EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(3), 378–392
https://doi.org/10.12912/27197050/200230
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Received: 2024.12.23
Accepted: 2025.01.23
Published: 2025.02.01

Calculating point runoff in the arid catchment areas of the Western Saharan Atlas: Case of Wadi Rhouiba catchment area (Ksour Mountains) in south-western Algeria

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ABSTRACT

In Algeria, frequent peak flows are currently estimated using empirical or analytical formulas established under geographical and climatic conditions other than those of Algeria, which is known for its spatial and climatic diversity. As a result, the errors committed by these extrapolated formulas can reach considerable values, leading to poorly dimensioned and erroneous flood protection structures. In this context, light was shed on the calculation of frequency flows and their appropriate adjustment tests in one of the arid to desert regions of the Wadi Rhouiba basin, part of the Western Saharan Atlas (Ksour Mountains region), south-west Algeria, based on instantaneous flow data measured at the Ain Hadjadj hydrometric station and empirical models. In this study, the authors confined themselves to the general characteristics of floods, such as their genesis, power and frequency, and to the hydrological potential and risks they represent. The catchment area covers a surface area of 2945.74 km^2, perimeter of 389.23 km, elongated shape (K_c = 2), very steep slopes exceeding 35%, favoring strong, rapid runoff, with a runoff concentration time (T_c = 21.21 h). All these conditions have contributed to classifying the basin as an arid to desert bioclimatic zone, offering a favorable environment for the development of heavy floods. Surface runoff in this arid region is closely associated with local rainfall patterns on the one hand, and the specificity that the region is landlocked between a series of barren mountains, on the other. Peak flows are considerably higher than average flows. These cures are rapid, characterized by an abrupt rise in water levels during the flood phase and a slower decrescence with a prolonged drying-up. Autumn is identified as the season with the greatest risk of flooding. Discharge during low-water periods bears witness to the phreatic potential generated by the Atlasic nature of the study region, highlighting a significant hydrological relationship between surface water and groundwater. The Exponential law gave the best fit of the maximum daily rainfall series from the Wadi Rhouiba watershed station, which are close and satisfactory to those of the flows calculated by Sokolovsky's empirical formula, which can then be readily exploited for the sizing of protection structures in arid to desert regions.

Keywords: arid, watershed, floods, Wadi Rhouiba, Ksour Mountains, Naâma, Western Saharan Atlas.

INTRODUCTION

Like many other countries in the world, Algeria is affected by devastating floods. This recurring event is one of the major challenges facing the country's urban areas, particularly the north and the south. In the past, these floods were mainly caused by the overflowing of large rivers onto large agricultural plains, but over the last twenty years or so, they have mainly affected large towns and urban centers, where they have resulted in the loss of many lives and considerable material damage (Aissa et al., 2016). Among the fourteen major risks listed by the UN, the risk of flooding in Algeria is one of the ten major risks present in the country and cited by Law 04–20 of 25th December 2004 on the prevention of major risks and disaster management in the context of sustainable development (FAO, 1960). It comes second after earthquakes and geological hazards in Algeria's ranking of major risks, given the scale of the material and the immaterial damage caused

(Nouri et al., 2016). Flooding remains the most widespread risk today, causing the most casualties and damage. It accounts for 58% of victims of natural disasters and economic losses (Aissa et al., 2016). For instance, the exceptional rainfall that hit several central regions between 28th and 31st March 1974 caused 52 deaths in the wilaya of Tizi-Ouzou alone, with 4.570 houses destroyed, 130 villages isolated and more than 18.000 people affected. Thirteen bridges and numerous kilometers of road were washed away by the floods, and the estimated material damage at that time was 27 million dinars (Baazi, 2002). The ancient Fergoug dam near Mascara completely failed as a result of the greatest flood in the Mactaa basin history, which occurred on November 27th, 1927 and was believed to have been around 5000 m^3/s (Argence et al., 2008). Exceptional rainfall (more than 240 mm), which fell on Bouzaréah during the night of 9th to 10th November 2001, caused by a local storm, generated catastrophic flooding, estimated at 730 m^3/s, over a catchment area of 10 km^2. This flood tore up and carried away huge quantities of earth (mud), trees and waste of all kinds. The deadly violence of this flood in Wadi Bab El (Algiers) caused almost 1.000 deaths and extensive material damage (Bouhellala et al., 2020). Historically, the last floods in the southern Algerian region (study area), which affected the towns of Tindouf and Béni Abbés, as well as Béchar, Djanet, Naâma (Ain Sefra, Tiout and Mechria) and El Bayadh, the far south of Algeria towards the Tassili, the Hoggar and the eastern Sahara, experienced showers accompanied by hail and strong gusts of wind during thunderstorms in September 2024. Rainfall totals reached or exceeded 70 mm in places, causing enormous casualties and material damage. The town of Ain Sefra (in the steppic region) experienced a more serious episode of torrential, sudden and violent rain, which ravaged the town a flash flood of the wadi Breïdj. Losses due to flooding have been increasing over the years, despite the efforts to reduce the risk (Amrouni, 2024). As a result, the management of surface and underground water resources is at the heart of humanity concerns and is becoming a key objective in the main socio-economic development programs (Kacemi, 2012). Consequently, dramatic floods are not always linked exceptional meteorological situations, but in many cases, they occur as ordinary, seasonal rainfall events (Khedim, 2021). Furthermore, in developing countries, the high probability of extreme events, combined with the rapid expansion of the urban population, the lack of effective planning and the disruption of natural drainage systems, exacerbate the vulnerability of urban food supplies (Amrouni, 2002; Li et al., 2017; Tramblay et al., 2019).

In addition, other factors, such the interactions between an already fragile environment, irregular rainfall, the resurgence of periods of drought since 1970 and increased socio-economic pressures are accentuating the degradation of the steppe environment (Benmansour, 2023). Protection against the major risk of flooding is an important aspect of sustainable development. Appropriate flood protection was, is and will remain a fundamental condition for a well-informed society (Rahmani, 2017). The study of floods in Algeria's wadis remains an unknown field, with only very occasional indications given in Algerian hydrological yearbooks (Derdour et al., 2017), floods and flood hydrographs and the majority of Algeria's wadis are less well known (Boutoutaou et al., 2014).

On the basis of this observation, this article aimed at studying the point runoff of arid watersheds in the Western Saharan Atlas: Case of the Wadi Rhouiba watershed (Monts des Ksour) south-west Algeria (2945.74 km^2), and finding a frequency distribution able to account for the rainfall regime of the Wadi Rhouiba basin, determining peak flows to shed light on the strategy for regulating river flows and managing catchment areas in arid zones, reflecting the rapid and dangerous storm-like aspect of its runoff.

