Algerian Journal of Environmental Science and Technology
September edition. Vol.9. Nº3. (2023)
ISSN : 2437-1114
www.aljest.org

Characterization of the functioning of the Aïn Telout karstic system by hydrodynamic methods (The Tlemcen Mountains, Algeria)

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ARTICLE INFO

Article History :
Received **: 02/12/2021**
Accepted **: 17/05/2022**

Key Words:

Karst; hydrodynamics; Aïn Tellout; Tlemcen Mountains.

ABSTRACT/RESUME

Abstract: *This article spot the light on characterization of functioning of Aïn Telout karstic system by hydrodynamic methods (The Tlemcen Mountains, Algeria). The approach adopted in this work is based on the analysis of discharges and rainfalls chronicles of Aïn Telout spring over four hydrological cycles 2010-2014, using the following methods: analysis of the classified discharges, analysis of the recession curves as well as the correlation and spectral analysis. The application of these methods has allowed us to characterize the hydrodynamic functioning of this hydrosystem. It is an inertial system, weakly karstified and poorly drained, with a mediocre dynamic volume estimated at 465,000 m³ and a residence time of water about 405 days. The application of correlation and spectral analysis has permitted extraction of some characteristics. The input signal (rainfall) shows a seasonal trend characteristic of the Mediterranean climate, while the simple correlogram of discharges of the Telout spring display a signal different from that of the input signal, reflecting the regulating character of this system. The simple and cross analysis show a memory effect of 60 days, a regulation time of 35 days and a response time of 15 days. The cross-correlogram indicate a double response of the system following rainfall solicitations, a rapid response of the system, which translates a transmissive character, followed by a second slow and very inertial response reflecting a second capacitive character of this system.*

I. Introduction

With a surface area of nearly 985.32 km², the carbonate massif of the Upper Jurassic of Tlemcen Mountains constitutes one of the main karst reservoirs of northern Algeria, which contains several hydro systems and cover 40% of the water needs of the local population.

Currently, the increased demand on water due to socio-economic pressure has led to a degradation of this resource, both qualitatively through pollution and quantitatively through overexploitation. This situation requires an optimised and sustainable management to protect and rationally exploit this hydric resource.

Before setting up a rational management strategy for karst water resources, it is essential to understand the functioning of the karst system, based on hydrodynamic, hydrogeochemical and isotopic approaches. To estimate the available karstic reserves, the degree of karstification, delimit the supply basin, the protection perimeter and evaluating the impact of anthropic extension on the aquifer.

The hydrological and hydrochemical research on karst aquifers of Tlemcen Mountains have been the subject of several studies [01, 02, 03, 04, 05, 06, 07,

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08, 09, 10, 11, 12]. However, many questions remain on the hydrodynamic functioning of the karst system of Aïn Telout (the mountains of Tlemcen, Algeria) that need to be answered. The objective of this work is to study the hydrodynamic functioning of this system .In addition, this work can provide theoretical support to water resource managers.

The methodology adopted in this article is to follow the hydrodynamic approach, which is based on the analysis of rainfall and discharge time series, by using the following methods: analysis of the classified discharges, analysis of the recession curves as well as the correlation and spectral analysis.

These methods have been applied on the chronicles of discharge of the Telout spring and rainfall recorded at the Mefrouch Tlemcen station ,over an observation period of four hydrological years (from September 2010 to August 2014), which are the only exploitable data on this spring.

I.1 Geographic location and geological context

Tlemcen's mountains are located in the North-Western part of Algeria. They are limited to the North by the plains of Maghnia, Hennaya and Sidi bel Abbes, to the South by the high plains of Oran, to the East by the mountains of Daia and to the west by Rhar Roubane. This mountainous barrier of 800m to 1400 m of altitude on average and culminating at 1843 m (Djbel of Tenouchfi), raised the calcaro-dolomitic formations of the upper Jurassic above the surrounding clayey plains in favour of the great sub vertical faults .These fissured formations are favourable to the infiltration of rainfalls and shelter aquifers with great productive capacity. There are about thirty isolated hydro-systems with a renewable underground reserve estimated at 200 Mm3/year [02, 05, 10].

Structurally, Mountains of Tlemcen are mainly affected by a brittle distensive tectonics, and cut into three main segments by longitudinal faults. These segments are respectively from West to East: the transverse of Tafna Magoura, the transverse of Oued Lakhdar and the transverse of Aïn Telout. Our study area belongs more precisely to the Eastern part of the Ouled Mimoune sigmoid block, which develops between the transverse of N20 of Oued Lakhdar and the Ain Telout fault [11].

