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BASEFLOW AND RECESSION DYNAMICS IN THE EL ABID RIVER BASIN: AN IntErO-BASED INTERPRETATION

SUMMARY

Understanding streamflow recession and baseflow variability is essential for water-resource management in semi-arid mountain basins. This study examined recession dynamics and estimated baseflow contribution in the El Abid River Basin, Central High Atlas, Morocco, using daily discharge and precipitation records from the Tizi N'Isli and Ait Ouchène gauging stations for 1976–2021. Recession sequences were identified using predefined discharge, precipitation, and minimum-duration criteria and were subsequently subjected to a quality-control procedure. Recession coefficients (α), master recession curves, estimated baseflow, and Baseflow Index (BFI) values were analysed, while basin-scale parameters derived from the IntErO model provided regional hydrogeomorphological context. Of the 345 and 131 initially extracted recession sequences at Tizi N'Isli and Ait Ouchène, respectively, 219 and 95 quality-controlled sequences were retained for the principal recession analyses. The mean recession coefficient was higher and considerably more variable at Tizi N'Isli (0.0502 day^{-1} ; CV = 124.3%) than at Ait Ouchène (0.0407 day^{-1} ; CV = 43.0%). The corresponding master recession coefficients were 0.0390 and 0.0323 day^{-1} , with coefficients of determination of 0.9949 and 0.9669 , respectively. These results indicate faster and more variable streamflow recession at Tizi N'Isli and slower, more uniform recession at Ait Ouchène. Long-term mean estimated baseflow discharge was higher at Ait Ouchène ($4.886 \text{ m}^3 \text{ s}^{-1}$) than at Tizi N'Isli ($3.176 \text{ m}^3 \text{ s}^{-1}$), whereas the long-term

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BFI was higher at Tizi N'Isli (62.8%) than at Ait Ouchène (57.0%). This distinction demonstrates that absolute baseflow magnitude, relative baseflow contribution, and recession rate describe different aspects of low-flow behaviour and should not be interpreted interchangeably. The basin-scale IntErO results indicate an elongated, topographically complex basin with heterogeneous lithology and land cover, providing a plausible regional setting for spatially variable hydrological responses; however, station-specific controls were not quantified directly. The findings provide a quality-controlled characterization of low-flow behaviour in the El Abid River Basin and support further catchment-specific investigation of the geological, topographic, climatic, and land-use factors governing recession and baseflow dynamics.

Keywords: baseflow, streamflow recession, recession coefficient, master recession curve, baseflow index, IntErO model, Central High Atlas

INTRODUCTION

Mountainous catchments in semi-arid and Mediterranean areas are strategic water sources that support streamflow during long dry periods by releasing groundwater (Gharnouki *et al.*, 2026). In these regions, baseflow is crucial to sustain river ecosystems, downstream water supply, and inputs to reservoirs. However, growing climate variability, increasing temperatures and shifting precipitation patterns are changing recharge processes and low flow conditions, thus requiring a better understanding of baseflow generation and recession dynamics for sustainable water resources management. Streamflow recession analysis has long been identified as one of the most efficient methods to study groundwater–surface water interactions (Thomas *et al.*, 2013).

During recession periods, direct runoff declines progressively and streamflow becomes more and more governed by delayed groundwater release. Consequently, recession characteristics provide valuable information on watershed storage capacity, aquifer connectivity, and hydrological resilience. Recession coefficients, master recession curves, and baseflow indices have therefore become widely used indicators for quantifying groundwater contributions and comparing the hydrological behaviour of different catchments.

The hydrological response of a river basin is shaped not only by climatic forcing but also by its physical-geographical characteristics (Zeng *et al.*, 2015). The morphology of the basin, the slope gradients, the configuration of the drainage network, the lithology, the properties of the soil, the elevation and the land cover determine the infiltration capacity, the groundwater recharge, the storage capacity and the runoff generation.

Mountain basins containing carbonate rocks are especially complex, because highly permeable formations of limestone and dolomite can greatly increase groundwater storage, whereas impermeable layers of marl and clay encourage rapid surface runoff. A key challenge in mountain hydrology is how these interacting controls shape the recession processes.

The Central High Atlas, Morocco provides an excellent natural laboratory in which to study these relationships. The El Abid River Basin is one of the major headwater catchments supplying the Bin El Ouidane Reservoir, one of Morocco's most important multipurpose reservoirs used for water supply, irrigation and hydropower production (Ennaji *et al.*, 2024). Despite its hydrological importance, relatively few studies have examined the spatial variability of baseflow generation and recession behaviour within this basin using long-term hydrometeorological observations.

A previous study in the El Abid River Basin assessed low-flow conditions using monthly discharge records for 1976–2018, focusing on minimum-flow indicators, low-flow severity thresholds, monthly discharge characteristics, and return-period estimates (Nafia *et al.*, 2024). The present study extends both the temporal resolution and the analytical scope of that earlier work by using daily discharge and precipitation records for 1976–2021, extracting quality-controlled recession sequences, estimating individual and master recession coefficients, separating baseflow from total streamflow, and calculating the Baseflow Index. It therefore advances the previous descriptive assessment of monthly low-flow conditions towards a process-oriented characterization of streamflow recession and delayed-flow dynamics.

In recent years, physically based hydrogeomorphological approaches have increasingly complemented traditional hydrological analyses by providing quantitative descriptions of watershed characteristics that govern runoff generation and sediment transport. The morphometric, geological, pedological, climatic and land use features are incorporated in the comprehensive assessment of the watershed response by the IntErO (Intensity of Erosion and Outflow) model among others (Spalevic, 2011; Filipovic and Spalevic, 2025).

Although IntErO has been extensively applied to evaluate erosion intensity, sediment yield, runoff potential, and watershed hydrological functioning in different environmental settings, its hydrogeomorphological outputs also provide valuable information for interpreting groundwater recharge conditions, storage capacity, and streamflow recession behaviour (Chalise *et al.*, 2019).

The present study combines classical streamflow recession analysis with a hydrogeomorphological interpretation based on IntErO-derived watershed characteristics to examine baseflow generation in the El Abid River Basin. Previous isotopic and geochemical investigations of Moroccan aquifer systems have shown that groundwater recharge, residence time, and aquifer functioning may vary considerably with the hydrogeological setting (Bouchaou *et al.*, 2008), thereby providing a broader regional context for the present analysis. Long-term daily discharge and precipitation records (1976–2021) from the Tizi N'Isli and Ait Ouchène gauging stations were analysed using established recession-analysis procedures (Rutledge and Daniel, 1994; Tallaksen, 1995; Tallaksen and van Lanen, 2023), including recession-sequence extraction, master-recession-curve construction, recession-coefficient estimation, and baseflow separation. The resulting hydrological indicators were interpreted in relation to the basin's

morphometric, geological, topographic, and climatic characteristics. The objectives of this study were therefore to: (i) characterize streamflow recession dynamics in the El Abid River Basin; (ii) compare station-scale recession behaviour and estimated baseflow contribution using recession coefficients and baseflow indices; (iii) interpret the observed differences within the regional hydrogeomorphological context provided by the basin-scale IntErO analysis; and (iv) identify implications for low-flow assessment and future station-catchment investigations in semi-arid Mediterranean mountain basins. The findings contribute to low-flow assessment and water-resources management in the upstream Bin El Ouidane watershed while recognizing that station-specific physical controls require separate catchment-scale evaluation.

MATERIAL AND METHODS

Presentation of study area

The Oum Er Rbia watershed is located in the heart of the Central High Atlas, between longitudes 5°W and $6^{\circ}30'\text{W}$ and latitudes 32°N and 33°N . The El Abid River is a perennial watercourse that originates at Jbel Masker (3,277 m), flows from east to west, and constitutes the main tributary of the Oum Er Rbia River (Ouakhir *et al.*, 2023). The El Abid River Basin, presented in Figure 1, is an important source of regional water availability and water resource management.

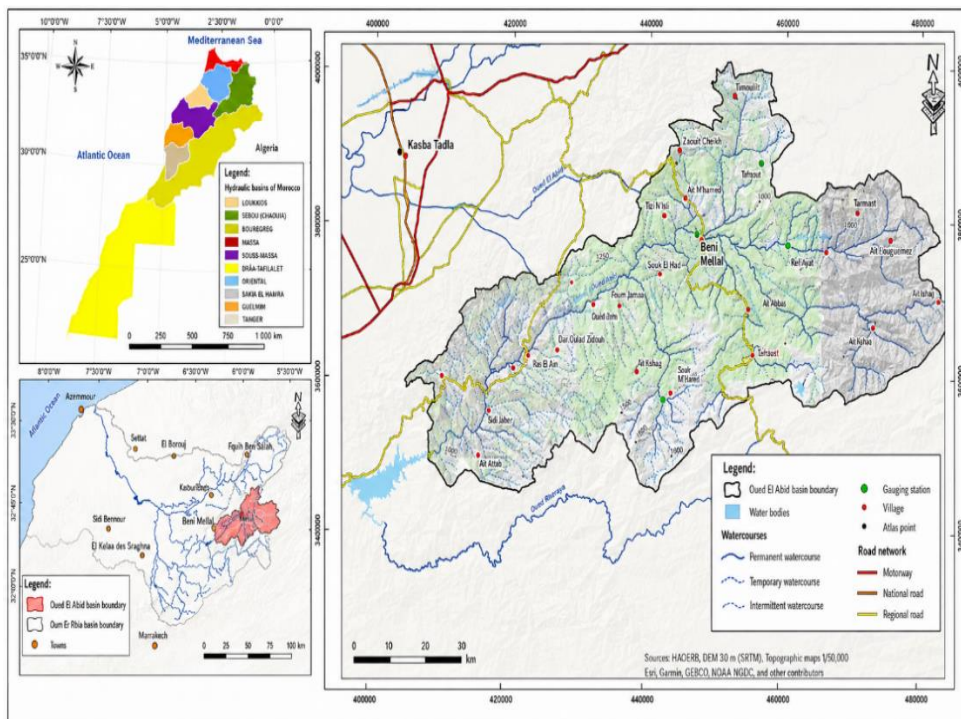


Figure 1. Presentation of the studied area at different scales

Application of the IntErO model

The hydrogeomorphological characteristics of the El Abid River basin (erosion intensity and outflow) were evaluated by using the IntErO model (Spalevic, 2011).

The present model is capable of integrating morphometric, geological, soil, climatic and land-use variables to produce quantitative indices describing catchment behaviour, surface runoff generation, erosion intensity and hydrological processes (Spalevic *et al.*, 2020; Ouakhir *et al.*, 2025; 2026a).