MATERIALS AND METHODS

Geographical context

Geographic presentation of the Naâma study region

The Naâma district covers a vast area of around 3 million hectares (29.825 km^2), forming part the high plains of the south Oranaise region. It is located in south-west Algeria (Figure 1). It is bordered to the north and the north-west by the 3 districts of Tlemcen, Sidi Bel-Abbes and El-Bayad, to the south by Béchar and to the west by the Algerian-Moroccan border via a 250 km border gap. Its population in 2018 was estimated at 281.168 inhabitants, a density of 9.43 inhabitants per km^2 (Ducrocq, 2006), with an increasingly semi-arid to desert climate. It is landlocked between the Tellian Atlas to the north and the Saharan Atlas to the south.

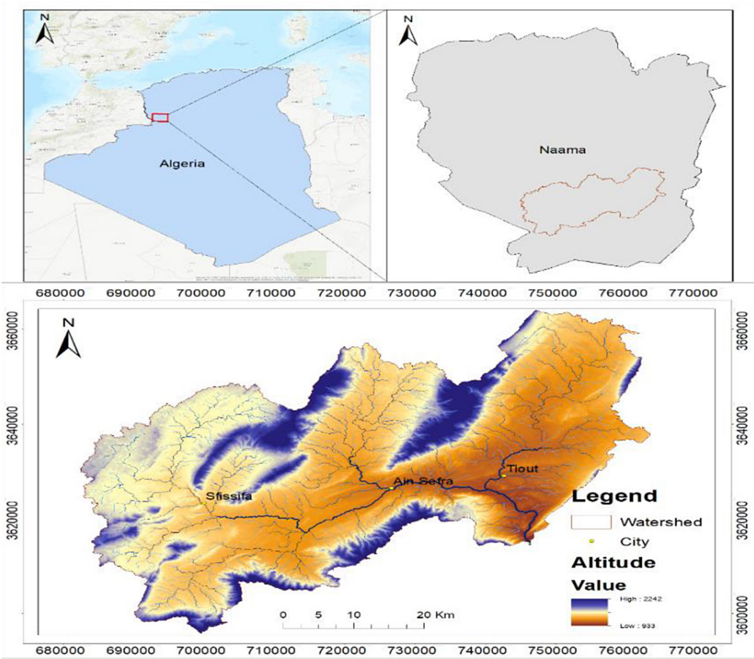

Figure 1. Map of the Wadi Rhouiba catchment study area

Morphological characteristics of the Wadi Rhouiba catchment

The Wadi Rhouiba basin (Fig. 1), marked by the Monts des Ksour, is part of the Sahara basin and it covers the territory of three towns (Sfissifa, Ain Sefra and Tiout). The basin is surrounded by rocky, barren mountains: to the north by Djebel Souiga, which rises to 1758 m, to the north-east by Djebel Afzouz (1787 m), to the south by Djebel Mekter (2053 m) and to the south-west by Djebel Mzi (2187 m), Mir El-Djebel (2059 m), geographically, it is located between the longitudes (1° 2' 59" and 0° 10' 86") West and the latitudes (32° 28' 52" and 33° 5' 9") North. To generate the hydrographic network of the Wadi Rhouiba catchment and its physical and morphometric characteristics, topographic maps, satellite images and SRTM (Shuttle Radar Topography Mission) digital terrain models (MNT), with a spatial resolution of 30 m (Figure 1) were used, projected into the coordinate system (WGS 84 UTM ZONE 31 N), which was used to create thematic maps (slope, hydrographic network, catchment area limits, contour, CN and other maps) using an S.I.G.

The Wadi Rhouiba basin covers an area of 2945.74 km^2, which is located in the south-west of Algeria in a pre-Saharan area, precisely the Ksour Mountains or (Western Saharan Atlas). It lies between longitudes (0°10' 55" and 1° 3' 13") West and latitudes (32° 28'32" and 33° 4' 56") North. The catchment area is also part of the high plateaus of north-western Algeria, characterized by a variety of topographical conditions. Altitudes range from 933 m to 2242 m above sea level. The main geometric formations found in the Ksour mountains form a relatively high massif, with peaks exceeding 2000 m, such Djebel Aïssa (2236 m), Djebel Mir Djebel (2059 m) and Djebel Mekter (2053 m) (Fig. 2).The basin is characterized by a series of mountains which have allowed the development of a more hierarchical (very dense) hydrographic network (Fig. 2), forming a number of wadis the flow of which runs parallel to the structures, favoring the concentration of flow towards the depressions. For the most part, these are temporary wadis. The most important wadis are the two Wads Breïdj and the Wadi Tirkount; the Wadi Tirkount receives water from the western slopes of the Djebel Aissa and Djebel Morhad, whereas the Wadi Breïdj drains the northern slopes of the Djebel Mzi and Mekter; it receives water from the Wadi Sfissifa which drains the northern slopes of the Djebel Mzi and Mekter. The Ain Sefra, which flows southward after meeting these two wadis (Tirkount and Breïdj), receives the waters of the Wadi Tiout and Rtem, which in turn give rise to the Wadi Rhouiba. This area forms the upstream portion of the large Saharan catchment area of the Wadi Namous, which silted up in the Great Western Erg,

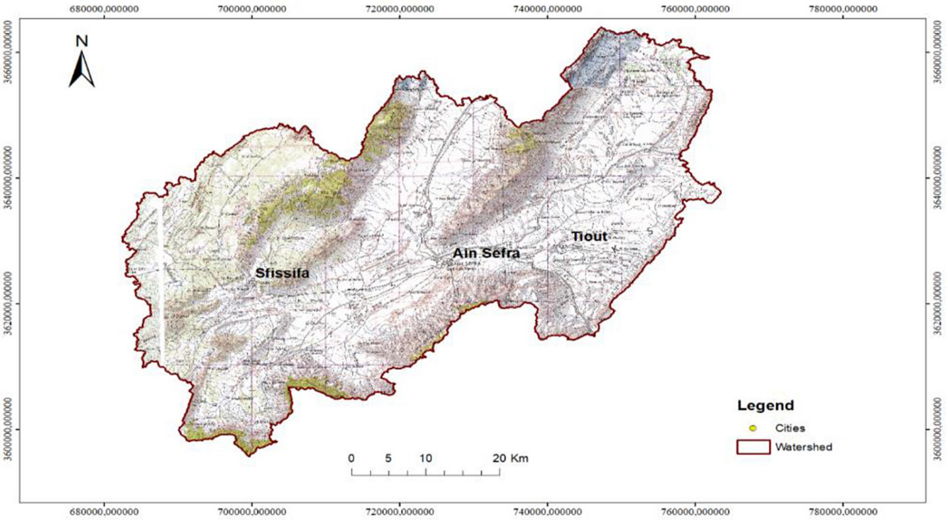

Figure 2. Topographical map of the Wadi Rhouiba catchment area

an area where the waters of the Ksour Mountains are lost over a distance of 350 km downstream to the Saharan plain.