The karstic system of Aïn Telout, wich is located at the East-Northern edge of Tlemcen Mountains, between latitude 0° 55′ to 1° 40′ and longitude 34° 47′ to 34° 57′ . This area is essentially formed by calcaro-dolomitic reliefs of Kimmeridgian age (Djbel Taourera 893m, Djbel Bou-amieur 1116m, Djbel Bou-Acha 1061m). Which rest on a sandstone formation of Sequanian age (The Boumediene sandstone). The supply basin of this aquifer has an anticlinal structure oriented Southwest-Northeast, with a dip towards to the North-East. Bordered to the East by the Aïn Telout fault oriented South-North, this latter had played vertically with the ascent of the dolomitic substratum against the relatively impermeable Plio-Miocene terrain .To the North, a Southwest-Northeast oriented fault may constitute the Northern limit of our system, where the Upper Jurassic carbonate formations plunge rapidly under very considerable thicknesses of marly Miocene . (Fig n°01, Fig n°02, Fig n°03)

The analysis of SAR radar image of the study area (the scene used in this work is a sentinel radar photo 1 band c, frequency 5.3 Ghz of 30/08/2019) ;has identified numerous anticlinal faults, which are manifested on the ground by anticlinal undulations oriented parallel to the fold. From a hydrogeological point of view, these anticlinal faults constitute seats of vertical hydric recharge and perhaps preferential directions of subterranean flows.

I.2 Climatology context

The climate of this region is of the semi-arid Mediterranean type, characterised by temperate winters and hot dry summers. It receives an average cumulative rainfall of around 447 mm/year. The solid precipitation sometimes appears briefly at altitudes above 600m and represents only a few percent of annual precipitation, the average annual temperature is around 16 C° with a very significant seasonal variation.

I.3 Hydrogeological context

This system gives rise to four springs, the main one and the most upstream known locally by Ain-Telout, downstream we note the existence of Ain-Sultane, Ain-Hami and Ain-Zitouna.

Aïn Telout spring, gushing out at an altitude of 728m through a North-South oriented normal fault. This spring has very low variations in discharge, which translates a good regulating capacity of the system (25 l/s on average). It drains the dolomitic formations of the Tlemcen Mountains (lower Kimmeridgian) and supplies the neighbouring towns with drinking and irrigation water (Fig n°03) [06].

I.4 Hydrographic Context

The studied region is drained by the Bouhaddi valley which constitutes the right tributary of the Isser valley, it takes its birth 09 Km South-East of Aïn Telout mountains, where it follows the trajectory of the Aïn Telout fault in South-North direction then changes direction and becomes North-West before flowing into Oued Isser. According to the structural and hydrological study, the wathershid area of our system has been estimated at 150.33 Km² (Fig n°01).

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Algerian Journal of Environmental Science and Technology
September edition. Vol.9. Nº3. (2023)
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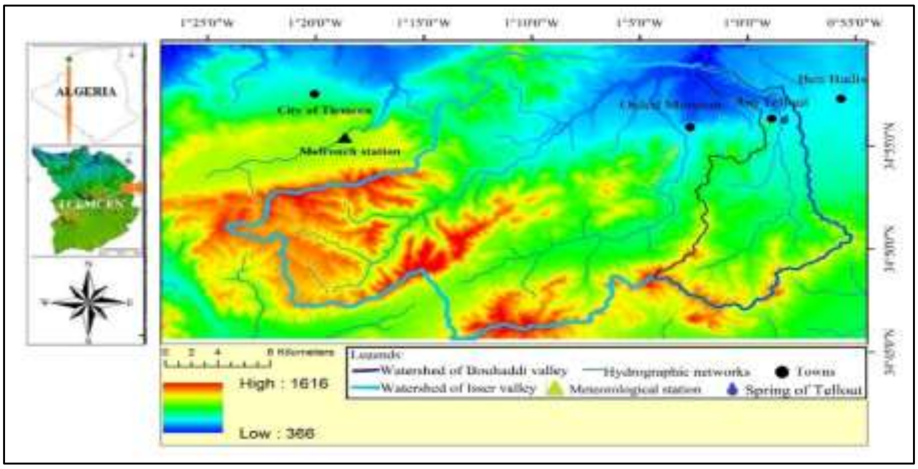

