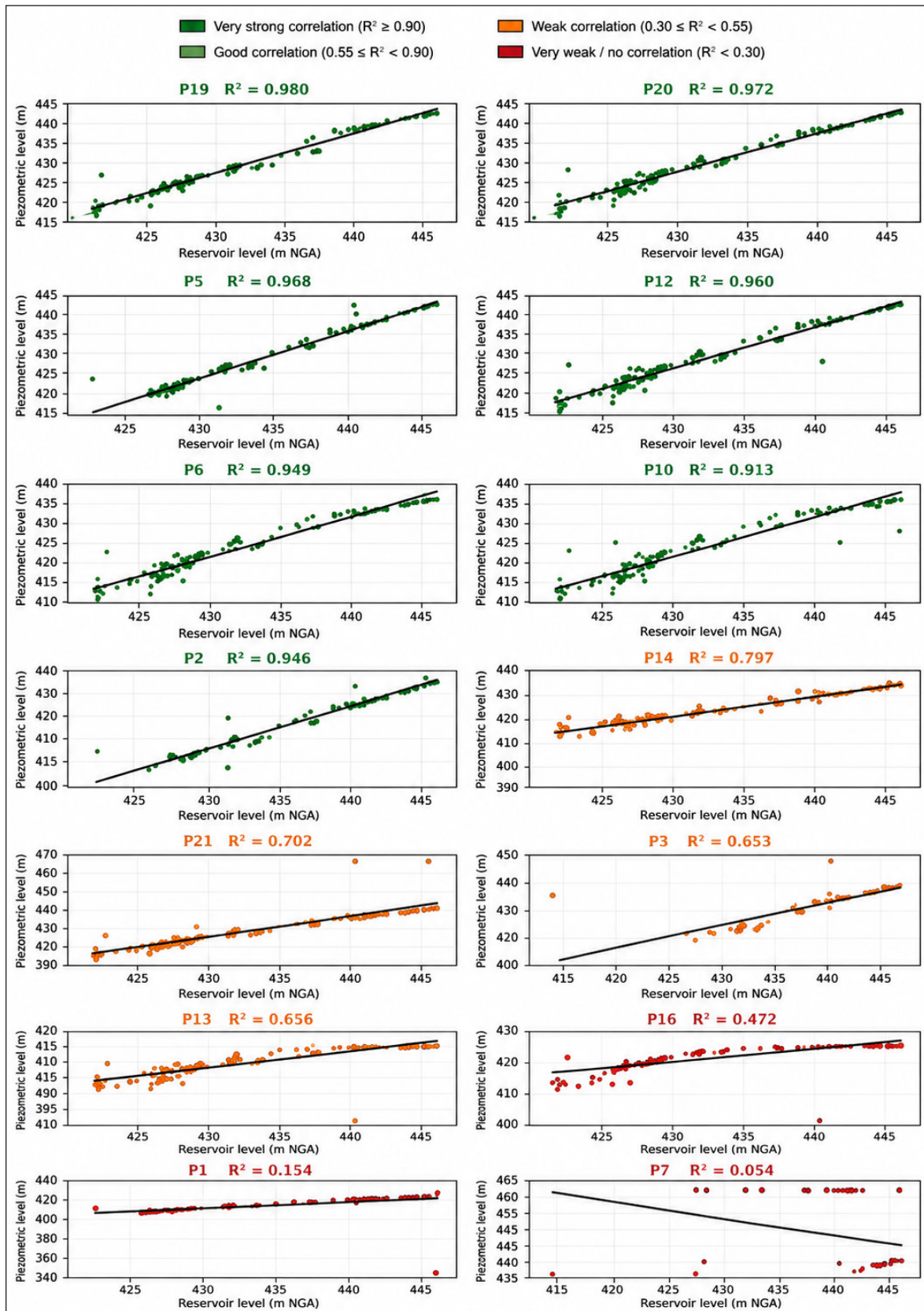


Fig. 4. Correlation between the water level observed in the reservoir and the water level recorded in the piezometers around the Ouizert Dam (2009-2026).

geological survey (Benfetta and Remini, 2008). The values are slightly higher than those previously reported by Benfetta *et al.* (2022) for SB19 ($R^2 = 0.950$) and SB16 ($R^2 = 0.802$), consistent with the additional eight years of monitoring data incorporated here.