The study of the Wadi Rhouiba catchment area has enabled identifying certain morphometric characteristics (Table 1). Wadi Rhouiba system is an elongated basin (K_c= 2) with a dense (2116.9 km), fairly branched hydrographic network that allows easy collection of rainwater to convey it to the outlet. The slope indices calculated (rock slope index I_p = 3.84 and overall slope index I_g = 3.56 m/km) show the presence of a fairly strong relief, favoring violent and torrential flow, with a time of concentration of 21.21 h.

Geological and lithological context of the Wadi Rhouiba basin

The Wadi Rhouiba watershed is characterized by a series of faulted synclines and anticlines from the Eocene, followed by the more or less parallel uplift of the Upper Pliocene in a general direction from south-west to north-east. The basin is enclosed between the Jurassic anticlines of Morghad, Aissa and Bouamoud to the north and Mekther, Mir El Djbel and Mzi to the south, which frame the Cretaceous sandstone synclines of Ain Sefra, Tirkount, Mekalis, Hendjir, Mekhizen and Sidi Maamar. The stratigraphic series in the Wadi Rhouiba basin region ranges from Upper Jurassic to Quaternary. The echelon-like shape and configuration of the elongated, boxed anticlines with straightened, overturned flanks, the axis of which runs roughly parallel to the direction of the chain, and the perched synclines with wide bottoms, represent the Atlasian style that characterizes the middle structural level (domain of isopaque folds). The major phase that structured the Atlas edifice produced SW-NE isopaque folds (Derdour, 2017), The folds tend to be ejected towards the SE. This Atlasic phase has been dated to the end of the Lutetian-Priabonian period (Brahim, 2013).

Quaternary formations: these are not thicker but cover large areas of the basin. They are known for their high permeability, as in the case of the Breïdj and the Tirkount wadis, which have left large alluvial deposits on their banks containing a water table that is exploited by numerous wells as part of land development.

Upper Jurassic Formation: This is a powerful sandstone-clay series that forms most of the major anticlines of the Ksour Mountains. It consists of massive sandstones with oblique stratifications and pelitic clays with an abundance of clays at the base of the formation. The sandstones are 30 to 40 meters thick. They are particularly exposed at Hassi El Meguil.

Table 1. Main morphometric characteristics of the Oued Rhouiba catchment

Surface B_v (km^2)	Perimeter, P_{bv}	Shape index, K_c	L of talweg (km)	H_{max} (m)	H_{min} (m)	Drainage density	Torrentiality coefficient	Concentration time (h)
2945.74	389. 23	2.00	113.86	2242	933	0.72	0.29	21.21

Formation Cretaceous series (Tiout and Rhoundjaia region): Tiout section (Kacemi.,2005) : This formation corresponds to the largest lithological unit is the vast Tiout, Ain Sefra and El Hendjir synclines. All three are separated by the Djebel Mekther anticline to the south as well as the Djebel Aissa and the Garet Dabba anticlines to the north. This is a very powerful 1065 m formation with quartz and clay dredges. It comprises a terrigenous detritic spread that became widespread at the end of the Lower Cretaceous. Depending on the lithological composition as well as the geomorphological and structural layout of the banks.

Figure 3 shows the geological map of the Wadi Rhouiba catchment, extracted from the geological map of Algeria (Coiffait et al., 1984). The predominant facies in the Monts des Ksour are sandstone formations (Jurassic and Cretaceous), but are usually clayey interspersed with compact marl or quartz beds, so their permeability remains very low overall. With the exception of the Albian sandstone, which is the most important water table in the region and the one most exploited by numerous boreholes, the large springs in the region are the natural outlets for this water table

Soil and land use in the Wadi Rhouiba catchment area

Vegetation cover in the basin in question is fairly thin. In the high plains of southern Oran, the arid climate does not allow the development of a plant cover capable of protecting the soil surface. In this arid environment, most species have acquired quite specific biological and morphological characteristics that enable them to overcome all the unfavorable environmental conditions. Despite the low rate of cover, steppe vegetation is a natural resource of great importance, particularly in protecting the soil against wind and water erosion and in structuring the soil's superficial horizons. According to the FAO (1960), any elimination or degradation of the plant cover or plant residues that protect the soil are the main cause of erosion. The natural vegetation of the study area is characterized by a steppe-like appearance, except in the mountains where there are remnants of primitive forests cut down by man, comprising Pinus Halepensis and juniperus phoenicea. Apart from these forest species, the appearance of the steppe changes with the rainfall gradient and the nature of the soil. Seven plant formations have been identified in the region (Mekki., 2007; Benito and Machado., 2012).

The nature of the soils and their distribution are closely related to the geomorphological units. A larger surface area is occupied by tree categories of soils: calcimagnesic soils, raw mineral soils, soils that have evolved little. The entire catchment area the Rhouiba wadi occupied by steppe formations and a large part by mountains (Fig. 4).

According to the hypsometric curve of the wadi Rhouiba catchment area, it can be seen that the slopes are classified into five categories, which are (0–3%) represents low slope land, whose altitudes