Fig n° 01. *Location map and topographic sketch of the study area*

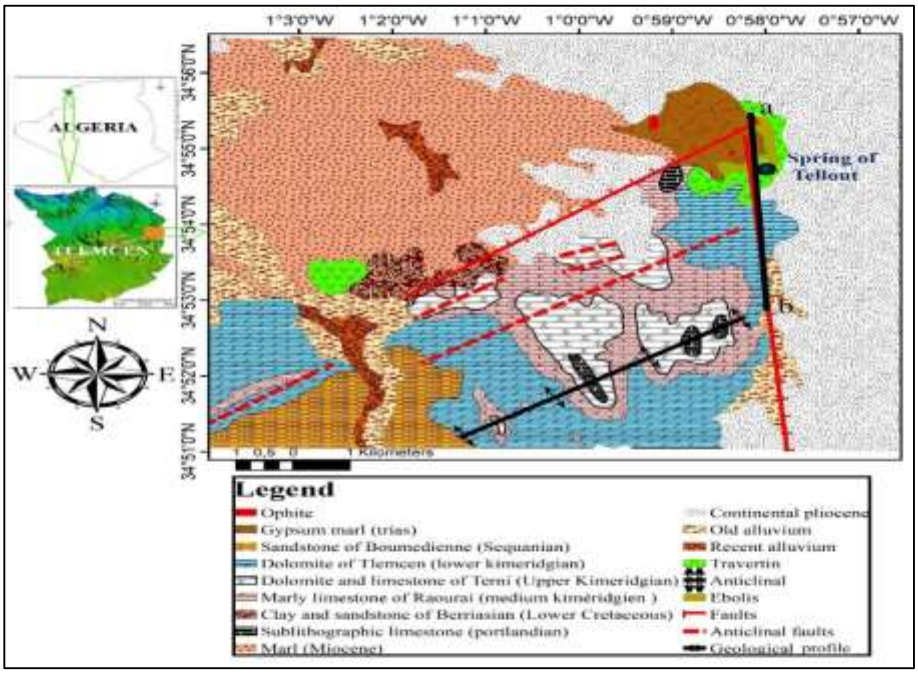

Fig n° 02. *Geological map of the study area.*

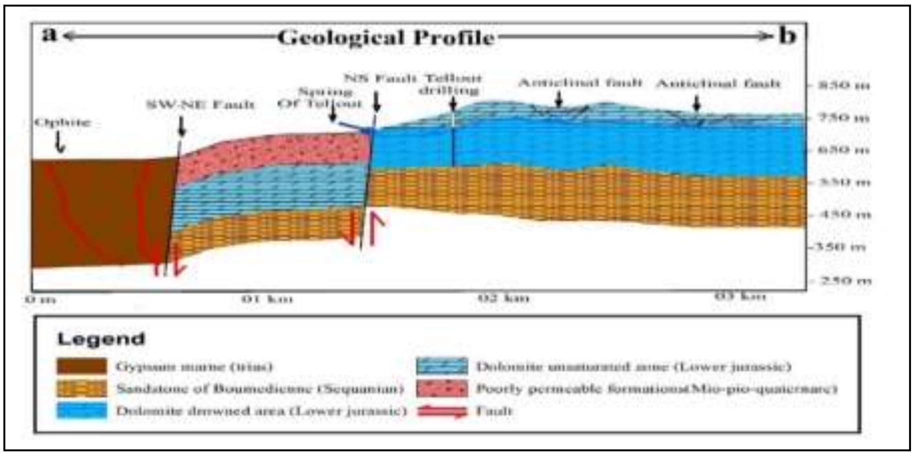

Fig n° 03. *Geological profile of the study area.*

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II. Methodology

II.1 Analysis of classified discharges

This is a classical method in hydrology and introduced by Mangin (1971) in karst hydrogeology, which allows the characterisation of the different flow regimes at the outlet (spring), such as the inflow of water from another system, the operation of an overflow, storage and leakage to another system [13].

This method consists of arranging the frequencies of occurrence of the discharge of spring into discharge classes to represent them graphically. The interpretation of the cumulative frequency curve obtained allows extracting some characteristics of the aquifer studied, in principle the interpretation is essentially based on changes in the slope of the cumulative frequency curve, which reflects a change in the law of flow. Then the curve obtained will be adjusted by a statistical law, only to describe the curve not to model it or to make predictions.

II.2 Recession curve analyse

Proposed by Mangin (1975) with the aim of estimating the water resources of karst systems, and classifying them by estimating certain hydrodynamic parameters (such as the infiltration speed coefficient η , base flow coefficient α,the dynamic volume Vd, the regulating power k and the delay to infiltration i).

This approach consists in giving a mathematical expression to the recession curve, which corresponds to the decreasing part of the hydrogram of a spring during a period not influenced by rainfall.

These recession curves are composed by two subterranean flow modalities (01); one represents infiltration or quick flow from the no saturated zone ;expressed analytically by a homographic function Ψ(t) (02) and the other represents reservoir emptying or base flow recession expressed analytically by the model of maillet's φ(t) (03) ,(Fig n°04).

$$Q(t) = \psi(t) + \varphi(t) \qquad (01).$$

$$\psi(t) = q_\circ \frac{(1-\eta t)}{(1-\varepsilon t)} \qquad (02).$$

$$\varphi(t) = Q_{R_\circ}\, e^{-\alpha t} \qquad (03).$$

With t: represent time, Q (t): is the discharge at time t, $Q_{R_\circ}$: correspond to the extrapolation of the base flow recession curve on the ordinate axis, $q_\circ$: the infiltration discharge at time t = 0, α: the base flow coefficient,ε: the coefficient of heterogeneity, η: the infiltration speed coefficient [14,15].