In the current investigation, these metrics served as further hydrogeomorphological indicators to enhance the understanding of streamflow recession traits and baseflow behaviour. The IntErO model was applied at the scale of the entire El Abid River Basin to provide an integrated hydrogeomorphological characterization of the study area.

Consequently, the resulting morphometric, lithological, climatic, and land-use parameters represent basin-scale descriptors rather than the individual upstream catchments draining to the Tizi N'Isli and Ait Ouchène gauging stations. Therefore, IntErO outputs were not used to quantitatively explain the observed differences between the two stations but rather to provide regional hydrogeomorphological context for interpreting the recession characteristics and baseflow behaviour.

Two basin-area values are reported in this study because they correspond to different definitions. The value of 3004 km² represents the official hydrological drainage area of the El Abid River Basin, whereas 3119.14 km² corresponds to the GIS-derived watershed area calculated during the IntErO analysis. Unless otherwise specified, the IntErO calculations use the GIS-derived basin area (3119.14 km²).

An extensive set of topographic, geological, land-use, hydrological, meteorological, and field data was used as input to the IntErO model. The basin morphometric parameters—area, elevation range, slope, drainage density, and watershed structure—were derived from a Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) with a spatial resolution of 30 m.

Lithological and permeability data were taken from the 1:50,000 geological map of the Central High Atlas.

Land-use and land-cover data were extracted from Google Earth Pro imagery and verified through field surveys conducted between 2021 and 2023. Drainage-network data, historical streamflow records, annual precipitation data, and air-temperature data were provided by the Hydraulic Agency of the Oum Er-Rbia Basin (HAOERB).

Supplementary field observations were used to verify the identified geomorphological characteristics. These datasets were integrated within IntErO to derive morphometric, lithological, climatic, land-use, and hydrogeomorphological indicators that provided regional context for interpreting the observed streamflow recession and baseflow dynamics.

Data Sources and pre-processing

The hydrological and climatological dataset used in this study was obtained from the Hydraulic Agency of the Oum Er-Rbia Basin (HAOERB), which is the authority responsible for monitoring and managing water resources in the study area.

Two gauging stations in the El Abid River Basin, Ait Ouchène and Tizi N'Isli, were selected based on the length, continuity, and reliability of their records. Both stations provide long-term precipitation (P) and discharge (Q) data, enabling detailed characterization of rainfall, streamflow, and baseflow dynamics. The period of record, station type, spatial coordinates (X and Y), and elevation (Z) for each station are summarized in Table 1.

Table 1. Hydro-meteorological stations used in this study (source: HAOERB)

Period	Station	Type	X (m)	Y (m)	Z (m)
1976–2021	Ait Ouchène	P/Q	434300	185100	1070
1976–2021	Tizi N'Isli	P/Q	432300	139600	1595

Before the analysis, the dataset underwent several pre-processing steps to ensure its quality and suitability for the analysis of water recession and groundwater flow.

First, the completeness and consistency of the daily time series for discharge and precipitation were verified. Periods containing missing or unreliable data were identified and excluded when necessary to avoid bias in the analysis.

Second, the dataset was filtered to isolate hydrologically relevant periods. Because recession analysis requires the exclusion of flows affected by rainfall, precipitation data were used to identify and remove periods influenced by rainfall events. This step ensured that the analysed discharge sequences were consistent with groundwater-controlled flow conditions.

Third, the discharge time series were organized at a daily time step, which is suitable for monitoring short-term changes while allowing aggregation over the longer periods required for streamflow-recession analysis.

Finally, the following methodological procedures were applied to the prepared dataset:

- a) detection and extraction of recession periods;
- b) construction of the master recession curve;
- c) estimation of recession coefficients;
- d) separation of baseflow from total streamflow; and
- e) calculation of the Baseflow Index.

The combined use of precipitation and discharge data from these two stations provides a reliable basis for analysing the temporal evolution and spatial distribution of base flow generation within the El Abid River basin. The overall methodological framework applied in this study is summarized in Figure 2.

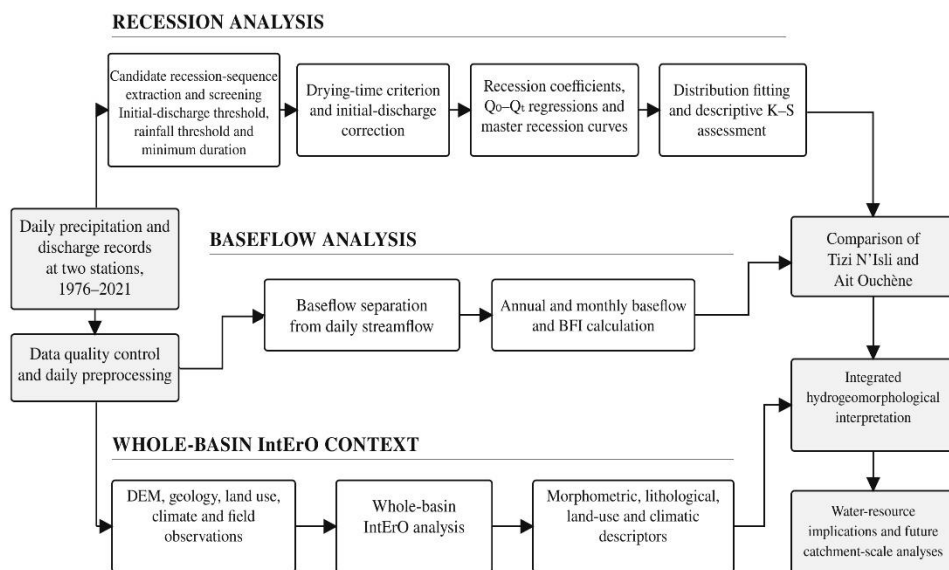


Figure 2. Methodological framework used to analyse streamflow recession, baseflow contribution, and basin-scale hydrogeomorphological characteristics in the El Abid River Basin

Recession analysis framework

The methodology used in this study is based on the premise that streamflow recession is not simply a period of decreasing discharge but a hydrological response associated with the gradual depletion of water stored within the catchment. During recession periods, the influence of rainfall and rapid surface runoff gradually diminishes, while streamflow is increasingly sustained by delayed water release from subsurface storage. This process is particularly important in the study area because seasonal variations in precipitation, high evapotranspiration, and heterogeneous geological formations may produce temporal and spatial differences in catchment storage and drainage behaviour. Recession analysis was therefore used as the principal framework for examining delayed-flow dynamics during periods of seasonal streamflow decline. Various methods have been proposed to characterize recession behaviour; however, approaches based on envelope curves or unrestricted recession-curve fitting may incorporate hydrograph segments that remain affected by direct runoff or rainfall-related disturbances. In this study, the sequential recession-curve method (Rutledge and Daniel, 1994; Tallaksen and van Lanen, 2023) was selected because it enables the systematic identification and extraction of recession sequences according to predefined hydrological and quality-control criteria. The retained sequences were subsequently used to estimate recession coefficients, construct master recession curves, and support the assessment of baseflow contribution.

Extraction of recession periods

Systematic recession sequences were extracted using the sequential recession-curve method to identify periods of persistent streamflow decline with minimal influence from rainfall and rapid runoff. Candidate sequences were first screened using a discharge threshold: any sequence starting above the mean discharge at the relevant station was excluded as being more likely to be post-event or mixed flow.

A second screening criterion was based on daily rainfall. In the preliminary analysis thresholds from 1 to 5 mm day⁻¹ were tested and 5 mm day⁻¹ was chosen because smaller thresholds excessively fragmented the recession series by terminating sequences after small rainfall amounts that did not produce any discernible streamflow response. Therefore, days with precipitation greater than 5 mm day⁻¹ were considered rainfall-affected and were excluded, whereas smaller amounts were not automatically treated as terminating a recession sequence. This approach accounts for the limited hydrological response that small amounts of rainfall may generate under semi-arid conditions because of interception, soil-moisture deficits, and evapotranspiration (Rutledge and Daniel, 1994; Tallaksen and van Lanen, 2023). Usually, shorter sequences do not have sufficient information to reliably characterize recession behaviour. Sequences that met these initial criteria were kept as candidates for the subsequent quality-control and correction procedure.

Correction of extracted sequences

In this study, the term optimization refers to the quality-control procedure applied to the initially extracted recession sequences. Its objective was to retain only those sequences that accurately represent groundwater-controlled streamflow recession. Sequences that did not meet *all* pre-defined quality criteria were therefore excluded from further analyses. The optimized recession sequences are therefore the final data set for the estimation of recession coefficients (α), the construction of master recession curves, and for all statistical analyses.

After the preliminary extraction of recession sequences, an additional correction step was applied in order to refine the beginning of each episode and eliminate residual perturbations. This stage is particularly important because even after rainfall has ceased, streamflow may remain temporarily influenced by drainage from hillslopes, channel storage, or delayed transfer from near surface compartments. If these effects are not removed, the first part of the sequence may not represent true aquifer recession. A recession sequence was discarded during the optimization procedure if it met one or more of the following conditions: (i) the initial part of the sequence remained influenced by rainfall or rapid surface runoff after application of the drying-time criterion; (ii) the sequence was shorter than the minimum duration of five consecutive days; (iii) the discharge trend did not exhibit a consistent monotonic recession after correction; or (iv) the initial discharge (Q_0) could not be adjusted to satisfy the recession consistency criterion. To account for

this transition period, the methodology uses the drying time relation proposed by Rutledge and Daniel (1994). This relation is written as (Eq. 1):

$$TR = A^{0.2} \quad (1)$$

where TR is the drying time (days) and A is the upstream drainage area (km²) contributing to the corresponding gauging station. The equation was applied separately to the Tizi N'Isli and Ait Ouchène catchments rather than to the entire El Abid River Basin, because the drying time depends on the contributing drainage area upstream of each station. The calculated T_R values were then used to exclude the initial portions of recession sequences that might still have been affected by delayed rainfall responses (Chakir *et al.*, 2024). The hydrologic interpretation of this formula is that the time for the effect of the rainfall to vanish increases with the size of the basin, but in a sublinear manner. The exponent 0.2 indicates that the response is not proportional. A larger basin does not require five or ten times more time simply because its area is larger. Instead, the increase in required drying time is more gradual, reflecting the fact that basin size influences water transfer and storage conditions, but does not alone control recession dynamics. This formula is therefore used as an empirical estimator of the delay necessary before a discharge sequence can be interpreted as a genuine recession controlled mainly by delayed subsurface release.