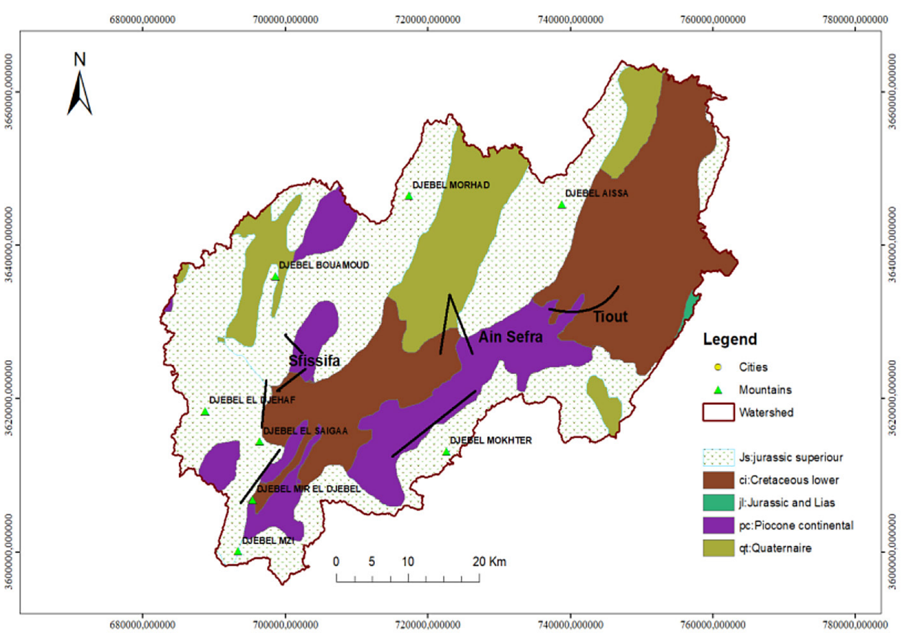

Figure 3. Geological map of Wadi Rhouiba catchment, modified

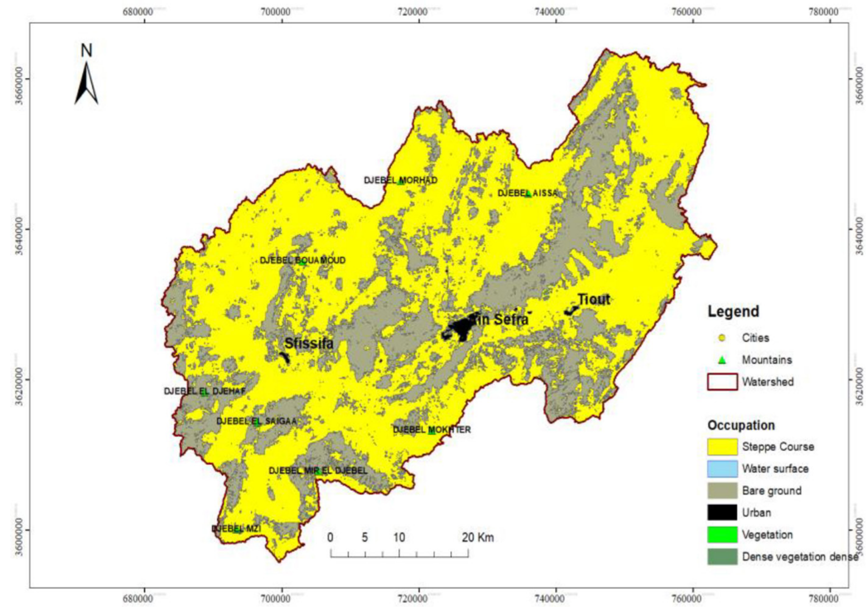

Figure 4. Land use map of the Wadi Rhouiba catchment

are generally lower than (1100 m), this slope is characterized by the presence of the recessed regions of El–Hendjir; as well as other valley areas such as the town of Ain Sefra (1071 m) and Tiout (1033 m), these areas are highly vulnerable to flooding, a moderate slope (3– 12%) towards altitudes (1100–1500 m), hence the presence of plateau in the Djebels, makes up 77.75% of the surface area of the Wadi Rhouiba catchment. A steep slope (12–20%) towards the altitudes (1500–1800 m), occupies approximately 8.47% of the surface of the basin, very steep and extreme slopes of 20–35%) and > 35% occupying the north and north-east of the basin corresponding to the presence of the mountainous zone for altitudes (1800–2242 m), occupying a surface of 2.45% of the total surface area of the basin, which favors the runoff with a rapid flow velocity (V = 1.5 km/h) in Wadi Rhouiba catchment and a concentration time of 21.21 h (Fig. 5).

RESULTS AND DISCUSSION

Climate

In the south of Oran, these mountainous massifs are exposed to a fundamentally desert climate on the steppe, with considerable variations in temperature between winter and summer and also between day and night, frequent and often very violent winds leading to intense evaporation. All these physical factors give the lower levels of

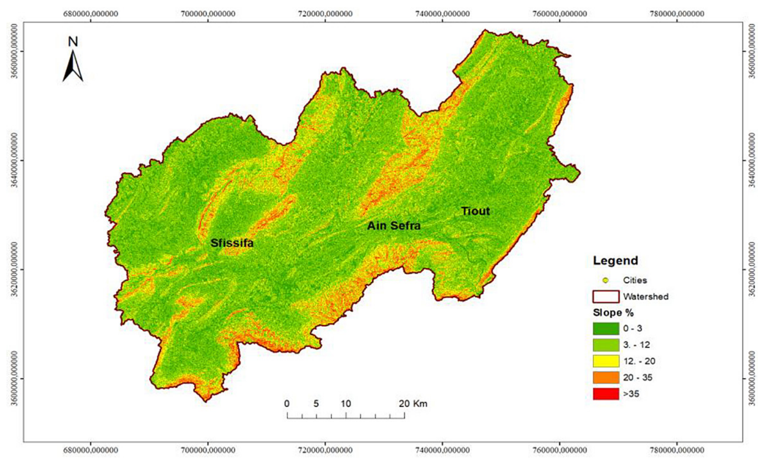

Figure 5. Map of slopes in Wadi Rhouiba catchment area

the Ksours a pronounced aridity. A study of the various climatic parameters of the Wadi Rhouiba catchment area over a period of (1978–2020), based on the Ain Sefra rainfall station alone and the Ain Hadjaj hydrometric station for a period of (1973–2020) covering the entire catchment area. These data were collected from the National Water Resources Agency (ANRH), while the climatic data are from the Ain Sefra meteorological station. The analysis of parameters and other climatic and hydroclimatic indicators are considered by hydrologists and hydrogeologists to be particularly discriminating in terms of the quantification and the exploitation or management of water resources, in relation to the geology and the spatial distribution of rainfall, hydrographic and land-use systems as we;; as, ultimately, the resource systems of rural and natural space and the systems of use of these resources by local populations. These climatic indicators are also indicators of the intensity of human impact on the natural environment. The region is characterized according to the following climatic indices: EMBERGER's climatic index (Q_2 = 16.17), DE MARTONNE's annual aridity index (I = 6.27) and Moral's annual aridity index (IM = 0.52). This enables the study area to be classified in the cool lower arid bioclimatic zone, with temperate to very cold winters and dry hot summers where rainfall is almost non-existent and evaporation is particularly high. The umbrothermal diagram for the Ain Sefra station indicates an aridity with a dry period that extends throughout year, with total monthly rainfall exceeding twice the temperature (Fig. 6).