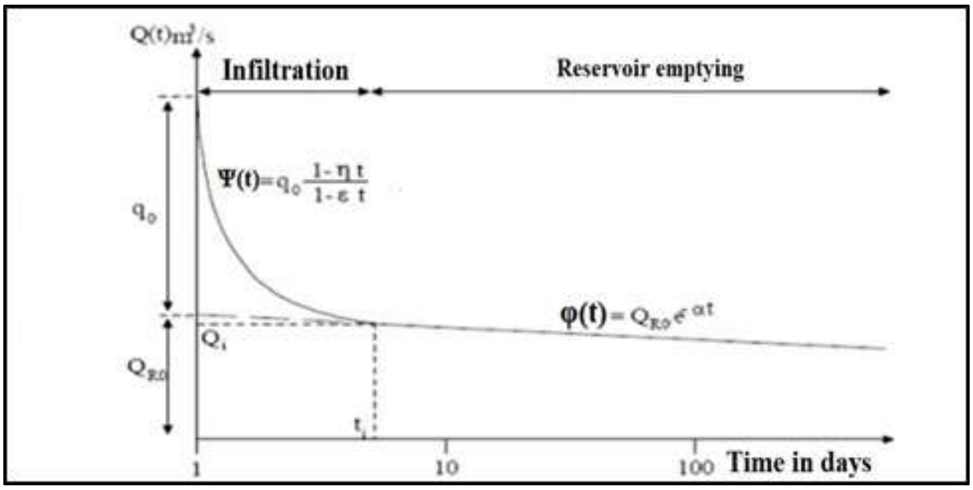

Fig n° 04. *Decomposition of the recession curve according to the method of Mangin (1975).*

II.3 Correlation and spectral analysis

They were defined by Jenkins and Watts (1968), Box and Jenkins (1974) and introduced by Mangin (1984) for the study of karst systems. This functional approach is based on the analysis of time series signals (discharge, rainfall, conductivity, temperature...) in order to extract the maximum amount of information on the functioning of karst systems [16,17,18,19,20,21,22,23,24,25].

The principle of this method is to assimilate the karst system as a filter (black box), which modulates the input signal (rainfall) into an output signal (hydrogram). The analysis of these signals provides information on the filter function (transfer function) of the reservoir and thus characterises the karst system [15, 18].

In other words, to characterise the filter of this system (quantify the degree of karstification and the importance of the karst reserves) we first carry out a simple analysis. On the two input signals (rainfall) and output signals (discharge). Subsequently we carry out a rainfall/discharge cross-analysis. These two analyses are carried out in the time domain (simple and cross correlation) and in the frequency

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Algerian Journal of Environmental Science and Technology
September edition. Vol.9. Nº3. (2023)
ISSN : 2437-1114
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domain (the analysis of simple and cross spectral density of variance).

From the hydrogeological point of view, the correlation and spectral analyses allow the estimation of some parameters (memory effect, regulation time, cut-off frequency… etc.) .which are used to characterise the functioning of karst systems and subsequently classify them according to the reference systems established by Mangin (1984)

The simple analysis makes it possible to evaluate the memory effect on the autocorrelogram which translates the inertia of the system (it is the k value for r(k)=0.2 fixed by Mangin 1984). At spectral scale the simple spectre of variance density; allows highlighting the periodic events of a time series and their frequency of appearance, to estimate the cut-off frequency which quantifies the regulation introduced by the system (it is the frequency for which the density of variance becomes zero or negligible) as well as the regulation time which represents the duration of influence of the input signal (rainfall) on the system.

The cross-correlogram analysis reflects the impulse picture of the system by studying the input -output signal (rainfall/discharge) relationships. On the time scale, the cross-correlogram provides information on the development of the drainage network; for example, a system with little inertia will give a peak cross-correlogram, while an inertial system will give a cross-correlogram in the form of a spread bump. [15, 18]

III. Results and Discussion

III.1 Analysis of classified discharges

It was applied on a fortnightly time step chronicle of Aïn Telout spring (period 2010-2014) with a class interval of 02 l/s .this latter has been estimated by Sturge's rule whose:

$$N=1+ (3.3\log n) \quad (04)$$

$$I= (Q_{max}-Q_{min}) /N \quad (05)$$

With: N (the number of classes), n (the number of individuals), I (class interval), Qmax and Qmin (represent respectively the maximum and minimum discharge value of the series considered).