The initial discharge value, Q_0 , was also checked. This correction is essential because the entire recession analysis depends on identifying a realistic starting point. If Q_0 is too high because it still contains the effect of recent rainfall or bank storage release, the calculated recession coefficient will be biased. This correction is performed by computing the slope of the last three discharges of the sequence, extrapolating that tendency backward, and removing previous values that deviate by more than 1.5% from the expected trend. The logic behind this procedure is that a true recession segment should follow a coherent and smooth decline. A deviation larger than 1.5% is interpreted as evidence that the beginning of the sequence is still perturbed and must therefore be adjusted. The 1.5% threshold was adopted as a quality-control criterion to minimize the influence of residual rainfall effects and short-term hydrological disturbances while preserving the natural recession behaviour.

Preliminary tests indicated that smaller thresholds resulted in excessive correction of otherwise consistent recession sequences, whereas larger thresholds allowed disturbed initial values to remain within the dataset. This threshold was maintained because it represents a reasonable compromise between over- and under-correction. This approach is consistent with quality-control principles commonly applied to streamflow recession analyses (Rutledge and Daniel, 1994; Tallaksen and van Lanen, 2023).

The optimization procedure was therefore performed after the initial extraction of recession sequences. Each candidate sequence was first screened using the discharge, rainfall, and minimum-duration criteria. The retained

sequences were subsequently corrected using the drying-time criterion, followed by adjustment of the initial discharge (Q_0) when necessary. Only sequences satisfying all quality-control criteria after these corrections were retained as optimized recession sequences for all subsequent analyses.

Construction of the master recession curve

After the individual recession sequences were extracted and corrected, they were used to construct a master recession curve. This curve provides a synthetic representation of the mean recession behaviour observed at a gauging station and can be used to compare stations or periods. Its theoretical basis is the exponential recession law first proposed by Maillet (1905). The formula is given in Eq. 2:

$$Q(t) = Q_0 e^{-\alpha t} \quad (2)$$

where $Q(t)$ is the streamflow discharge at time t ($\text{m}^3 \text{s}^{-1}$), Q_0 is the discharge at the beginning of the recession period ($\text{m}^3 \text{s}^{-1}$), t is the elapsed time since the beginning of the recession (days), and α is the recession coefficient (day^{-1}).

The recession coefficient α quantifies the rate at which streamflow decreases during a recession period. Throughout this study, α is expressed in day^{-1} because daily discharge data were used, while the time variable t is expressed in days. Higher α values indicate faster streamflow recession, whereas lower values indicate slower recession. Because α may also be influenced by antecedent hydrological conditions, catchment structure, evapotranspiration, and the relative contributions of different flow pathways, it should not be interpreted alone as a direct measure of aquifer-storage capacity or groundwater contribution.

This equation assumes that the rate of streamflow decline is proportional to the discharge remaining during the recession period. The recession coefficient α is therefore a key parameter describing the rate of streamflow decline. A high value of α indicates rapid recession. However, α alone should not be interpreted as direct evidence of limited catchment-storage capacity or weak groundwater support, because recession behaviour may also be influenced by antecedent hydrological conditions, catchment structure, evapotranspiration, and the relative contributions of different flow pathways.

Lower α values indicate slower streamflow recession. To estimate recession behaviour more robustly, this study applied the correlation method. Instead of fitting each recession sequence separately and then averaging the coefficients, this method relates the discharge at the beginning of the sequence to the discharge measured after a fixed time interval. The relationship is expressed in Eq. 3:

$$Q_t = a_t \cdot Q_0 \quad (3)$$

where Q_t is the discharge after a fixed time interval t ($\text{m}^3 \text{s}^{-1}$), Q_0 is the initial discharge at the beginning of the recession period ($\text{m}^3 \text{s}^{-1}$), and a

t is the recession ratio (dimensionless) corresponding to the selected time interval t .

According to the Maillet (1905) recession equation, the recession ratio is directly related to the recession coefficient by:

$$at = e^{-\alpha t} \quad (4)$$

where α is the recession coefficient (day^{-1}) and t is the elapsed time (days). Thus, a_t represents the fraction of the initial discharge remaining after t days of recession. Because a_t depends on both α and the selected time interval, it is dimensionless and should not be confused with the recession coefficient α . This formula can be understood as a practical reformulation of the exponential recession law.

If the recession process is approximately exponential, then the ratio between discharge at time (t) and initial discharge should remain relatively stable across comparable episodes.

The recession ratio a_t represents the average proportion of the initial discharge remaining after t days. A value of a_t close to unity indicates only a slight reduction in discharge over the selected time interval and therefore a slow recession. Conversely, a substantially lower value indicates a greater reduction in discharge and faster recession. The corresponding recession coefficient α is calculated from a_t using Eq. 4.

Baseflow separation and baseflow index

The recession analysis was complemented by a specific treatment of baseflow, which corresponds to the part of total streamflow sustained by groundwater discharge. During seasonal low flow conditions, this component becomes dominant because direct runoff is minimal or absent. In mountainous basins with complex lithology and variable storage conditions, the analysis of baseflow is essential for understanding how and where the river continues to be fed during dry periods. To isolate baseflow from daily streamflow, the graphical inflection method was adopted. The method was applied to the complete daily discharge time series for both gauging stations (1976–2021). Inflection points were identified at the transition between direct runoff recession and groundwater-controlled recession, following the change in the slope of the hydrograph. Rainfall-affected periods identified during the recession-sequence extraction procedure were excluded before baseflow separation to avoid contamination by stormflow. Baseflow was then estimated by connecting successive inflection points with straight-line segments, assuming a gradual groundwater contribution between consecutive turning points. The procedure was applied consistently to all recession periods using the same selection criteria described previously.

The graphical inflection method was implemented in MATLAB (MathWorks, Inc., Natick, MA, USA), where the daily discharge series were processed using a semi-automated workflow. Candidate inflection points were

identified automatically from the hydrograph, whereas final verification was performed visually to ensure that only hydrologically consistent groundwater-controlled recession segments were retained. The same baseflow-separation procedure, parameters, and daily time step were applied consistently to both Tizi N'Isli and Ait Ouchène stations and to both annual and monthly calculations. After separation, the Baseflow Index was calculated using the following formula (Eq. 5):

$$\mathbf{BFI} = \left(\frac{\sum V_{base}}{\sum V_{total}} \right) \times 100 \quad (5)$$

where $\sum V_{base}$ is the cumulative baseflow volume over the selected period, and $\sum V_{total}$ is the cumulative total streamflow volume over the same period. This formula expresses the percentage contribution of groundwater-supported flow to total streamflow.

Because daily discharge data were used, the daily volumes were obtained from:

$$V = Q\Delta t \quad (6)$$

where Q is the mean daily discharge in $\text{m}^3 \text{s}^{-1}$, and Δt is the daily time step of 86,400 seconds. Annual BFI was calculated directly from the ratio between the cumulative annual baseflow volume and the cumulative annual total streamflow volume:

$$\mathbf{BFI}_{annual} = \frac{\sum_{d=1}^n V_{base,d}}{\sum_{d=1}^n V_{total,d}} \times 100 \quad (7)$$

Thus, the annual BFI was not calculated as the arithmetic mean of the twelve monthly BFI values. For each calendar month, monthly BFI was calculated separately as:

$$\mathbf{BFI}_{monthly} = \frac{\sum V_{base,month}}{\sum V_{total,month}} \times 100 \quad (8)$$

The monthly values therefore represent ratios calculated from the cumulative baseflow and total streamflow volumes within each month. Differences between annual and monthly BFI may occur because the annual value is discharge-weighted: months with high streamflow volumes contribute more strongly to the annual BFI than low-flow months. The BFI quantifies the relative contribution of baseflow to total streamflow over a specified period of time. A high BFI indicates that baseflow is a large proportion of total streamflow, whereas a low BFI indicates a greater relative contribution from rapid runoff. However, BFI does not directly quantify absolute baseflow discharge, aquifer storage capacity or the persistence of groundwater discharge during dry periods. These characteristics were evaluated

jointly through absolute baseflow values, monthly BFI patterns, recession coefficients and master recession curves.

The optimized recession coefficients were analysed separately for Tizi N'Isli ($n = 219$) and Ait Ouchène ($n = 95$). Descriptive statistics included the minimum, maximum, mean, standard deviation, coefficient of variation, median, mode, and first and third quartiles. Candidate theoretical probability distributions were fitted separately to each station dataset, and goodness of fit was evaluated using the Kolmogorov–Smirnov (K–S) statistic and associated p-values. Because the distribution parameters were estimated from the same observations used in the K–S analysis, the p-values were interpreted as descriptive goodness-of-fit indicators rather than exact hypothesis-test probabilities. The distribution with the highest descriptive p-value was treated as the leading candidate among the tested models, not as a uniquely established probability model.

RESULTS

Extraction of the recession sequences at the studied stations (1976–2021)

The extraction procedure identified 345 candidate recession sequences at Tizi N'Isli during 1976–2021, of which 219 sequences, or 63.5%, were retained after quality control (Table 2). The remaining 126 sequences were excluded because they failed to satisfy one or more of the predefined rainfall, minimum-duration, monotonicity, drying-time, or initial-discharge criteria. Although more candidate sequences were identified at Tizi N'Isli than at Ait Ouchène, this difference alone does not demonstrate greater hydrological variability or establish the effects of elevation, precipitation, or snow processes, because these potential controls were not evaluated quantitatively at the station-catchment scale.

The optimized recession sequences (219 at Tizi N'Isli and 95 at Ait Ouchène) constituted the final dataset used for all subsequent recession analyses presented in this study.

Table 2. Summary of extracted and optimized recession sequences

Station	Extracted recession sequences	Optimized recession sequences used in subsequent analyses	Retention rate (%)
Tizi N'Isli	345	219	63.5
Ait Ouchène	131	95	72.5

At Ait Ouchène, 131 recession sequences were initially identified, of which 95 were retained after quality control, corresponding to a retention rate of 72.5% (Table 2). Although fewer sequences were identified at this station than at Tizi N'Isli, a larger proportion satisfied the predefined selection criteria. This result indicates that the identified recession periods at Ait Ouchène more frequently met the requirements for inclusion in the subsequent analyses. When considered together with the longer recession periods and lower recession coefficients

presented below, this pattern is consistent with a more persistent groundwater contribution, although the number and retention rate of recession sequences alone are insufficient to establish this interpretation.

Monthly distribution of recession sequence curves

The monthly allocation of the preserved recession sequences exhibited distinct seasonal fluctuations at both measurement sites from 1976 to 2021 (Figure 3). The frequency of recession sequences varied among months, with distinct periods of higher and lower occurrence at each station. This distribution was consistent with seasonal hydroclimatic variability in the Central High Atlas, although the effects of individual climatic controls were not quantified in the present study.