Good and weak correlations: Four piezometers showed good correlations with the reservoir level: P14 ($R^2 = 0.797$), P21 ($R^2 = 0.702$), P13 ($R^2 = 0.656$) and P3 ($R^2 = 0.653$). The regression slopes for these wells vary noticeably, suggesting water circulation under the combined effect of fracturing and partial deterioration of the layers crossed by the piezometers. The relatively lower R^2 values at P3 (530 m from the dam axis) and P13 (1,800 m from the axis, near the downstream spring) probably reflect a locally lower fracture intensity, or residual effectiveness of the grouting curtain in their respective zones.

Three piezometers showed weak to very weak correlations: P16 ($R^2 = 0.472$), P1 ($R^2 = 0.154$) and P7 ($R^2 = 0.054$). The weak correlation at P16 may reflect locally lower fracture permeability or partial clogging of the piezometer screen. For P1 and P7, the near-zero R^2 values and the limited number of observations ($n = 141$ and $n = 47$, respectively) make it difficult to distinguish genuine hydraulic disconnection from instrumental artefacts (poor installation, screen clogging, or insufficient data coverage). The negative slope at P7 (0.481) indicates a response opposite to reservoir variations,

inconsistent with direct hydraulic connection. It is most likely attributable to a local confined aquifer responding to seasonal recharge rather than to reservoir-induced pressure changes. Further investigation of the technical condition of P1 and P7 is recommended before their hydraulic disconnection is confirmed.

Spatial pattern of the hydraulic gradient

The piezometric profile along the left bank (Fig. 3b and 5) confirms a strong hydraulic gradient directed from the reservoir towards the downstream spring zone. The gradient computed from the spatial profile (piezometers P5 to P13) reaches 7-10 m of head loss per kilometre during moderate-level campaigns (reservoir level 430-436 m NGA), rising to approximately 14.9 m km^{-1} at the peak level of February 2026 (440.35 m NGA). These values are comparable to the gradients reported at Fom El Gherza Dam (Labadi and Achour, 2011) and at Beni Haroun Dam (Chebbah and Kabour, 2023).

Taken together, the piezometric data show that the permeability of the fractured rock mass is anisotropic, with preferential flow paths oriented along the two principal fracture systems identified at the site. The hydraulic connection between the reservoir and the downstream spring remains active and intense more than three decades after impoundment.

Leakage rate analysis and statistical threshold: The segmented regression applied to the