According to the Fig n°05 and the table n°01, our statistical series follows a distribution of normal law P (Q) ~N (18.48; 3.26).The curve of the classified discharges obtained presents two breaks; one at 21 l/s and the other at 23 l/s, these two breaks correspond to the important increase of the discharges more than the frequency of appearance. According to the Marsaud (1997) classification, these anomalies correspond respectively to the contribution of a reserve from a previous cycle and the contribution of water from another system.

Table n°01. *Results of Analysis of classified discharges*.

Discharge classes (l/s)	Numbers of observed discharge	Cumulative observed frequency %	Numbers of calculated discharge	Cumulative calculated frequency %
< 14	11	11,45	8,13	8,47
[14-16[	16	28	13,3	22,33
|16-18|	18	46,87	20,9	44,12
|18-20|	21	68,75	22,8	67,9
|20-22|	15	84,37	17,32	85,95
|22-24|	11	95,83	9,12	95,46
>24	4	100	4,35	100

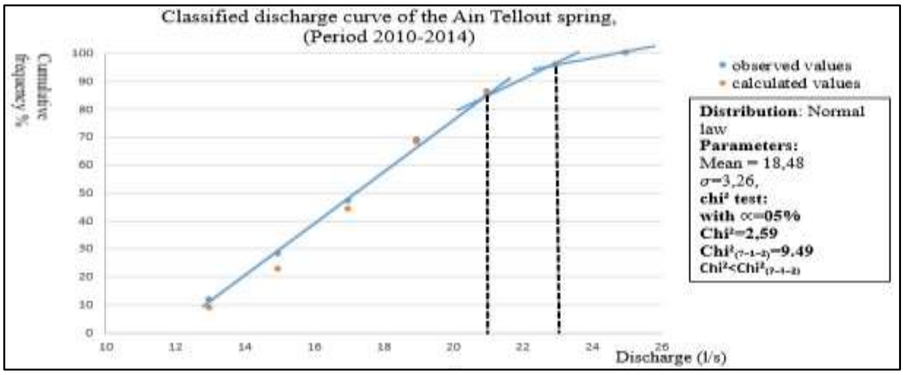

Fig. n°05. *The classified discharge curve of the Aïn Telout spring.*

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III.2 Application of recession curve analysis

To characterize the Aïn Telout system, three recession curves were studied (from 2010 to 2014) at fortnightly time step; the results are reported on Table n°02.

According to the results obtained, we note that the recessions begin in month of May with periods of recession that sometimes exceed five months (the character of the Mediterranean climate). The peak discharges of this spring are not very high due to the slow recharge of this aquifer.

The low values of the homographic function coefficients such as the infiltration speed coefficient ŋ (ŋ ≈ 0.017 on average) and the heterogeneity coefficient ε (ε≈0.048 on average) of the three recessions reflect a slow infiltration (a long infiltration time ti=58 days on average).

The values of the base flow coefficient α are close and very low (α <4.5*10-3), reflecting the character of a very inertial system with little karstification.

The dynamic volume which corresponds to the mobilisable water reserve of the drowned zone is of the order of Vd=465,000 m³, indicating the presence of a modest reserve.

After calculation of the parameters I and K of Mangin classification [14] obtained by the recession curves of Aïn Telout spring; the results obtained give high values of K and I (0.84<=I<=0.91 and K=1.11), I represents the delay to infiltration; A high value of I translates a slow or complex infiltration. While K represents the regulating power; which reflects the capacity of the system to store precipitation and distribute it over time.

In reality, the parameter K, which is the ratio between the dynamic volume expressed in m³ and the annual transit volume expressed in m³/year, represents the average residence time of water expressed per year [26], for Aïn Telout spring, it is estimated at 1.11 years or 405 days.

The transfer of these parameters (K and I) on the Mangin classification, place our spring in the domain 5, which corresponds to the little or no Karstic system. These results are consistent with the observations made in the field (the low variability of the discharges of this spring, the peak discharges are not very high Qmax=30 l/s, the residence time of water which exceeds one year) and some previous studies which prove the inertial character of this system (Fig n°06) [04, 06, 07, 08, 09, 12].