The duration characteristics of the initially extracted recession sequences are presented in Table 3. At Tizi N'Isli, the 345 extracted sequences lasted between 5 and 28 days, with a mean duration of 17 days. At Ait Ouchène, the 131 extracted sequences lasted between 5 and 30 days, with a mean duration of 18 days. Thus, recession sequences were more frequently identified at Tizi N'Isli, whereas their mean and maximum durations were slightly higher at Ait Ouchène. These descriptive differences are consistent with somewhat more persistent recession conditions at Ait Ouchène; however, the differences in duration were small and were not tested for statistical significance.

Table 3. Characteristics of extracted recession sequences (1976–2021)

Stations	Extracted recession sequences (n)	Minimum Duration (days)	Maximum Duration (days)	Mean Duration (days)
Tizi N'Isli	345	5	28	17
Ait Ouchène	131	5	30	18

The minimum sequence duration of five days at both stations reflects the predefined duration criterion applied during recession-sequence extraction. The monthly frequency and duration of the extracted sequences are considered together below to describe the seasonal recession patterns at the two gauging stations (Figure 3).

Considered together, the sequence frequency shown in Figure 3 and the duration statistics presented in Table 3 indicate different descriptive recession patterns at the two stations. Tizi N'Isli had a larger number of extracted recession sequences and a slightly shorter mean duration, whereas Ait Ouchène had fewer sequences with slightly higher mean and maximum durations. Because the differences in duration were small and were not tested statistically, they should be interpreted cautiously.

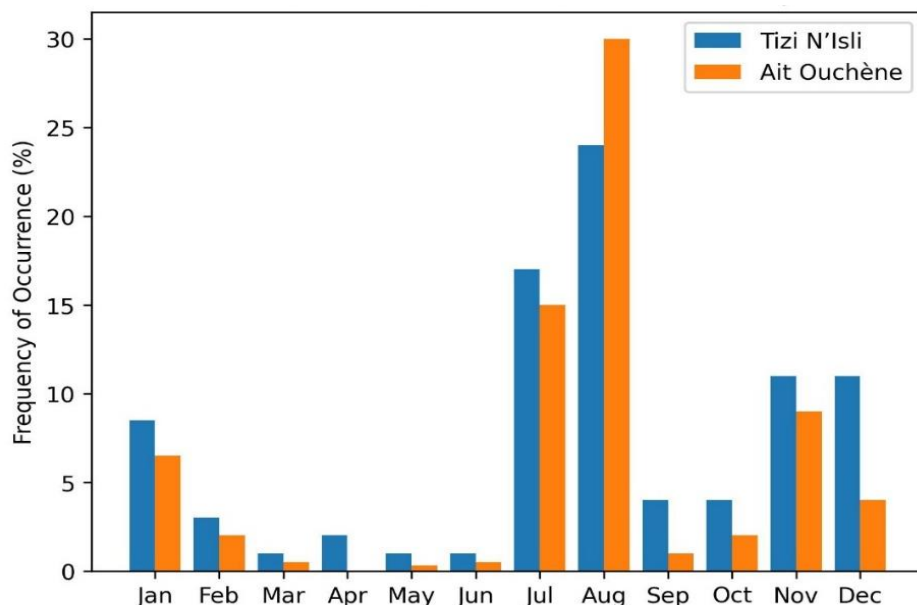


Figure 3. Monthly distribution of recession sequences at the two gauging stations

The observed contrast in sequence frequency may be associated with differences in the physical and hydrological characteristics of the areas draining to the two gauging stations. However, elevation, lithology, groundwater-storage properties and climatic forcing were not compared quantitatively at the individual station-catchment scale.

The results therefore demonstrate spatial variability in the frequency of recession sequences between the two stations, whereas the differences in their mean and maximum durations were relatively small.

Characterisation of recession coefficients within the river basin

Recession coefficients differed between the two gauging stations in their mean values, ranges and variability during 1976–2021 (Table 4). Their seasonal variation is shown in Figure 4. Together, these indicators describe differences in the rate and temporal variability of streamflow recession at Tizi N'Isli and Ait Ouchène.

Table 4. Statistical characteristics of recession coefficients (α) derived from optimized recession sequences

Station	α min	α max	α mean	σ (Standard Deviation)	CV (%)
Tizi N'Isli	0.0149	0.6644	0.0502	0.0624	124.30
Ait Ouchène	0.0197	0.0968	0.0407	0.0175	43.00

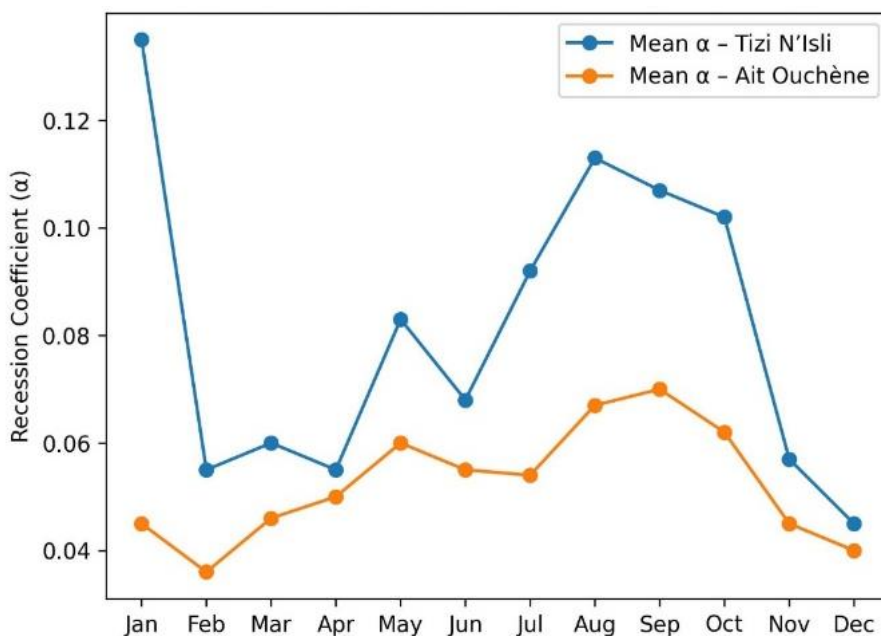


Figure 4. Seasonal variation of recession coefficients (α) calculated from optimized recession sequences

The mean recession coefficient was higher at Tizi N'Isli (0.0502 day^{-1}) than at Ait Ouchène (0.0407 day^{-1}) (Table 4), indicating a higher average rate of streamflow decline during the analysed recession sequences. Recession coefficients were also considerably more variable at Tizi N'Isli, where the coefficient of variation was 124.3%, compared with 43.0% at Ait Ouchène. The α values ranged from 0.0149 to 0.6644 day^{-1} at Tizi N'Isli and from 0.0197 to 0.0968 day^{-1} at Ait Ouchène. These results indicate substantially greater dispersion of recession rates at Tizi N'Isli.

In conceptual terms, higher α values represent faster streamflow recession, whereas lower values represent slower depletion during recession periods. The results are therefore consistent with a more variable recession response at Tizi N'Isli and a comparatively more uniform response at Ait Ouchène. However, recession coefficients alone do not quantify groundwater-storage capacity or the relative groundwater contribution to total streamflow; these interpretations must be considered together with the master recession curves and BFI results.

The wider range of α values at Tizi N'Isli may reflect greater temporal heterogeneity in recession conditions, although the available results do not allow these differences to be attributed specifically to shallow or deep groundwater-storage components. The narrower range observed at Ait Ouchène indicates a less variable recession response but does not, by itself, demonstrate the dominance of groundwater-fed flow. The monthly variation in α values at both stations is illustrated in Figure 4.

Monthly mean α values showed different temporal patterns at the two stations (Figure 4). At Tizi N'Isli, the highest monthly mean occurred in January, followed by another period of elevated values from August to October, while lower values were observed in February–April and November–December. At Ait Ouchène, α values generally increased from spring towards late summer, reached their maximum in September, and subsequently declined. Therefore, the two stations did not exhibit an identical seasonal pattern. The causes of these monthly variations cannot be established from the present analysis because evapotranspiration, snowmelt and seasonal groundwater-storage changes were not quantified.

At Tizi N'Isli, the monthly mean α exceeded 0.11 day^{-1} in August, indicating relatively rapid recession during the analysed sequences in that month. However, the highest monthly mean was observed in January rather than during the summer. At Ait Ouchène, monthly mean α values showed a narrower range and reached approximately 0.07 day^{-1} in September. The smaller monthly variation at Ait Ouchène is consistent with a less variable recession response. Nevertheless, the seasonal patterns cannot be attributed directly to elevation, slope, evapotranspiration, soil moisture or groundwater recharge because these potential controls were not evaluated quantitatively at the station-catchment scale.

Overall, the recession coefficients indicate contrasting recession behaviour at the two gauging stations. Tizi N'Isli had a higher mean α and substantially greater variability, indicating faster average streamflow decline and a more heterogeneous recession response. Ait Ouchène had a lower mean α and a narrower range of values, consistent with slower and more uniform recession. These differences may be associated with climatic and catchment characteristics, but the relevant controls were not quantified separately for the areas draining to the two stations. Moreover, the recession coefficients describe the rate of streamflow decline and should not be interpreted alone as direct measures of groundwater-storage capacity or annual baseflow contribution.

Analysis of recession curves

Figure 5 presents representative graphical examples derived from the optimized recession sequences. These graphical subsets illustrate the Q_0 – Q_t relationships, whereas all statistical analyses were conducted using the complete optimized datasets of 219 sequences at Tizi N'Isli and 95 sequences at Ait Ouchène. They showed strong linear relationships between initial discharge (Q_0) and discharge after the defined time interval (Q_t), consistent with the linearized form of the exponential recession model. These examples illustrate the model fit but should not be interpreted as representing the goodness of fit of every retained recession sequence.

Across the retained recession sequences, the regressions between Q_0 and Q_t produced coefficients of determination ranging from approximately 0.87 to 0.96 (Figure 5). These values indicate that the relationship derived from the exponential recession equation explained a large proportion of the observed variation.

Nevertheless, model adequacy should be evaluated together with residual diagnostics or error measures where available.