The 43-year rainfall record is characterized by inter-annual and monthly irregularities, with an annual average of 172.63 mm and a maximum rainfall of 440.2 mm in 2008. Average monthly rainfall is around 27.23 mm for the wettest month (October) and 3.65 mm for the driest month (July) (Fig. 7).

On the basis of the seasonal distribution of the study region (Fig. 8), it can be said that the rainfall regime is of the APHE type (autumn, spring, winter, summer), favorable to vegetative activity despite the length of the dry period, which extends from April to October.

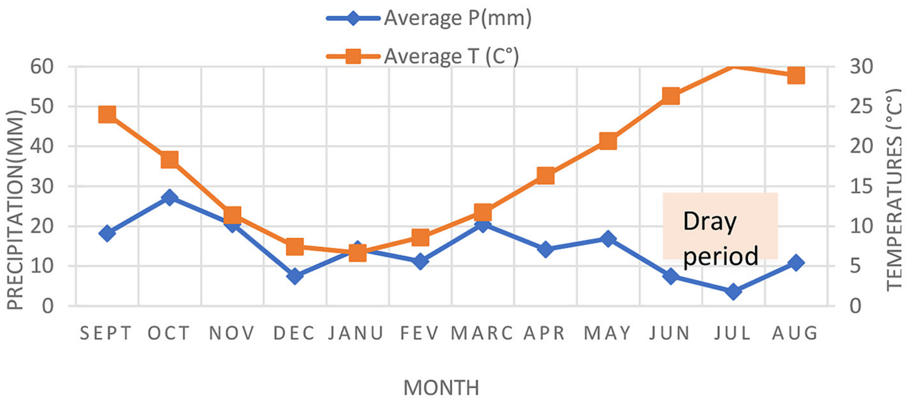

Figure 6. Umbrothermal diagram for the Ain Sefra station

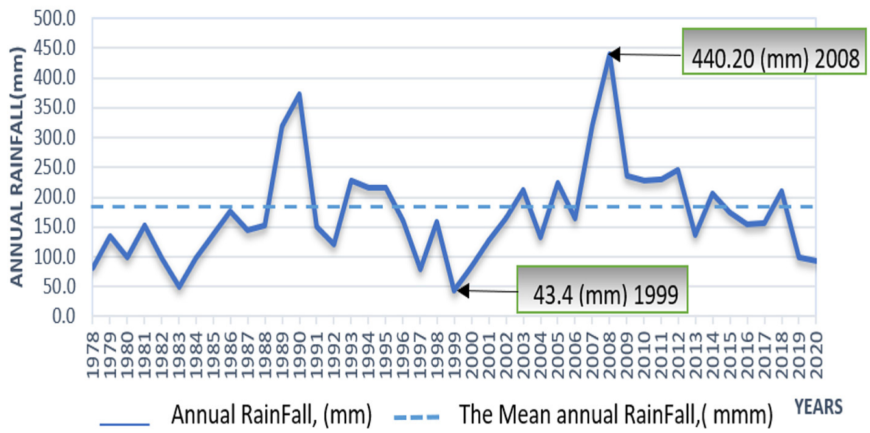

Figure 7. Variation in annual rainfall at the Ain Sefra station

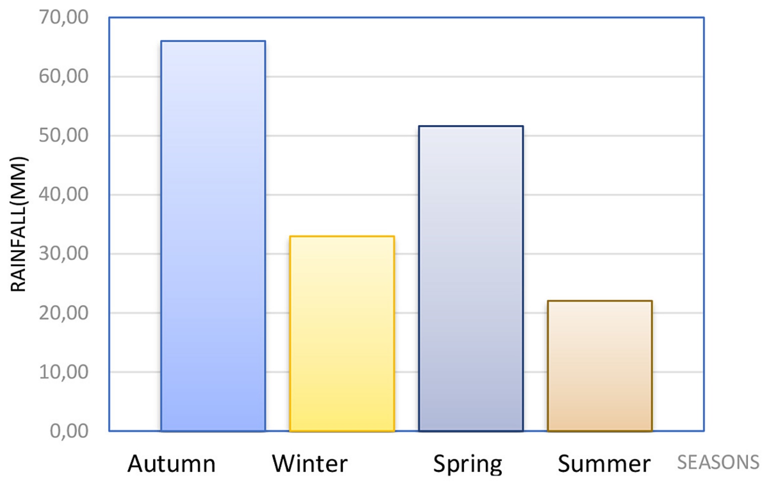

Figure 8. Seasonal distribution of the Ain Sefra station

Study of flood flows based on hydrometric observation series

The study of the hydrological regime Wadi Rhouiba was carried out on the basis of the series hydrometric observations available on the various hydrological and the hydraulic variables recorded at the hydrometric station. These data concern liquid flows on a monthly and annual scale. For floods in the Wadi Rhouiba catchment, given their volume of inflow and high flow velocities: the average flood velocity exceeds 1.50 m/s, especially in the mountains, due to their extreme violence and the force with which they carry solid materials. As a result, any development of any kind must first and foremost take into account the erosion and siltation caused by flooding, especially on engineering structures such bridges. These flows are generated by rainfall of short duration and higher intensity. The morphology of the basin helps to amplify the peak flows observed at the outlet, which is the Ain Hadjadj station, with maximum flows of 750.84 m^3/s, recorded on 24/10/2000. This is due to the fact that the study area is classified as a cool lower arid to desert bioclimatic zone with an APHE type rainfall regime, which means that autumn is reported to be a season of alert and high risk with a large number of floods, hence majority of floods recorded during the study period: (19/09/1979, 12/11/1993; 03/11/1982, 24/10/2000 and 13/12/2012) with maximum daily flows exceeding 500 m^3/s, the floods are generally of short duration, with fairly short rise times and slower ebbs, generally followed by a prolonged drying up. The morphometric, geological and vegetation conditions of the study area are not conducive to the rapid and violent nature of flooding in the Wadi Rhouiba catchment, which causes enormous damage (Figure 9).