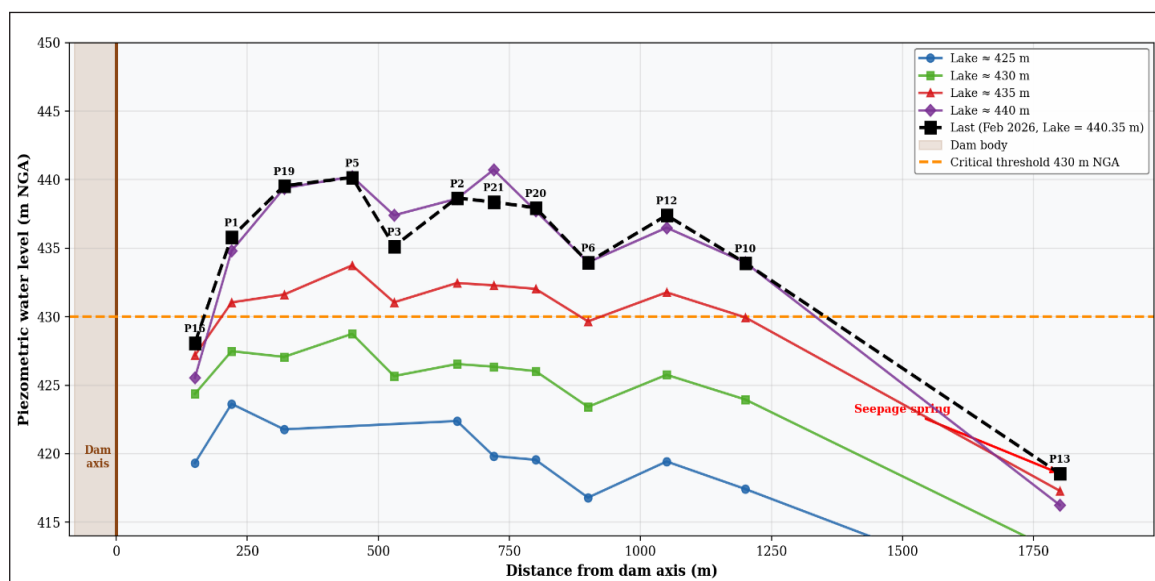


Fig. 5. Spatial piezometric profile along the left bank of the Ouizert Dam (2009-2026).

monthly mean leakage-reservoir series ($n = 436$ months, 1989-2026) detected the optimal breakpoint at 437.9 m NGA. The Chow test confirmed that this structural break is highly significant ($F = 204.1$, $df = 2$ and 432 , $p < 0.001$), rejecting the null hypothesis of a single homogeneous leakage-level relationship. Below the breakpoint, the Darcian regime yields a slope of $25.9 \pm 2.5 \text{ L s}^{-1} \text{ m}^{-1}$ ($R^2 = 0.545$, $n = 362$ months); above it, the enhanced-seepage regime yields a slope of $151.9 \pm 20.0 \text{ L s}^{-1} \text{ m}^{-1}$ ($R^2 = 0.761$, $n = 74$ months), about six times steeper. Monthly mean values were used to avoid the pseudo-replication of the autocorrelated daily series. The results are summarised in Table 2 and illustrated in Fig. 6.

The Durbin-Watson statistic on the segmented-model residuals ($DW = 0.44$) indicates positive serial autocorrelation, as is expected for a hydrological time series. Three assumptions underlying the Chow test are only partially met here and temper the interpretation of its nominal significance. First, the breakpoint was estimated from the same data rather than fixed a priori, so the reference distribution of the statistic departs from the standard F and the p-value is best

read as a lower bound on the true probability. Second, the widening of the residual scatter above the threshold points to heteroscedasticity between the two regimes, which the classical test does not accommodate. Third, the residuals are positively autocorrelated ($DW = 0.44$), as noted above. None of these caveats overturns the result – the six-fold change in slope and the stability of the breakpoint are far too large to be generated by these effects – but the F-statistic should be regarded as indicative of a strong structural break rather than as an exact probabilistic statement.

The statistically detected breakpoint (437.9 m NGA) is close to the operationally identified threshold of approximately 430 m NGA reported by Benfetta and Remini (2008) and Benfetta *et al.* (2022). The ~ 8 m difference likely reflects the fact that the operational threshold was identified visually from a smaller dataset, whereas the present analysis uses 37 years of records and an objective minimisation criterion. For consistency with prior work and operational practice at the dam, the 430 m NGA threshold is retained as a reference level, with the understanding that the statistically optimal transition occurs at 437.9 m NGA.