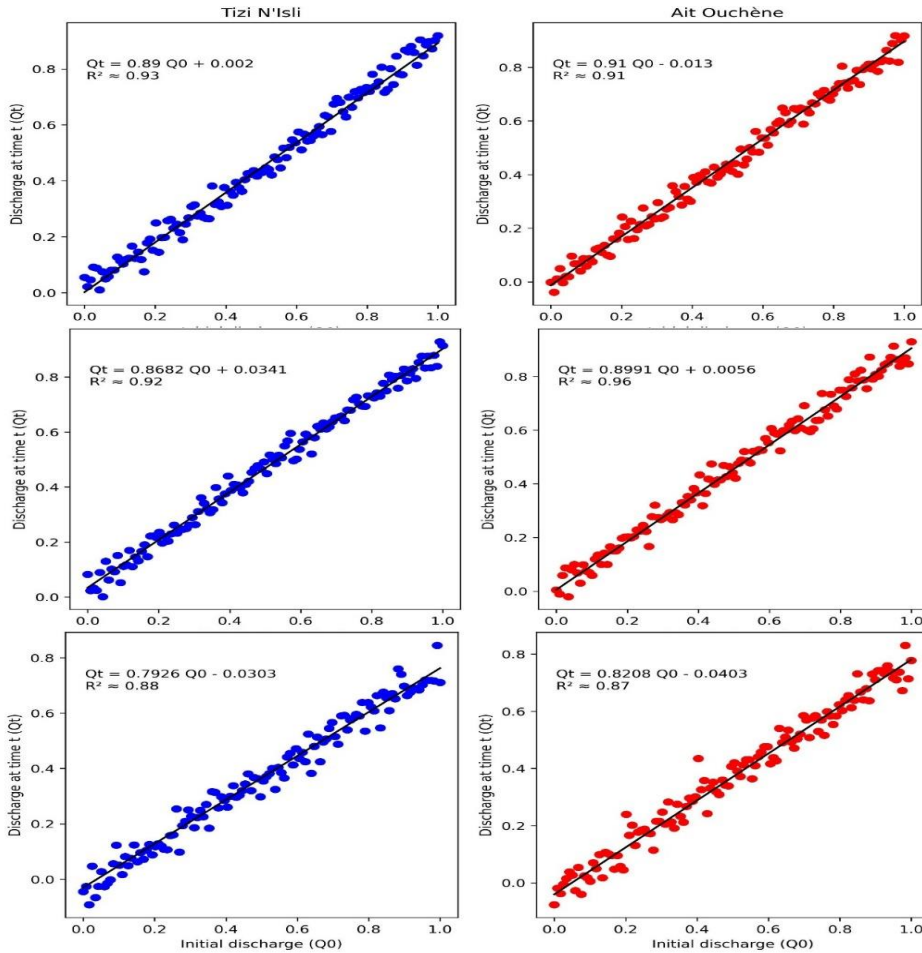


Figure 5. Relationship between Q_0 and Q_t for selected optimized recession sequences at Tizi N'Isli and Ait Ouchène.

Note: The graphical samples are presented for illustration only and do not represent the complete datasets used for the statistical analysis, which comprise 219 sequences at Tizi N'Isli and 95 sequences at Ait Ouchène.

The variation in regression slopes among the analysed recession sequences indicates that the rate of streamflow decline was not uniform among events. This variability may reflect differences in initial flow conditions, seasonal hydrological conditions and the relative contribution of different subsurface-flow pathways. However, the available discharge data do not allow the observed differences to be attributed specifically to shallow or deep groundwater-storage components. Such

an interpretation would require additional hydrogeological, piezometric or tracer-based evidence.

At Ait Ouchène, the regression slopes shown in Figure 5 ranged from 0.82 to 0.91, while the coefficients of determination reached approximately 0.96. For a fixed time interval, a higher Q_t - Q_0 regression slope indicates that a larger proportion of the initial discharge remained at time t and is therefore consistent with slower recession. The relatively limited scatter around the fitted regression lines supports a more uniform response in the illustrated sequences. Nevertheless, these regression characteristics alone neither demonstrate enhanced groundwater retention nor identify the geological and topographic factors responsible for the observed pattern.

The comparison indicates contrasting recession behaviour at the two gauging stations. Tizi N'Isli showed a higher mean recession coefficient and greater temporal variability, whereas Ait Ouchène showed lower recession coefficients and a more uniform response in the analysed regressions. These results are consistent with faster and more variable streamflow recession at Tizi N'Isli and slower recession at Ait Ouchène. The comparatively buffered response at the downstream station may be influenced by the integration of flow contributions along the river network, but this mechanism and the associated changes in storage capacity were not evaluated quantitatively.

Master recession curve analysis for baseflow dynamics

The master recession curves, constructed from the temporal evolution of the normalized discharge ratio (Q_t/Q_0), provided a composite representation of average streamflow-recession behaviour at the Tizi N'Isli and Ait Ouchène stations (Figure 6). At both stations, the normalized discharge decreased approximately exponentially with time, indicating that the Maillet exponential model provided an appropriate representation of the aggregated recession pattern. This result describes the average behaviour of the retained recession sequences and does not imply that individual recession events or the hydrological regime of the entire basin were uniform or stable.

The master recession curves showed a continuous decrease in the normalized discharge ratio (Q_t/Q_0) with time, consistent with the progressive decline of streamflow during recession periods. The fitted exponential curves yielded high coefficients of determination, with $R^2 = 0.9949$ at Tizi N'Isli and $R^2 = 0.9669$ at Ait Ouchène (Figure 6). These results indicate that the Maillet exponential equation closely represented the aggregated recession curves used in the analysis. However, the fit of the master curves does not demonstrate that every individual recession sequence followed the same pattern. The reported R^2 values refer exclusively to the master recession curves and should not be confused with those obtained from the individual Q_0 - Q_t regressions.

The master recession curve declined more rapidly at Tizi N'Isli than at Ait Ouchène (Figure 6). The corresponding master recession coefficient was also higher at Tizi N'Isli ($\alpha = 0.0390 \text{ day}^{-1}$), indicating a faster average decrease in

normalized discharge during the analysed recession period. This result is consistent with the higher mean α and greater variability of individual recession coefficients previously observed at this station. However, the available analysis does not establish whether the faster recession resulted from limited storage capacity, shallow subsurface flow, steep slopes or other catchment characteristics.

The master recession curve at Ait Ouchène declined more gradually, with a lower master recession coefficient of $\alpha = 0.0323 \text{ day}^{-1}$ (Figure 6). This result is consistent with the lower variability and narrower range of individual α values observed at this station and indicates slower average streamflow recession. The pattern may reflect more persistent release from hydrologically connected storage and the integration of upstream flow contributions. However, the present analysis does not quantify effective storage capacity or demonstrate that the upstream area of Ait Ouchène contains more permeable geological formations than the area draining to Tizi N'Isli.

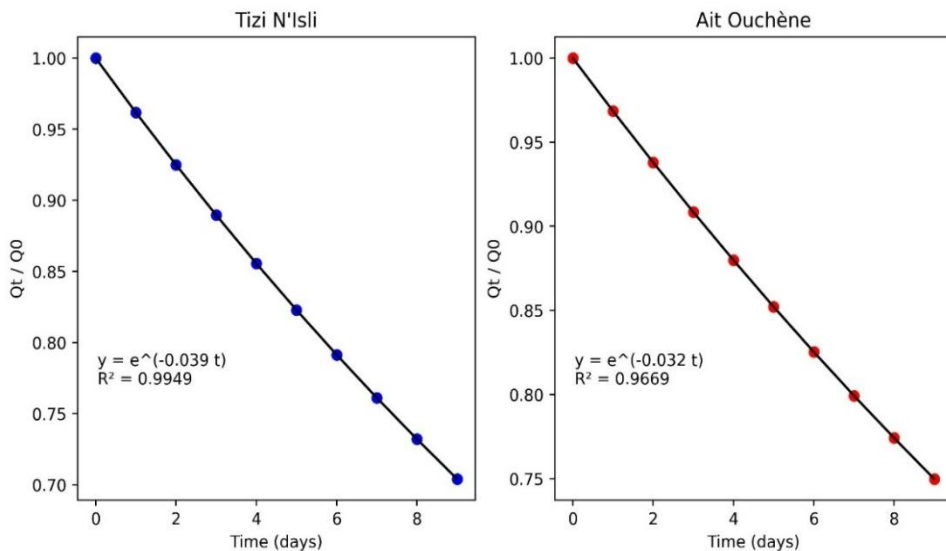


Figure 6. Master recession curves constructed from optimized recession sequences

The Q_0 - Q_t regressions and master recession curves provide complementary descriptions of the analysed recession sequences. The Q_0 - Q_t relationships characterize the proportional decline in discharge over defined time intervals, whereas the master curves summarize the temporal evolution of normalized discharge across the retained sequences. Both analyses indicate that average recession behaviour at the two stations can be represented approximately by an exponential model.

The observed differences between the stations may be related to topographic, geological and groundwater-storage characteristics, but these potential controls were not quantified at the individual station-catchment scale.

The master recession curves identified different average recession rates at the two gauging stations: discharge declined more rapidly at the upstream Tizi N'Isli station and more gradually at the downstream Ait Ouchène station. This contrast is consistent with more persistent release of stored water at Ait Ouchène, although groundwater storage was not measured directly. The station-specific recession parameters may support the characterization and modelling of low-flow behaviour in the El Abid River Basin, but their predictive application requires independent validation.

Statistical analysis and probability distributions of recession coefficients

The empirical distributions of recession coefficients (α) were characterised using the complete quality-controlled datasets: 219 values at Tizi N'Isli and 95 at Ait Ouchène. The statistical analyses were performed using the complete optimized datasets ($n = 219$ for Tizi N'Isli and $n = 95$ for Ait Ouchène). Any equal-sized samples or subsets displayed in the graphical representations were used only for visualization and do not correspond to the full datasets used for the statistical calculations. The corresponding descriptive statistics and theoretical probability distributions are presented in Tables 4–6. The central 50% of α values ranged from 0.0310 to 0.0618 day⁻¹ at Tizi N'Isli and from 0.0261 to 0.0507 day⁻¹ at Ait Ouchène (Table 6). The wider interquartile range and higher coefficient of variation at Tizi N'Isli indicate greater dispersion and more variable recession behaviour.

These distributional characteristics were consistent with the master recession curves and Q_0 – Q_t relationships. Tizi N'Isli showed faster and more variable recession, whereas Ait Ouchène showed slower and less variable recession. Together, these results indicate an upstream–downstream contrast between the two gauging stations. However, additional gauging stations and catchment-specific analyses would be required to establish a continuous hydrological gradient within the El Abid River Basin.

The distributions of recession coefficients exhibited significant diversity in α values and marked distinctions between the two measuring locations. These results indicate that a single recession parameter may not adequately represent streamflow recession at both locations. Station-specific recession characteristics should therefore be considered in low-flow modelling and water-resources assessments. Although topography, lithology, groundwater storage and flow pathways may contribute to the observed differences, their effects were not tested directly in this analysis.