Table n°02. *The Values of the coefficients of the functions Ψ (t) and φ (t) for the different recessions of the spring of Aïn Telout.*

Recession	Annual Rainfall (mm)	The coefficients of the homographic function Ψ(t)			The coefficients of the Maillet function φ(t)			Ti (D)	K	I
		Q₀ (m^3/s)	η (j-1)	ε (j-1)	α (j-1)	QR_0 (m^3/s)	Vd (m^3)			
May - September 2011	393.5	0.007	0.01754	0.0257	0.0026	0.016	468475,9	57	0.80	0.91
May - September 2013	474.2	0.0016	0.017	0.069	0.00436	0.021	651457,1	58	1.11	0.84
May - August 2014	344.9	0.0016	0.017	0.048	0.0045	0.018	278553,6	59	0.54	0.88

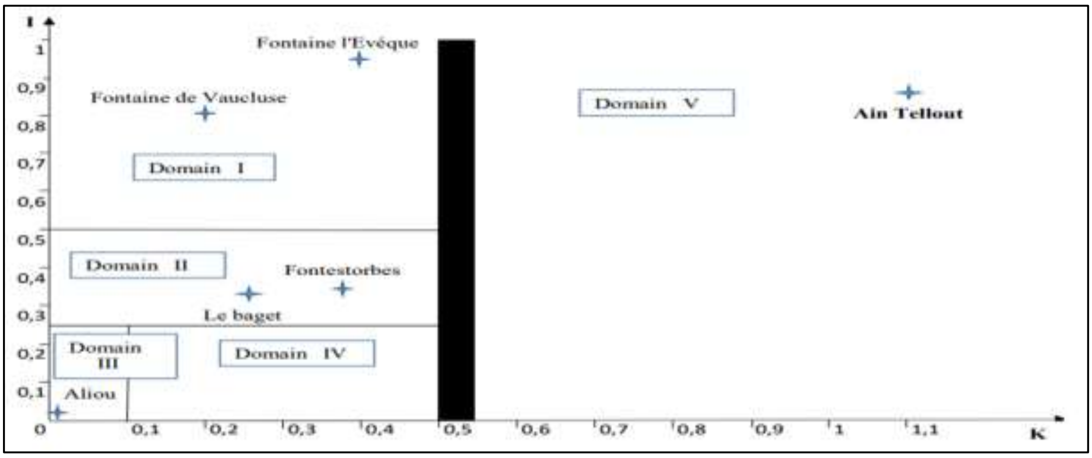

Fig n°06. *The Position of the spring of Aïn Telout according to the classification of Mangin 1975.*

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September edition. Vol.9. Nº3. (2023)
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III.3 Correlation and spectral analysis

In this study, the different methods of the correlation and spectral analysis were carried out using Statistica v.10 software. Applied on the one hand on the rainfall of the Mefrouche Tlemcen station as an input signal (this is considered as representative). and on the other hand on the average discharges of the Aïn Telout spring as an output signal ,for the hydrological period September 2010-August 2014 ,with an observation window of 480 days and a time step k= 15 days.

It is very important to note that the large time step can be used to study the behaviour of karst systems in the long term. [18, 30], as well as to study inertial systems which are characterized by a spread time response [27, 28, 29]. In addition, the previous studies on Aïn Telout system have shown a very inertial character of this last [04,06,07,08].For this reason, we have tried in this section to use this discharge chronicle at fortnightly time step, which constitutes the only exploitable data from this spring.

III.3.1 Simple Analysis

III.3.1.1 Analysis of the input signal (rainfall)

In the long-term, the correlation analysis of the input signal (rainfall) with an observation window of 480 days shows the presence of an annual periodicity (one peak for each 12 months). The spectral density of variance shows the influence of two periodicities, one annual and the other seasonal, which appear respectively as two peaks around 12 and 06 months. This periodicity characterises the Mediterranean climate, which is composed by two equal and well-separated seasons; a rainy season that extends from September to April (snowy at altitude) and a dry season in summer that sometimes extends into autumn (Fig n°07).

The analysis of the noise (Fig n°08) on a log frequency-log spectral density scale; clearly present a structured random Brownian noise β=-1.4, for the low frequencies (at the annual and seasonal scale) then beyond the frequency f=0.34 (T=2.9 months) it becomes pure random Gaussian β=-0.06 for the medium and high frequencies (for fast events).

According to the analysis, our input signal is periodic at the annual scale and random at the monthly scale, so our cross-correlogram could be a good impulse picture of the system. [15, 31, 32, 33].

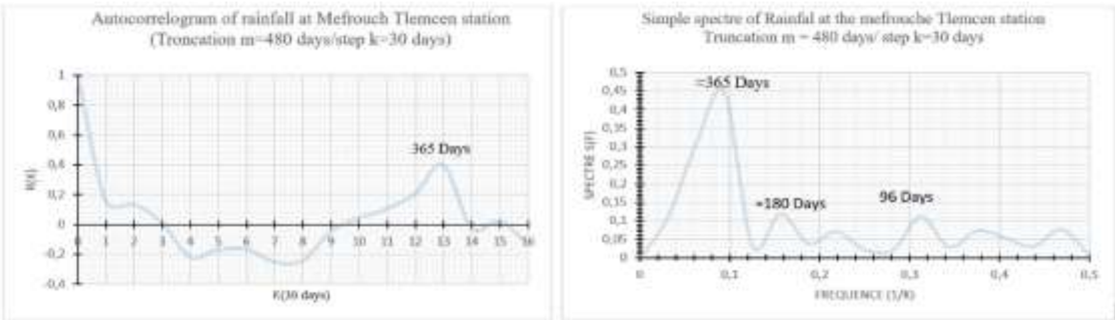
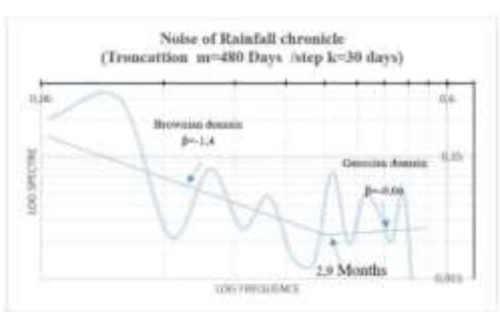