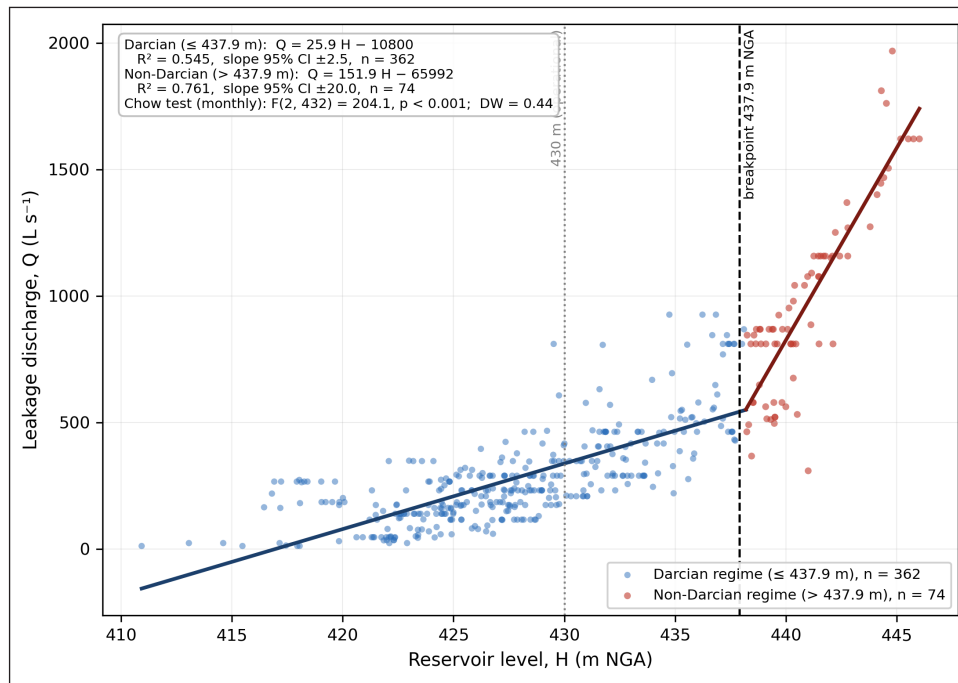


Fig. 6. Leakage discharge as a function of reservoir level, Ouizert Dam (1989-2026), shown as monthly means. Blue points: Darcian regime (≤ 437.9 m NGA); red points: enhanced-seepage regime (> 437.9 m NGA). Solid lines: segment-wise least-squares regression. Dashed vertical line: statistically detected breakpoint (437.9 m NGA, Chow test on monthly means $F = 204.1$, $p < 0.001$). Dotted vertical line: operational threshold (430 m NGA) for reference

Table 2. Results of the segmented regression and Chow test for the leakage discharge-reservoir level relationship, Ouizert Dam (1989-2026)

Parameter	Regime 1 (Darcian, ≤ 437.9 m NGA)	Regime 2 (enhanced-seepage, > 437.9 m NGA)	Chow test	Interpretation
n (months)	362	74	—	Regime 1 covers most of the operational range
Slope ($L s^{-1} m^{-1}$)	25.90	151.86	—	$\sim 6\times$ steeper above the threshold
95% CI slope	± 2.45	± 20.01	—	Both significantly non-zero
R^2	0.545	0.761	—	Stronger fit in the enhanced-seepage regime
Breakpoint	—	—	437.9 m NGA	Statistically detected threshold
F-statistic	—	—	204.1	Highly significant structural break
df (Chow test)	—	—	2 and 432	Numerator, denominator degrees of freedom
p-value	—	—	< 0.001	Rejects the single-regime null hypothesis
Durbin-Watson	—	—	0.44	Positive residual autocorrelation (typical of time series)

The variation of leakage rate with reservoir level confirms that, below ~ 430 m NGA, the relationship is moderate and approximately linear, in agreement with Darcy's law for flow through a fractured but largely unaltered rock mass. Above the threshold, the slope becomes markedly steeper and the scatter widens, indicating the activation of additional flow paths at high reservoir stages. This transition to an enhanced-seepage regime most plausibly reflects a change in the geometry of the conducting medium — the progressive engagement of fractures that remain hydraulically inactive at lower stages — rather than a departure from Darcian physics within individual fractures. Whether the flow within the newly activated pathways becomes genuinely non-Darcian (i.e.

governed by a Forchheimer or turbulent law) cannot be established from the discharge-stage relationship alone and would require direct velocity-gradient or Reynolds-number evidence. The two-regime behaviour nonetheless provides a sound operational management criterion for the Ouizert Dam.