The theoretical probability distributions fitted to the retained recession coefficients are compared in Table 5. The analysis included 219 α values for Tizi N'Isli and 95 for Ait Ouchène. Because the distribution parameters were estimated from the same observations used in the Kolmogorov–Smirnov analysis, the reported p-values were treated as descriptive goodness-of-fit indicators rather than exact hypothesis-test probabilities. Accordingly, the distributions were evaluated

as approximate representations of the observed α values rather than as definitively confirmed probability models.

For Tizi N'Isli, the log-normal distribution yielded the highest descriptive K–S p-value among the tested models ($p = 0.945$), followed by the GEV ($p = 0.812$) and logistic distributions ($p = 0.421$) (Table 5).

Table 5. Kolmogorov–Smirnov (K–S) goodness-of-fit test results (p-values) for the theoretical probability distributions fitted to the optimized recession coefficients (α) at the Tizi N'Isli and Ait Ouchène gauging stations

Distribution	p-value (Tizi N'Isli)	p-value (Ait Ouchène)
Beta	0.078	0.041
Beta (4)	0.109	0.059
Chi-square	< 0.0001	< 0.0001
Erlang	< 0.0001	< 0.0001
Exponential	< 0.0001	< 0.0001
Fisher-Tippett (1)	< 0.0001	< 0.0001
Fisher-Tippett (2)	0.229	0.072
Gamma (1)	< 0.0001	< 0.0001
Gamma (2)	0.084	0.033
GEV	0.812	0.531
Gumbel	< 0.0001	< 0.0001
Log-normal	0.945	0.412
Logistic	0.421	0.889
Normal	0.094	0.071
Standard normal	< 0.0001	< 0.0001
Student	< 0.0001	< 0.0001
Weibull (1)	< 0.0001	< 0.0001
Weibull (2)	0.131	0.087
Weibull (3)	0.198	0.048

Several additional distributions also had p-values above the nominal 0.05 threshold, indicating that the available sample did not provide sufficient evidence to reject them under the applied K–S criterion. In contrast, the exponential, Gumbel, Gamma (1) and Weibull (1) distributions yielded $p < 0.0001$ and showed substantially larger discrepancies from the observed α distribution. Because the model parameters were estimated from the same data and no information criteria

were reported, the log-normal distribution should be regarded as the leading descriptive candidate rather than a definitively established best-fitting model.

At Tizi N'Isli, the log-normal distribution had the highest descriptive K–S p-value. Its identification as the leading descriptive candidate is also consistent with the positive asymmetry indicated by the mean α (0.0502 day^{-1}) exceeding the median (0.0432 day^{-1}).

This difference reflects the influence of a smaller number of relatively high recession coefficients. The distribution therefore indicates substantial heterogeneity in recession rates, although it does not identify the specific hydrological processes responsible for that variability (Table 5).

At Ait Ouchène, the logistic distribution yielded the highest descriptive K–S p-value ($p = 0.889$), followed by the GEV ($p = 0.531$) and log-normal distributions ($p = 0.412$). These results identify the logistic distribution as the leading descriptive candidate among the tested models, but they do not establish it as the unique probability model for the observed α values.

In contrast, the exponential, Gumbel, Gamma (1) and Weibull (1) distributions yielded $p < 0.0001$ and were inconsistent with the observed α values under the applied K–S criterion.

The comparatively narrow empirical distribution and the smaller difference between the mean (0.0407 day^{-1}) and median (0.0376 day^{-1}) indicate less pronounced asymmetry than at Tizi N'Isli. However, the stability and symmetry of the distribution should not be inferred from K–S p-values alone.

The observed α distributions differed between the two stations. Tizi N'Isli showed greater dispersion and more pronounced positive asymmetry, with the log-normal distribution emerging as the leading descriptive candidate. At Ait Ouchène, α values were less dispersed, and the logistic distribution yielded the highest descriptive K–S p-value. These results support an upstream–downstream contrast in recession characteristics but do not establish a continuous hydrological gradient across the basin.

The statistical parameters presented in Table 6 further illustrate the differences between the two stations. At Tizi N'Isli, both the mean (0.0502 day^{-1}) and median α (0.0432 day^{-1}) were higher than at Ait Ouchène (0.0407 and 0.0376 day^{-1} , respectively), indicating faster typical recession among the analysed sequences.

At Tizi N'Isli, the mean exceeding the median, together with the wider interquartile range, was consistent with positive asymmetry and supported the log-normal distribution as the leading descriptive candidate.

At Ait Ouchène, the first and third quartiles were 0.0261 and 0.0507 day^{-1} , respectively, giving an interquartile range of 0.0246 day^{-1} . These lower and more concentrated α values indicate slower and less variable recession than at Tizi N'Isli. Overall, the statistical parameters support a contrast between faster, more variable recession at Tizi N'Isli and slower, less variable recession at Ait Ouchène. They do not, however, provide direct estimates of groundwater-storage capacity or annual groundwater contribution (Table 6).

Table 6. Statistical parameters of recession coefficients (α) calculated from optimized recession sequences

Statistical parameter	Tizi N’Isli	Ait Ouchène
Mean α	0.0502	0.0407
Master α	0.0390	0.0323
Modal α	0.0450	0.0340
Median α	0.0432	0.0376
α at frequency 0.25 (Q_1)	0.0310	0.0261
α at frequency 0.75 (Q_3)	0.0618	0.0507

Contribution of baseflow to streamflow within the Basin (1976–2021)

Interannual variations in estimated baseflow and total discharge were analysed at the Tizi N’Isli and Ait Ouchène gauging stations for 1976–2021 (Figure 7).

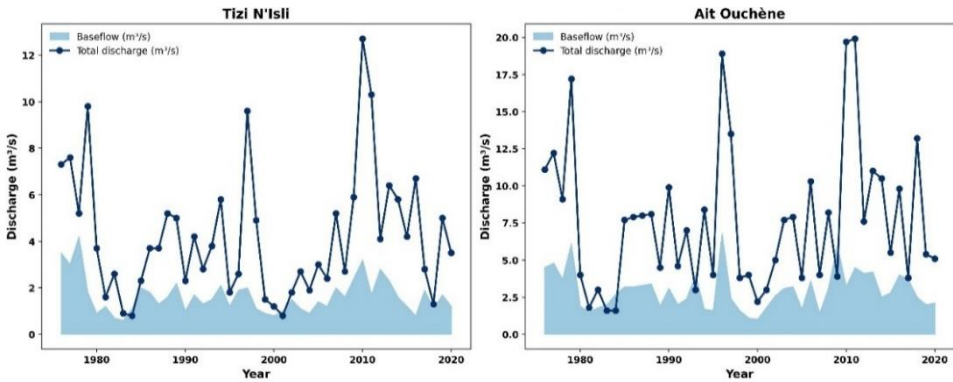


Figure 7. Annual variability of baseflow and total discharge at the Tizi N’Isli and Ait Ouchène gauging stations in the El Abid River Basin (1976–2021).

The comparison shows how the estimated baseflow component varied in relation to total streamflow at each station. Because baseflow was estimated using the graphical inflection method described in the methodology, it should be interpreted as an estimate of delayed-flow contribution rather than as a direct measurement of groundwater discharge.

Long-term mean estimated baseflow was higher at Ait Ouchène ($4.886 \text{ m}^3 \text{ s}^{-1}$) than at Tizi N’Isli ($3.176 \text{ m}^3 \text{ s}^{-1}$), consistent with the higher long-term mean total discharge at Ait Ouchène (8.571 versus $5.056 \text{ m}^3 \text{ s}^{-1}$) (Table 7). In contrast, the long-term BFI was higher at Tizi N’Isli (62.8%) than at Ait Ouchène (57.0%). Thus, estimated baseflow represented a larger relative proportion of total streamflow at Tizi N’Isli, whereas its absolute mean discharge was greater at Ait

Ouchène. The higher BFI at Tizi N'Isli should therefore not be interpreted as evidence of a greater absolute groundwater discharge or storage capacity.

The two stations showed contrasting recession and estimated baseflow characteristics. Tizi N'Isli had a higher long-term BFI but also higher and more variable recession coefficients, indicating a larger relative baseflow proportion together with faster and less uniform streamflow recession.

Ait Ouchène had a lower long-term BFI but slower and less variable recession, consistent with more persistent release of delayed flow during recession periods. These results do not provide direct estimates of groundwater-storage capacity. Differences in lithology, soil permeability, topography and aquifer properties may contribute to the observed contrast, but their effects were not quantified separately for the two station catchments.

Overall, the long-term BFI, recession coefficients and monthly BFI values provided complementary but distinct information on low-flow behaviour at the two stations.

The long-term BFI quantified the relative contribution of estimated baseflow to total streamflow, the recession coefficients described the rate and variability of streamflow decline, and the monthly BFI values characterized seasonal changes in relative baseflow contribution. Their combined interpretation provides a more complete description of low-flow behaviour than any single indicator alone, although it does not directly identify groundwater–surface water exchange processes or their physical controls.

The long-term mean values in Table 7 and the monthly BFI values in Figure 8 show differences in the magnitude and seasonal distribution of estimated baseflow between the two stations. The long-term BFI was higher at Tizi N'Isli (62.8%) than at Ait Ouchène (57.0%), indicating that estimated baseflow accounted for a larger relative proportion of total streamflow at Tizi N'Isli. However, the higher long-term BFI should not be interpreted as evidence of greater groundwater-storage capacity or more persistent baseflow support during dry periods.

Ait Ouchène had lower and less variable recession coefficients and a lower master recession coefficient, demonstrating slower and more uniform streamflow recession. Together with the monthly BFI pattern, these results are consistent with more persistent delayed-flow support at Ait Ouchène during low-flow periods, although effective groundwater storage was not quantified directly.

Table 7. Comparison of long-term mean baseflow discharge, long-term mean total discharge, and annual Baseflow Index (BFI) at the Tizi N'Isli and Ait Ouchène gauging stations (1976–2021)

Station	Mean baseflow discharge ($\text{m}^3 \text{s}^{-1}$)	Mean total discharge ($\text{m}^3 \text{s}^{-1}$)	Annual BFI (%)
Tizi N'Isli	3.176	5.056	62.80
Ait Ouchène	4.886	8.571	57.00

The monthly BFI values shown in Figure 8 represent mean calendar-month values derived from the monthly BFI ratios calculated over 1976–2021.