The study area is affected by cures and floods, with a very rapid character that allows it to be classified as an area exposed to frequent flooding

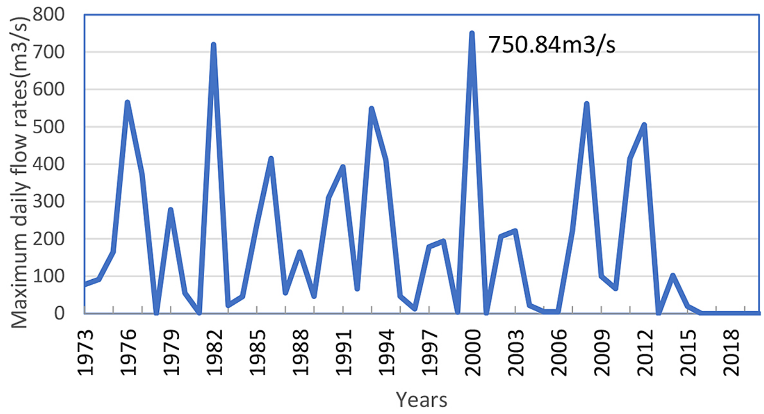

Figure 9. Variation in peak flows in Wadi Rhouiba

(major risk) during the authonian season, floods recorded according to the history of floods in the region. Among the floods that have left very serious consequences, directly affecting the lives of citizens and the region's basic infrastructure, the flood of 27 September 1976, for example, with a peak flow rate of 566 m^3/s, recorded by the gauging station at Ain Hadjaj, which is the outlet of the Wadi Rhouiba basin, caused major material damage in the town of Ain Sefra. Another heavy downpour on 5th May 1990 caused one of the most devastating floods in the history of the town of Ain Sefra, with very heavy human and material damage. A peak flow of 392.72 m^3/s and a volume of 27. According to the hydrological study of the Wadi Rhouiba catchment area, the basin is characterized by steep slopes that encourage run-off, with a run-off speed of around 1.5 km/h. As a result of this heavy rainfall, all the watercourses in the basin experienced hydrological swellings and significant flows downstream and the water level reached more than 2 meters high in the urban center of Ain Sefra. For the flood of 24th October 2000, the peak flow recorded was the order of 750.84 m^3/s. Another example is the flood of 18/19/10/2007, when heavy rainfall of 190 mm in the commune of Aïn Sefra caused flooding of the El Breïdj and Tirkount (Mouileh) wadis, which run through the center of the town of Aïn Sefra and the flood of 19/20/05/2011, with an average annual rainfall of 229.8 mm, causing two deaths and material damage. The history of flooding in the study area shows that the flow regime is highly irregular, directly influenced by the presence of the mountains, with an altitude >2000 m, favoring rapid and violent storm-type run-off. This favors the phenomena of the endoreism process in a climate that can be extremely arid to desert-like.

The floods are rapid, with a sudden rise in water levels during the flood phase and slower, more regular descent during the ebb phase. This is justified by the data from hydrometric observations (gauging) at the level of Wadi Rhouiba. The typical hydrographs observed show a slight difference between the two periods of the flood: a faster rising phase and a slower falling or recession phase. The examples of gauged flood hydrographs, presented in Figure 10, show that the shape of the hydrograph is multimodal, given the asynchronous flood bodies formed in the Wadi Rhouiba catchment. Analysis of the flood hydrographs for Wadi Rhouiba at Ain Hadjadj shows that the flood and deflooding times vary between (9–14) hours and (15–28) hours respectively, depending on the center of gravity of the watered area in relation to the catchment outlet. The ratio of flood to rise time varies between (1.4–2.5).

Frequency analysis of maximum daily flows

Frequency analysis of a long series of peak flows A series of peak flows from floods gauged at the hydrometric station controlling the Wadi Rhouiba watershed, at the Ain Hadjadj station alone, spanning (1973–2020), a sample of maximum flows over 48 years, can be used to estimate the return time of a particular value. This prediction is based on the definition and implementation of a frequency model, which is an equation describing (modeling) the statistical behavior of a process. These models describe the probability of occurrence of an event of a given value. It is the choice of frequency model (and more specifically its type) that will determine the validity of the frequency analysis results. Three frequency models were used

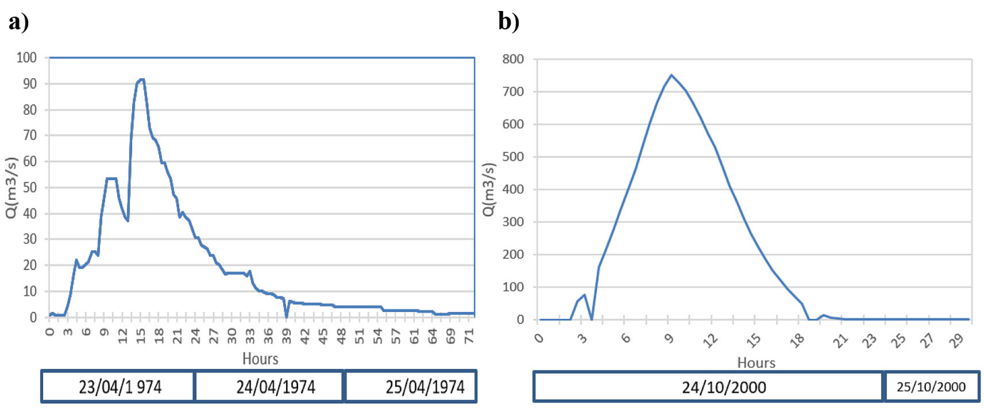

Figure 10. Example of a flood hydrograph for Wadi Rhouiba: a) the flood from 23/04/1974 to 25/04/1974; b) the flood from 24/10/2000 to 25/10/2000

to describe the statistical behavior of extreme values: the Gamma, GUMBEL and Exponential statistical distributions.

Table 2 gives the statistical characteristics of the maximum flows gauged, compared with those of the Gamma, GUMBEL and Exponential laws that best fit the maximum flow data (Fig. 11).

From visual examination, the graph representing the fit achieved, even if it may appear rudimentary, remains one of the best means of judging the quality of a fit and should always be a preamble to any statistical test, shows that the Exponential law has the advantage of being a suitable model for the gauging station at Ain Hadjadj, the annual maximum daily rainfall values of which correlate well with this law, and shows good behavior compared with the other two laws with lower dispersion test values. The Exponential law gave the best fit to the maximum daily rainfall series from the Wadi Rhouiba watershed station. It provides an acceptable ranking of points. As a result, this law can be used to estimate flood occurrence probabilities and return periods (Table 3).

Frequency analysis of daily peak flows

Frequency analysis of a long series of peak flows A series of peak flows from floods gauged at the hydrometric station controlling the Wadi Rhouiba watershed, at the Ain Hadjadj station alone, extending from (1973–2020), i.e. a sample of maximum flows over 48 years, can be used to estimate the return time of a particular

Table 2. Comparison of the characteristics of the laws and sample.