Fig n°07. *Autocorrelogram and the simple spectre of variance of rainfalls at Mefrouch Tlemcen station over the period September 2010-August 2014.*



β : Represents the slope of the log spectre-log frequency line

-1<β<1: characterizes the pure random Gaussian domain.

-3<β<-1: characterizes the structured random Brownian domain

Fig n°08. *The noise of the long-term rainfall of the Mefrouch station over the period September 2010-August 2014.*

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III.3.1.2 Analysis of the output signal (Discharge)

The simple correlogram of the discharges of Aïn Telout spring displays a slow decreasing ,different from the input signal,with an annual periodicity that corresponds to the hydrological cycle (one peak every 365 days) (Fig n° 09).

This correlogram reaches the value of the memory effect (Rxx (k) =0.2) after 60 days, and becomes zero after 75 days. This reflects the strong time dependence of the events affecting the discharge chronicle, and indicates that this system has a considerable memory effect, due to a less developed drainage network. It is an inertial system with low functional karstification.

The simple spectral of variance has a weak ordinate at frequency f= 0, probably due to weak multiannual regulation, so that the reserves released during a hydrological cycle do not benefit to the following cycle. This hypothesis is consistent with the residence time of the water calculated by the recession curve method (T residence =405 days) and the low dynamic volume of this system.

Our system may have a regulation time of 35 days, which is estimated by the maximum order of the spectre at frequency f=0 divided by its integral [18, 15, 34].

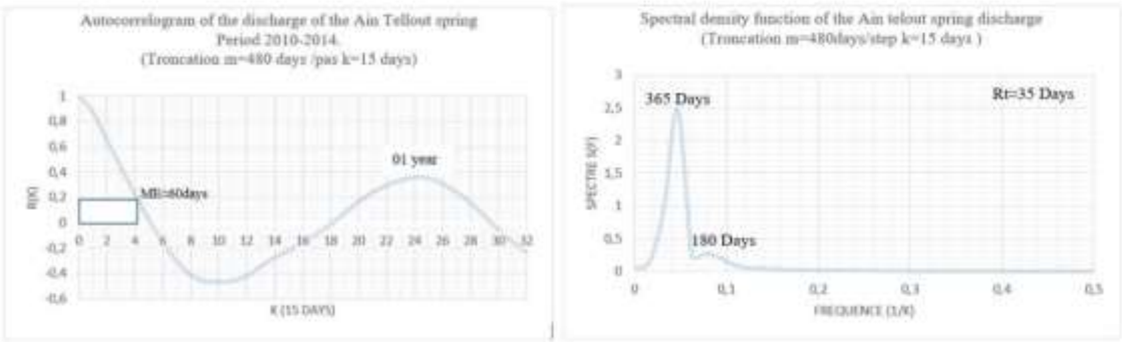

***Fig N°09.** Autocorrelogram and simple spectre of variance of discharges of Aïn Telout spring over the hydrological period September 2010 - August 2014.*

III.3.2 Cross analysis (rainfall/discharge)

The cross-correlogram of Aïn Telout presents a spread out response, which reaches its maximum after 15 days, this value represents the response time of the system after a rainfall solicitation [23]. The duration of the impulse response is around 78 days, which translates a significant regulating power.

This correlogram reveals a marked response in its negative part, which means that it, does not provide a good impulse picture of the system, can be explained by the loss of information at the fortnightly time step, or by a disturbance in the input signal. This curve shows a poorly individualised peak, then slowly decreases, and crosses the axis after 97 days. This can be explained by a bimodal response of the system after a rainfall event, the first peak at 15 days represents the fast flow, followed by a slow flow, which corresponds to an important capacitive effect (Fig n°09).