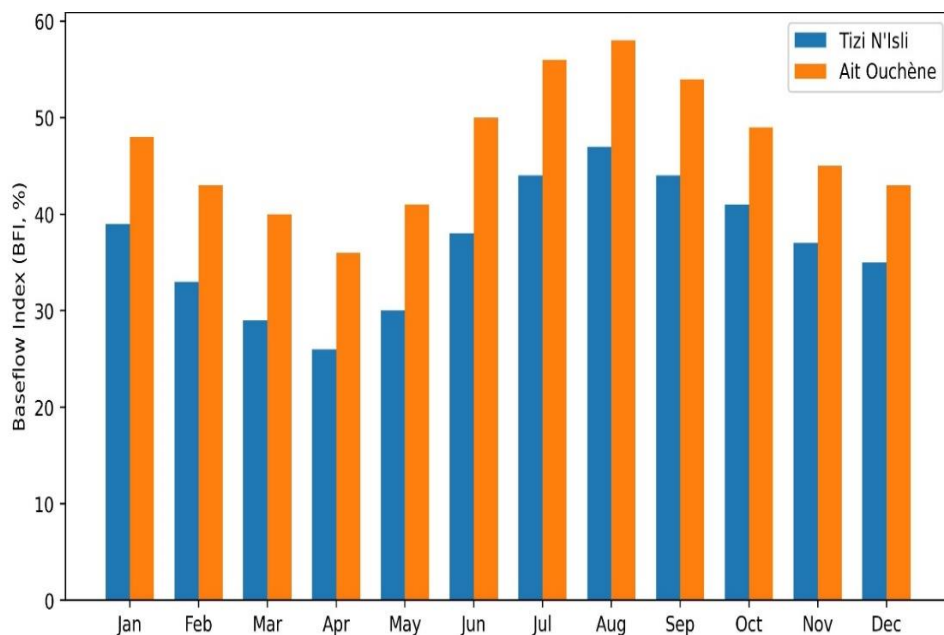


Figure 8. Monthly variation of baseflow index (1976–2021)

They were higher at Ait Ouchène than at Tizi N'Isli in every month. At both stations, monthly BFI increased from spring towards summer and reached its maximum in August, at approximately 58% for Ait Ouchène and 47% for Tizi N'Isli. The lowest values occurred in April, at approximately 36% and 26%, respectively. This monthly pattern differs from the long-term BFI reported in Table 7 because the long-term value was calculated from the cumulative baseflow and total streamflow volumes over the entire study period and was therefore weighted by streamflow volume. Consequently, the higher mean monthly BFI values at Ait Ouchène can coexist with the higher long-term BFI at Tizi N'Isli, as the two indicators reflect different temporal aggregation and weighting procedures.

In summary, the long-term mean absolute baseflow discharge was higher at Ait Ouchène ($4.886 \text{ m}^3 \text{ s}^{-1}$) than at Tizi N'Isli ($3.176 \text{ m}^3 \text{ s}^{-1}$), whereas the long-term BFI was higher at Tizi N'Isli (62.8%) than at Ait Ouchène (57.0%). By contrast, the mean calendar-month BFI values shown in Figure 8 were higher at Ait Ouchène throughout the year. This difference reflects the distinct temporal aggregation and streamflow weighting of the long-term and monthly indicators. The recession analysis additionally showed slower and less variable streamflow recession at Ait Ouchène. Therefore, absolute baseflow discharge, long-term BFI, monthly BFI, and recession coefficients describe complementary but distinct aspects of low-flow behaviour.

Hydrogeomorphological characteristics derived from the IntErO model

The basin-scale IntErO parameters provided a regional hydrogeomorphological context for interpreting recession behaviour in the El Abid River Basin. Because these parameters were calculated for the entire basin, they do not represent the specific upstream catchments associated with the Tizi N'Isli and Ait Ouchène gauging stations (Table 8).

Table 8. Integrated morphometric, hydrological, and IntErO Model Parameters

Category	Characteristics	Symbol	Unit	Value
Morphometry	Official basin area	A	km ²	3004
	GIS-derived basin area	F	km ²	3119.14
	Basin length	Lb	km	130
	Main channel length	L / Lv	km	99 / 175.85
	Distance source–mouth	Lm	km	93.79
	Basin width	l	km	49
	Compactness index	kc	–	2.04
	Drainage density	Dd	km/km ²	1
	Channel frequency	Cf	channels/km ²	0.22
Topography	Max basin elevation	Hmax	m	3699
	Mean basin elevation	H1	m	3063
	Basin outlet elevation	Hmin	m	791
	Elevation of the mouth	H2	m	809
	First contour altitude	h0	m	900
	Global slope index	Ig	m/km	8.2
	Specific relief	Ds	m	80
Hydrology & Climate	Torrential rainfall	hb	mm	112.8
	Average annual precipitation	Hyr	mm	347.1
	Mean annual temperature	to	°C	16.8
Lithology (Permeability)	Highly permeable rocks	fp	–	0.20
	Moderately permeable rocks	fpp	–	0.32
	Low permeability rocks	fo	–	0.48
Land Use / Cover	Forest areas	fs	–	0.49
	Grasslands, orchards	ft	–	0.32
	Bare/degraded land	fg	–	0.19
Basin Structure (IntErO)	Larger sub-basin area	Fv	km ²	2272.15
	Smaller sub-basin area	Fm	km ²	846.99
	Watershed perimeter	O	km	484.16
Erosion coefficient	Soil resistance coefficient	Y	–	1.4
	Basin planning coefficient	Xa	–	0.91
	Visible erosion coefficient	φ	–	0.50

Consequently, the IntErO outputs were not used to establish direct quantitative relationships with station-specific recession coefficients or BFI values, but only to describe the broader physical setting in which the observed recession patterns occurred.

The combined morphometric, lithological, climatic and land-use parameters provide a regional description of the hydrogeomorphological setting of the El Abid River Basin. However, because only one basin-scale set of IntErO parameters was calculated, these results cannot explain the contrasting recession characteristics

observed at Tizi N'Isli and Ait Ouchène. Such an assessment would require separate delineation and IntErO analysis of the upstream catchment associated with each.

The defined hydrological drainage area of the El Abid River Basin is 3,004 km², but the GIS delineation utilized in the IntErO analysis yielded an area of 3,119.14 km², resulting in a discrepancy of 115.14 km² or 3.83%. This discrepancy may reflect differences in basin-boundary definition and GIS delineation procedures. The GIS-derived area was used consistently in the IntErO calculations.

The reported basin length ($L_b = 130$ km) and width ($l = 49$ km), giving a length-to-width ratio of approximately 2.65, indicate an elongated basin planform. The IntErO parameter O (484.16 km) signifies the perimeter of the watershed and must not be misconstrued as the length or configuration of the drainage network (Chalise *et al.*, 2019; Mohammadi *et al.*, 2021).

The natural main-channel length ($L_v = 175.85$ km) is considerably greater than the shortest source-to-outlet distance ($L_m = 93.79$ km), giving a channel-length ratio of approximately 1.87. The basin extends from a minimum elevation of 791 m to a maximum elevation of 3,699 m, corresponding to a total relief of 2,908 m. Drainage density was 1.0 km km⁻², and channel frequency was 0.22 channels km⁻². These basin-scale parameters describe an elongated, topographically diverse basin with an extensive drainage pathway.

However, their effects on infiltration, runoff concentration and station-specific recession behaviour were not tested quantitatively and are therefore interpreted only as regional morphometric context.

The geological setting is characterized by Jurassic limestone and dolomitic formations interstratified with marls, clays and alluvial deposits. The IntErO permeability coefficients indicate that low-permeability formations occupy 48% of the basin ($f_o = 0.48$), moderately permeable formations 32% ($f_{pp} = 0.32$), and highly permeable formations 20% ($f_p = 0.20$). These coefficients describe the basin-scale distribution of permeability classes rather than the hydraulic behaviour of individual lithological units. Fractured or karstified carbonate formations may favour infiltration, groundwater recharge and delayed subsurface flow, whereas marl- and clay-rich formations generally restrict infiltration and promote surface runoff. However, the spatial distribution of these formations within the individual station catchments was not analysed.

The soil-resistance coefficient ($Y = 1.4$) and visible-erosion coefficient ($\varphi = 0.5$) are IntErO erosion-model inputs representing soil resistance to erosion and the observed type and extent of erosion, respectively. They should not be interpreted as direct measures of soil infiltration, groundwater-storage capacity or streamflow-recession behaviour. Consequently, the combined morphometric, lithological, permeability and erosion parameters provide a plausible regional hydrogeomorphological context but do not directly explain the differences in α or BFI between Tizi N'Isli and Ait Ouchène, nor the log-normal distribution of α values. Establishing such relationships would require separate IntErO analyses of

the two upstream catchments followed by quantitative comparison with their respective recession and BFI indicators.

Land-cover coefficients indicate that forests occupy 49% of the El Abid River Basin ($f_s = 0.49$), grasslands, meadows, pastures, and orchards 32% ($f_t = 0.32$), and bare land, cultivated land, and surfaces without grass cover 19% ($f_g = 0.19$) (Table 8). Forest cover may promote infiltration and reduce rapid surface runoff, although canopy interception and evapotranspiration can limit its net contribution to groundwater recharge. Conversely, bare and cultivated surfaces are generally associated with lower surface protection and more rapid runoff. These coefficients provide basin-scale land-cover context but do not directly explain the differences in recession behaviour between the two gauging stations.

The climatic parameters at the basin scale utilized in the IntErO assessment comprised an average annual precipitation of 347.1 mm (Hyr), an average annual air temperature of 16.8 °C (t_o), and a torrential rainfall volume of 112.8 mm (hb) (Table 8). In the IntErO model, hb denotes the volume of intense precipitation utilized in the computation of water retention and peak outflow (Chalise *et al.*, 2019; Mohammadi *et al.*, 2021).

These values characterize the general climatic setting of the El Abid River Basin but do not represent the full spatial variability associated with its large altitudinal range. Although precipitation seasonality, evapotranspiration, and snowmelt may influence recharge and streamflow recession, their individual effects on α and BFI were not quantified in the present study. Snow-related processes should therefore be regarded only as possible explanatory factors, particularly in the higher parts of the basin.

The hydrological processes of the El Abid River Basin can be understood in the context of Mediterranean mountain and karst systems, where geological structures and seasonal precipitation produce spatial and temporal variations in recharge and discharge patterns (Hartmann *et al.*, 2013). In the El Abid and Srou watersheds, the lithological composition, alterations in land use, precipitation patterns, and historical hydrological circumstances have been recognized as significant determinants affecting sediment transport and behaviour (Ouakhir *et al.*, 2026b). These studies support the idea that geological and climatic characteristics can be credible regional factors affecting observed hydrological patterns. However, the present study does not establish that carbonate formations or any other physical cause are responsible for the changes in baseflow characteristics and recession observed between the two gauging stations.

Overall, the IntErO results document substantial basin-scale variability in morphometry, permeability, land cover and climatic conditions. These characteristics provide a relevant regional context for interpreting streamflow recession but do not establish the physical causes of the differences observed between Tizi N'Isli and Ait Ouchène. Separate hydrogeomorphological analyses of the two upstream station catchments would be required to test the relationships between physical watershed properties, recession coefficients and BFI.