Features	Gamma Law	Exponential law	Gumbel's law	Sample
Minimum	0.00	0.00	0.00	0.01
Maximum	No	No	No	750.84
Average	207	207	207	207
Standard deviation	263	212	188	211
Median	112	142	167	134
Coefficient of variation (Cv)	1.27	1.02	0.949	1.02
Asymmetry (Cs)	2.54	2.00	1.14	1.04

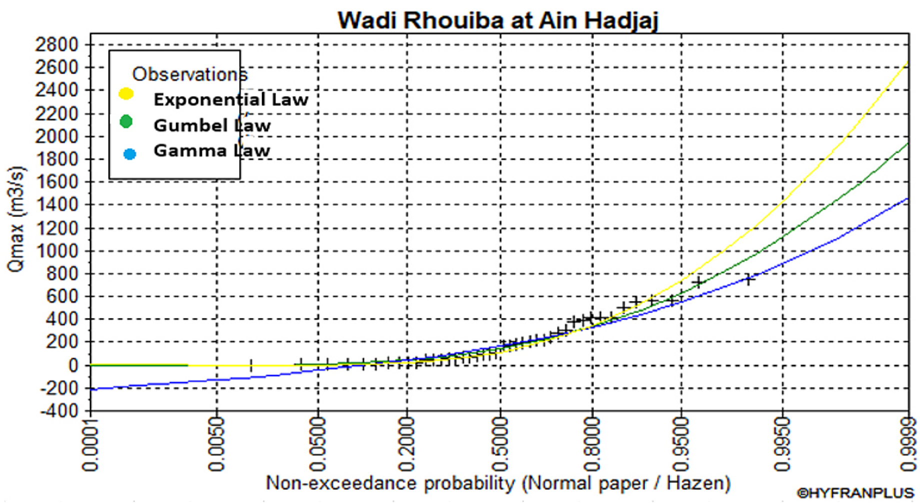

Figure 11. Adjustment of maximum flow rates to Gamma, Exponential and Gumbel laws

Table 3. Return flows adjustment according to an exponential law, for the different return periods T = 10 years 20 years 50 years 100 years 200 years and 1000 years.

Period of back	10	20	50	100	200	1000
Q(m^3/s)	484	631	825	972	1120	1460

value. This prediction is based on the definition and implementation of a frequency model, which is an equation describing (modeling) the statistical behavior of a process. These models describe the probability of occurrence of an event of a given value. It is the choice of frequency model (and more specifically its type) that will determine the validity of the frequency analysis results. Three frequency models were used to describe the statistical behavior of extreme values: the Gamma, GUMBEL and Exponential statistical distributions. The maximum annual flow measured is 750.84 m^3/s (Fig. 12).

Flooding occurs during the Authonian period (generally during the months of September and October) with maximum daily flows exceeding 500–700 m^3/s, with low frequencies of 40% and 20% respectively, depending on the flood gauge (which has caused enormous damage to the region's socio-economic fabric, Figure 13.

Study of flood flows based on empirical models

Before starting to calculate flood flows based on empirical models, it is necessary to determine the time of concentration required to calculate flood flows.

Table 4 shows the various concentration time values for the Wadi Rhouiba watershed at the considered study site, taking into account its morphometric and hydrographic characteristics (slope, gradient, surface area, perimeter). It can be seen that the value adopted is that of the average of five formulas (Giandotti, Kirpich, Californian, Bourrier and SCS (soil conservation service) giving a value of 21.21 hours. This time-of-concentration value is used to calculate the corresponding maximum daily rainfall (mm) and its intensity (mm/h) in Table 6. This time of concentration is at the origin of floods with rapid concentration and torrential flow.

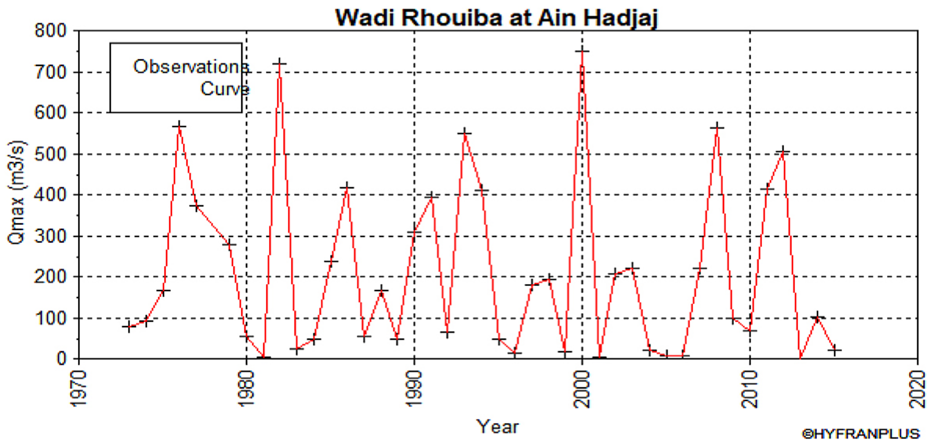

Figure 12. Variation in maximum annual flow of Oued Rhouiba (1973–2020)

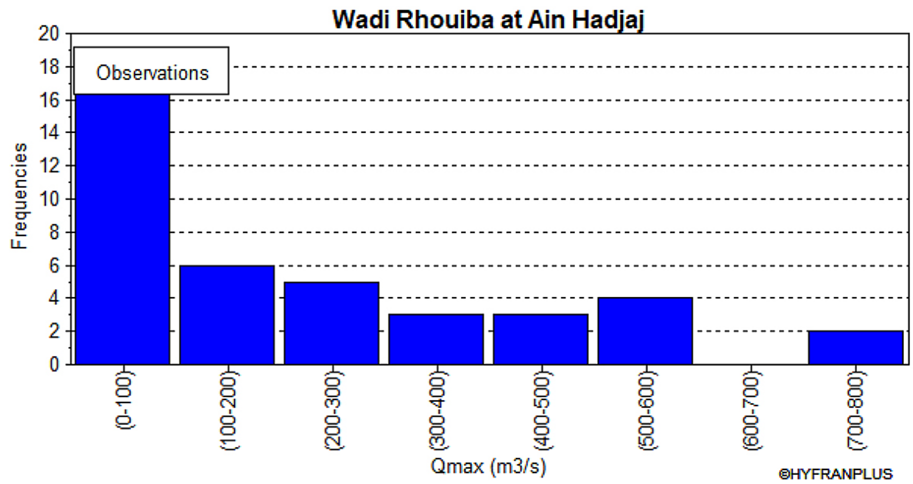

Figure 13. Frequency of maximum annual flood flows

Table 4. Estimated time of concentration (T_c, hours)

Calculation formulas	Expression	T_C (h)
Giandotti	$T_c = \frac{4\sqrt{S} + 1.5\sqrt{L}}{0.8\sqrt{H_{moy} - H_{min}}}$	25.84
Kirpich	$T_c = 0.6615\ L^{0.77}\ I_g^{-0.385}$	37.71
Californien	$T_c = \frac{0.87\ L^3}{(H_{max} - H_{min})^{0.386}}$	14.28
Bourrier	$T_c = \frac{4\sqrt[3]{S}\ L}{\sqrt{P_{BV}}}$	14.03
SCS	$T_c = \frac{0.87\ L^3}{(H_{max} - H_{min})^{0.385}}$	14.18
The selected T_C value	The average	21.21

Note: T_c – watershed concentration time (hours); L – talweg length (km); S – watershed surface area (km^2), H_{max}, H_{min}: maximum and minimum altitudes in the Wadi Rhouiba watershed, I_g – overall watershed slope index (m/m), PBV – watershed perimeter (km). The values S, L, H_{max}, H_{min}, are shown in Table 1.