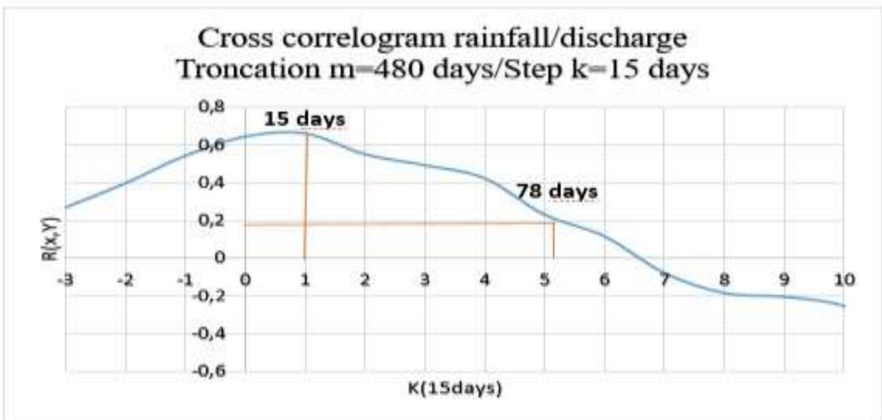

***Fig n°09.** The cross correlogram of rainfall/discharge of Aïn Telout spring over the hydrological period September 2010 - August 2014.*

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September edition. Vol.9. N°3. (2023)
ISSN : 2437-1114
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The results obtained in this study are consistent with previous work carried out on the Aïn Telout system. Bouanani et al (2005) by applying correlation and spectral analysis to the hydrographic system of Isser, witch drain the study area and located in the same geological context with the Aïn Telout system (Fig n°01), highlighted values of memory effect and regulation time close to the results obtained in this study (Table n°03), As well as the inertial character of aquifers in this region linked to weakly karstified formations. Moreover Khaldi (2005), Azzaz and Charechali (2008), Azzaz and Khaldi (2012), Azzaz and Emblanch (2018) have demonstrated by hydrochemical study the inertial character, the great geographical extension and the weak karstification of the system under study.

The time step adopted in this study provides only approximate results and constitutes a limitation .The sampling of this source at a finer time step (daily or hourly times step for example) would provide more precise results on the functioning of this system. Table n°03, Presents a comparison between the system of Aïn Telout and the system of isser.

Table n°03. *Comparison between the system of Aïn Telout and the system of isser.*

Author	**Region**	**Karstic system**	**Memory effect (rk=0,2)**		**Cutoff frequency**	**Regularization times (day)**
Bouanani (2004) [12]	Basin Tafna (Western Algeria)	Isser	63 days		0,018	43 days
This work	Basin Tafna (Western Algeria)	Aïn Telout	60 days		/	35 days

IV. Conclusion

The analysis of the time series of the discharges from the Aïn Telout spring as well as the rainfalls recorded at the station of Mefrouch Tlemcen during four hydrological cycles 2010-2014, allowed characterizing the hydrodynamic functioning of this karstic system.

The analysis of classified discharges has shown that the flows of the spring of Aïn Telout during flooding periods are oringinary from a previous hydrological cycle and from another system.

The analysis of recession curves reveals low values of the base flow coefficient (α <4.5*10-3), the infiltration speed coefficient ($\eta \approx 0.017$ on average) and the heterogeneity coefficient ε ($\varepsilon \approx 0.072$ on average). Translating the character of an inertial and poorly karstified system with a modest dynamic reserve estimated at 465,000 m³ and a residence time of 405 days.

The application of correlation and spectral analysis has allowed the extraction of some characteristics of this system. The analysis of the input signal (rainfall) displays a seasonal trend characteristic of the Mediterranean climate, while the simple correlogram of the discharges of the Aïn Telout spring shows a signal different from that of the input signal, reflecting the regulating character of this system.The simple and cross analysis presents a memory effect of 60 days, a regulation time of 35 days and a response time of 15 days. The cross-correlogram illustrates a double response of the system following rainfall solicitations, a fast response of the system, which translates a transmissive character, followed by a second slow response reflecting a second capacitive character of the system.

All these parameters characterise an inertial system with little karstification and poor drainage. The Sampling of this spring at a finer time step (daily or hourly times step for example) would provide more precise results on the functioning of this system.

V. Acknowledgement

I am extremely grateful to the Agency National of Water Resources for their help, which provided me the necessary data for this work.

I would like to thank, for the help and the information they generously received from me: Dr Boudjema Abdou (University of Tlemcen), Dr Mammeri Zakaria, Mr Abdel Rafik Rostan (Direction of water resources of Tlemcen) as well as to the two

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anonymous reviewers for their valuable comments on this article.

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Please cite this Article as:
Mamoune A.,Azzaz H.,Harek H.,Hamimed A., Characterization of the functioning of the Aïn Telout karstic system by hydrodynamic methods (The Tlemcen Mountains, Algeria), ***Algerian J. Env. Sc. Technology***, **9:3 (2023) 3213-3223**

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