DISCUSSION

Recession dynamics and baseflow contribution in the Basin (1976–2021)

The interpretations of recession coefficients, master recession curves, frequency distributions, and fitted probability distributions presented below are based on the optimized recession sequences retained after the quality-control procedure described in the methodology: 219 sequences at Tizi N'Isli and 95 at Ait Ouchène. The joint analysis of recession curves, recession coefficients (α), and baseflow indices (BFI) provides insight into the station-specific low-flow behaviour observed within the El Abid River Basin during 1976–2021 (Nafia *et al.*, 2024). The master recession curves show that the average recession behaviour of the retained sequences can be represented by an exponential model, consistent with the classical conceptualization of aquifer drainage introduced by Maillet (1905) and widely applied in hydrological studies (Tallaksen, 1995; Tallaksen and van Lanen, 2023). This result characterizes the aggregated recession response and does not imply that every individual recession event followed an identical exponential pattern.

The hydrogeomorphological interpretation presented below should be considered at the basin scale because the IntErO model was applied to the entire El Abid River Basin. Consequently, the observed differences between the Tizi N'Isli and Ait Ouchène stations are interpreted primarily from the hydrological analyses, including the recession coefficients, master recession curves, and Baseflow Index, whereas the IntErO parameters provide complementary regional context rather than station-specific quantitative explanations. The master recession curves show excellent agreement with the exponential recession model, with $R^2 = 0.9949$ at Tizi N'Isli and $R^2 = 0.9669$ at Ait Ouchène. These coefficients of determination refer specifically to the aggregated master recession curves and are distinct from the R^2 values of 0.87–0.96 obtained from the individual Q_0 – Q_t regressions. The corresponding master recession coefficients were $\alpha = 0.0390 \text{ day}^{-1}$ at Tizi N'Isli and $\alpha = 0.0323 \text{ day}^{-1}$ at Ait Ouchène, indicating a faster average decline in normalized streamflow at Tizi N'Isli and a more gradual recession at Ait Ouchène. This contrast is consistent with more persistent release of delayed flow at Ait Ouchène. However, groundwater-storage capacity was not measured directly, and the potential effects of slope, drainage density, lithology, and fracturing were not evaluated separately for the upstream catchments associated with the two gauging stations.

The statistical distributions of recession coefficients (α) are consistent with the observed differences in recession behaviour between the two stations. At Tizi N'Isli, α values showed broader dispersion and a higher frequency of large values than at Ait Ouchène, indicating greater variability in streamflow-recession rates. Higher α values correspond to faster declines in streamflow during individual recession periods, whereas lower values correspond to slower declines. Among the tested distributions, the log-normal distribution produced the highest descriptive K–S p-value at Tizi N'Isli and was consistent with the positive asymmetry of the observed α values. However, the fitted distribution does not identify the relative

contributions of quick flow, shallow subsurface flow, or groundwater discharge. At Ait Ouchène, α values occupied a narrower range, and the logistic distribution had the highest descriptive K–S p-value. This pattern indicates a more consistent recession response than at Tizi N'Isli; however, it does not by itself demonstrate a more uniform aquifer structure or greater groundwater-storage capacity.

The analysis of the Baseflow Index (BFI) complements the recession analysis by estimating the relative contribution of baseflow, or delayed-flow components, to total streamflow. The long-term BFI was higher at Tizi N'Isli (62.80%) than at Ait Ouchène (57.00%), indicating that estimated baseflow represented a larger proportion of total streamflow at Tizi N'Isli over the complete study period. However, this higher long-term BFI should not be interpreted as evidence of greater groundwater-storage capacity or larger absolute groundwater discharge.

The recession analysis shows faster and more variable streamflow decline at Tizi N'Isli, whereas Ait Ouchène is characterized by slower and less variable recession. By contrast, the mean calendar-month BFI values shown in Figure 8 were higher at Ait Ouchène throughout the year and reached approximately 58% in August.

This apparent contrast results from the different temporal aggregation and streamflow weighting of the two indicators: the long-term BFI is calculated from cumulative baseflow and total-streamflow volumes over the complete study period, whereas Figure 8 presents mean calendar-month BFI ratios. Therefore, these indicators describe complementary aspects of baseflow contribution and should not be interpreted as direct measures of groundwater-storage capacity.

The results therefore reveal two contrasting but complementary low-flow behaviours:

- (i) Tizi N'Isli exhibits a higher long-term relative contribution of estimated baseflow, together with faster and more variable streamflow recession.
- (ii) Ait Ouchène exhibits a larger long-term mean absolute baseflow discharge, slower and less variable streamflow recession, and higher monthly BFI values during the dry period.

These findings describe differences in the magnitude, relative contribution, and recession characteristics of estimated baseflow at the two stations but do not provide direct measurements of groundwater-storage capacity or groundwater depletion.

The observed spatial variability may be associated with differences in lithology, structural characteristics, topography, and climatic forcing, all of which can influence infiltration, water storage, and subsurface flow pathways. Similar hydrological complexity has been reported in Mediterranean mountainous and karst environments, where the interaction between permeable or fractured formations and seasonal precipitation produces spatially and temporally variable recharge–discharge responses (Ladouche *et al.*, 2001; Hartmann *et al.*, 2013). However, because the IntErO analysis was conducted for the entire El Abid River Basin rather than separately for the upstream catchments of the two gauging

stations, these factors should be regarded as plausible regional influences rather than demonstrated causes of the observed differences between Tizi N'Isli and Ait Ouchène.

The hydrological behaviour observed within the El Abid River Basin is consistent with a mixed system comprising relatively rapid streamflow responses and more persistent delayed-flow components, with clear differences between the two gauging stations.

This contrast has potential implications for low-flow assessment and water-resources management, particularly under increasing hydroclimatic variability. At Ait Ouchène, the slower recession and higher monthly BFI values during the dry period indicate a comparatively more persistent contribution of estimated baseflow. This contribution may help sustain the downstream water supply and inflow to the Bin El Ouidane Reservoir during periods of reduced flow. However, its magnitude and importance for reservoir storage and management were not explicitly evaluated in the present study.

CONCLUSIONS

This study examined streamflow-recession characteristics and estimated baseflow dynamics at the Tizi N'Isli and Ait Ouchène gauging stations in the El Abid River Basin (Central High Atlas, Morocco) during 1976–2021. The applied approach combined recession-sequence analysis, master recession curves, probability-distribution analysis, baseflow separation using the graphical inflection method, and basin-scale hydrogeomorphological characterization using the IntErO model.

The master recession curves were closely represented by the exponential Maillet model, indicating that the aggregated recession behaviour of the retained sequences can be described by an exponential decline. However, this result does not imply that every individual recession event followed an identical pattern or that groundwater-storage capacity was measured directly.

The two gauging stations exhibited contrasting recession characteristics. Tizi N'Isli had a larger number of extracted and retained recession sequences, a higher mean recession coefficient ($\alpha = 0.0502 \text{ day}^{-1}$), and substantially greater variability ($\text{CV} = 124.3\%$). Its master recession coefficient was also higher ($\alpha = 0.0390 \text{ day}^{-1}$), indicating faster average streamflow recession. Ait Ouchène had fewer recession sequences but slightly higher mean and maximum durations, together with a lower mean recession coefficient ($\alpha = 0.0407 \text{ day}^{-1}$), lower variability ($\text{CV} = 43.0\%$), and a lower master recession coefficient ($\alpha = 0.0323 \text{ day}^{-1}$). These results indicate slower and less variable streamflow recession at Ait Ouchène. However, the differences in sequence duration were small and were not tested for statistical significance.

The estimated baseflow results provide complementary information on low-flow behaviour. Long-term mean absolute baseflow discharge was higher at Ait Ouchène ($4.886 \text{ m}^3 \text{ s}^{-1}$) than at Tizi N'Isli ($3.176 \text{ m}^3 \text{ s}^{-1}$), whereas the long-term BFI was higher at Tizi N'Isli (62.80%) than at Ait Ouchène (57.00%). Monthly

BFI values, however, were higher at Ait Ouchène throughout the seasonal cycle shown in Figure 8 and reached approximately 58% during summer. These findings demonstrate that absolute baseflow discharge, long-term relative baseflow contribution, monthly BFI, and recession coefficients describe different aspects of low-flow behaviour and should not be interpreted interchangeably. They also do not provide direct measurements of groundwater-storage capacity or groundwater depletion (Smakhtin, 2001).

The basin-scale IntErO analysis indicates that the El Abid River Basin has an elongated geometry, substantial altitudinal variation, moderate drainage density, heterogeneous lithological conditions, contrasting permeability classes, and diverse land-cover characteristics. These properties provide a relevant regional context for interpreting streamflow recession. However, because the IntErO model was applied to the entire basin rather than separately to the upstream catchments of the two gauging stations, the present study does not establish direct quantitative relationships between specific hydrogeomorphological properties and the observed differences in α or BFI.

Lithology, fracturing, topography, land cover, and climatic forcing should therefore be regarded as plausible regional influences rather than demonstrated station-specific controls. Seasonal snow accumulation and snowmelt may also affect streamflow variability in the higher parts of the basin, but these processes were not quantified in the present study. Baseflow recession may reflect nonlinear storage–discharge behaviour, as described by Wittenberg (1999).

Overall, the results demonstrate marked differences in recession rates, variability, and estimated baseflow characteristics between Tizi N’Isli and Ait Ouchène. They provide useful information for low-flow assessment, hydrological modelling, and water-resources management in a semi-arid Mediterranean mountain basin.

Future research should delineate and analyse the upstream catchment of each gauging station separately, apply the IntErO model at the station-catchment scale, incorporate snow observations or snowmelt modelling, and quantitatively test the relationships between physical watershed characteristics, recession coefficients, and BFI. The distinct calculation and temporal aggregation procedures used for the long-term BFI and mean calendar-month BFI values should also be explicitly documented to ensure their correct interpretation.

CONFLICT OF INTERESTS

The authors declare no conflicts of interest related to this article.

AUTHOR CONTRIBUTIONS

K.N.: Conceptualisation, methodology, formal analysis, investigation, data curation, and writing – original draft. M.F.: Conceptualisation, methodology, formal analysis, investigation, data curation, and writing – original draft. M.H.: Investigation, data curation, and validation. M.E.G.: Conceptualisation, supervision, methodology, and validation. N.E.: Formal analysis, visualisation, and

writing – review and editing. H.O.: Methodology, supervision, validation, and writing – review and editing. V.S.: Conceptualisation, supervision, validation, and writing – review and editing. All authors reviewed and approved the final manuscript and agreed to be accountable for its content.

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