Because the piezometers are read at roughly monthly intervals (median 30 days), a cross-correlation between reservoir level and each piezometric series was evaluated at the resolution of one sampling interval (Fig. 7). Both series carry a shared long-term trend and seasonal component, which can inflate the absolute correlation between them; the diagnostic used here therefore relies not on the magnitude of the correlation but on

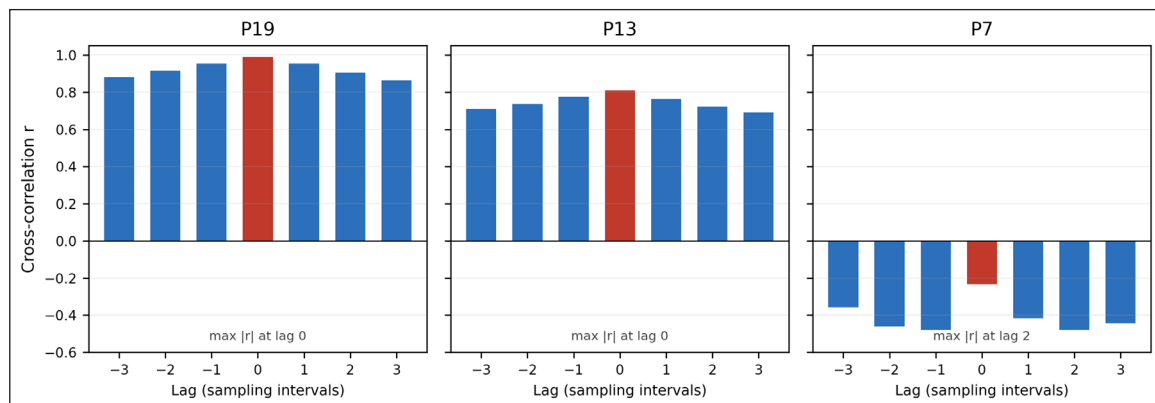


Fig. 7. Cross-correlation between reservoir level and piezometric level at lags of -3 to $+3$ sampling intervals (about one month each) for three representative wells — P19 (very strong connection), P13 (good connection) and P7 (no coherent connection). The red bar marks zero lag. The correlation peaks at zero lag for P19 and P13, indicating a synchronous, direct hydraulic response, whereas P7 shows only weak, negative values.

the position of its maximum relative to the neighbouring lags. For all strongly connected wells the correlation peaks sharply at zero lag (e.g. P19, $r = 0.990$ at zero lag against about 0.95 at $\pm$ one interval) — a feature that a shared trend alone cannot produce and that indicates a synchronous response within the monthly sampling resolution, supporting a direct hydraulic connection rather than a delayed or damped one. P7, by contrast, shows only weak, negative cross-correlations with no coherent lag structure, consistent with hydraulic disconnection. These coefficients are computed on the raw series and are reported as a qualitative indication of lag structure rather than as unbiased measures of association. Lags shorter than the sampling interval cannot be resolved; future campaigns should include synchronised, high-frequency (weekly or better) measurements of reservoir level and piezometric heads, on which prewhitened cross-correlation could be computed to refine the time-lag characterization.

Conclusions

This study analysed the relationship between the piezometric levels of 14 monitoring wells on the left bank of the Ouizert Dam and the corresponding reservoir level over 2009-2026, with the aim of identifying the origin and the preferential pathways of the persistent leakage observed since impoundment in 1989.

The left bank exhibits a marked spatial differentiation of hydraulic behaviour: seven piezometers (P19, P20, P5, P12, P6, P10, P2) show a very strong correlation with the reservoir level ($R^2 \geq 0.913$), four (P14, P21, P3, P13) show a good correlation, and three (P16, P1, P7) show a weak or very weak correlation. Regression slopes close to or slightly exceeding unity at the strongly correlated piezometers indicate near-direct hydraulic transmission through the fractured rock mass, whereas slopes below 0.8 reflect partial hydraulic isolation or lower local fracture permeability.

The existence of two distinct flow regimes was confirmed for the first time by a rigorous statistical test: segmented regression detected the optimal hydraulic threshold at 437.9 m NGA (Chow test on monthly means: $F = 204.1$, $p < 0.001$), with the Darcian-regime slope ($25.9 \pm 2.5 \text{ L s}^{-1} \text{ m}^{-1}$) about six times smaller than the enhanced-seepage-regime slope ($151.9 \pm$

$20.0 \text{ L s}^{-1} \text{ m}^{-1}$). The spatial piezometric profile confirms a clear hydraulic gradient towards the downstream spring zone, reaching 14.9 m km^{-1} at peak reservoir level (440.35 m NGA, February 2026).

The rise in verified maximum leakage discharge, from 930 L s^{-1} in 1996 to about $1,967 \text{ L s}^{-1}$ in 2013, indicates that the geomechanical evolution of the fractured rock mass is ongoing, and that remedial measures should be considered by the dam operator.

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Declarations

The authors have no competing interests.

References

- Benfetta, H. and Remini, B. 2008. Les fuites d'eau à travers le barrage algérien de Ouizert. *Sécheresse* 19(3): 185-192.
- Benfetta, H., Achour, B. and Ouadja, A. 2017. Water leaks in dams around the world: some Algerian examples. *Larhyss Journal* 31: 195-218.
- Benfetta, H., Remini, B., Achour, B. and Ouadja, A. 2022. Enhancement of the study of water leaks on the left bank in the Ouizert Algerian dam. *Larhyss Journal* 51: 129-143.
- Chebbah, L. and Kabour, A. 2023. Characterization of leakage water flows in the subsoil of Beni Haroun dam by hydrogeological approach. *Acta Hydrologica Slovaca* 24(1): 14-23.
- Chow, G.C. 1960. Tests of equality between sets of coefficients in two linear regressions. *Econometrica* 28(3): 591-605.
doi:10.2307/1910133
- de Rubertis, K. 2018. *Monitoring Dam Performance: Instrumentation and Measurements*. American Society of Civil Engineers, Reston, Virginia, USA, 422 p.
- Hu, J., Ma, F. and Wu, S. 2018. Comprehensive investigation of leakage problems for concrete gravity dams with penetrating cracks based on detection and monitoring data: A case study. *Structural Control and Health Monitoring* 25(4): e2127.
doi:10.1002/stc.2127

- ICOLD (International Commission on Large Dams) 2013. *Historical Review on Ancient Dams*. Bulletin 143. ICOLD, Paris, France, 68 p.
- Labadi, A. and Achour, S. 2011. Apport de l'analyse piézométrique dans l'étude des fuites du barrage voûte à assises calcaires de Foug El Gherza, Biskra, Algérie. *Courrier du Savoir* 11: 25-32.
- Muggeo, V.M.R. 2003. Estimating regression models with unknown break-points. *Statistics in Medicine* 22(19): 3055-3071.
doi:10.1002/sim.1545
- Toran et Cie (Madrid) 1970. *Avant-projet détaillé du Barrage de Ouizert*. Agence Nationale des Barrages, Algiers, Algeria.
- Torabi Haghighi, A., Marttila, H. and Kløve, B. 2014. Development of a new index to assess river regime impacts after dam construction. *Global and Planetary Change* 122: 186-196.
doi:10.1016/j.gloplacha.2014.08.019
- Toumi, A. and Remini, B. 2006. La problématique des fuites d'eau du barrage Hammam-Grouz (Algérie). *Larhyss Journal* 5: 41-48.
- Toumi, A. and Remini, B. 2018. The problem of water in Beni Haroun reservoir (Algeria). *Jordan Journal of Civil Engineering* 12(3): 402-423.

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