Table 5. Formulas for calculating the flow rate of frequent return points

Calculation formulas	Expression	Parametres
Giandotti	$Q_{max\%} = \frac{C\ S(H_{moy} - H_{min})^{1/2}}{4\sqrt{S} + 1.5\ L} P_{tc}$	$Q_{max\%}$: maximum flood flow in m^3/s of the same frequency as that of short-duration rain, C : topographic coefficient varies between 66–160, we take C =160, S : catchment area for Oued Rhouiba (km^2), L : length of main talweg (km); P_{tc} : short-duration rain (mm).
Possenti	$Q_{max\%} = \frac{\mu\ S\ P_{max\%}}{L_P}$	$P_{max\%}$: maximum daily rainfall corresponding to the given return period (m), μ : coefficient between 700–800, we choose μ = 750, L_p : length of main talweg (km).
Turraza	$Q_{max\%} = \frac{C\ S\ I_t}{3.6}$	C : runoff coefficient, 0.6< C <0.8, C = 0.6, I_t : rainfall intensity for a given frequency corresponding to the time of concentration (mm/h).
Sokolovsky	$Q_{max\%} = \frac{0.285\ \propto\ P_{tc}}{T_c} f$	α : watershed runoff coefficient (α = 0.6), f : coefficient de forme de l'hydrogramme de crue, f = 1.2, P_{tc} : short-term rainfall (mm).
Alexeev	$Q_{max\%} = 0.34\ P_{tc}^{4/3}$	P_{tc} : short-term rainfall (mm).

The maximum instantaneous flow Q_{max}% can be estimated for different return frequencies from the many empirical formulas applied in Algeria. These formulas use estimates of maximum daily rainfall and rainfall for a duration equal to the time of concentration (T_c) (Table 7).

Table 6 shows the quantiles of maximum daily rainfall frequencies and their intensities required for calculating frequency point flows.

In the light of these formulas, the authors opted for the results of the average of the formulas used, with the exception of the Alexeev formula, which gives low values. The design of major hydraulic structures is based on the calculation of the design flood. Classical statistical methods, such as adjustments to statistical laws to derive the corresponding flow or rainfall from frequencies of 100 years to 1000 years and more, are widely used in Algeria; If the values obtained for point flows using frequency analysis of maximum daily flows (Table 3) are compared with those obtained by empirical formulae (Table 7), it can be found that the values for point flows are similar only for Sokolovsky's empirical formula (Table 8).

CONCLUSIONS

This is a first initiative to shed light on a region located in the Western Saharan Atlas (south-west Algeria) to determine and analyze the hydrological behavior of the Wadi Rhouiba catchment area, among its physical and hydrological characteristics, such as its surface area of 2945.74 km^2, with an elongated shape (K_c = 2), a 113.86 km long talweg with a very dense and branched hydrographic

Table 6. Frequency quantiles of daily maximum rainfall and their intensities corresponding to T_C = 21.21 h

Return time (years)	P_{tc} (mm) 24-hour duration	L (mm/h) for T_c = 21.21 h
1000	167.67	7.91
200	121.41	5.72
100	104.07	4.91
50	87.30	4.12
20	67.55	3.18
10	53.87	2.54

Table 7. Estimated frequency peak flood discharge for the Oued Rhouiba watershed

Formulas	Return period (years)					
	10	20	50	100	200	1000
Giandotti	1227.97	1539.91	1990.24	2372.47	2767.88	3822.32
Possenti	1084.67	1360.20	1757.97	2095.60	2444.87	3376.24
Turraza	1246.85	1563.58	2020.83	2408.93	2810.42	3881.06
Sokolovsky	390.58	489.80	633.04	754.61	880.38	1215.76
Alexeev	67.17	93.53	131.68	166.43	204.81	314.35
The selected value $Q_{max\%}$ (m^3/s) the average	987.52	1213.57	1539.91	1816.90	2103.44	2867.55

Table 8. Comparison of peak flow values obtained using the maximum daily frequency point flow method and empirical formulas

Return period (years)	10	20	50	100	200	1000
$Q_{max\%}$(m^3/s) (according to the maximum daily flow analysis method)	484	631	825	972	1120	1460
$Q_{max\%}$(m^3/s) (according to Sokolovsky's formula)	390.58	489.80	633.04	754.61	880.38	1215.76

network as well as fairly steep slopes favoring rapid and torrential flow and a time of concentration of approximately 21.21 h. These characteristics have created the conditions conducive to flooding and violent, rapid floods with higher intensities in mainly urban areas (given that the confluence of the two main wadis (Wadi Breïdj and Wadi Tirkount) is in the center of the town of Ain Sefra), the downstream western side of the Wadi Rhouiba, and the same for the downstream eastern side where the Wadi Tiout is located. The floods are of the stormy type with maximum daily flows in excess of 750 m^3/s; with rainfall at times no longer reflecting the reality of the regenerated flows, this incompatibility could be due to anthropic and physical conditions (landlocked area between a series of mountains, spatial diversity), also due to high line losses and the small size of the rainfall units or "cells" producing runoff and an insignificant low flow around 0.02 m^3/s occurs in the Rhouiba wadi, reflecting the presence of the groundwater's phreatic potential and the existence of a relationship between surface water and groundwater. Floods in the Wadi Rhouiba basin are characterized by a very short, abrupt rise time and a fairly slow fall time, marked by prolonged drying up. A study of the extreme flows of the Wadi Rhouiba has enabled to confirm the irregular nature of these flows, with a violent torrential character due to the high intensity of precipitation during the Authonian period. The region is characterized by the Authonian season, a time of great risk and heavy flooding, when most extreme flow records at the Ain Hadjaj hydrometric station alone exceed 500 m^3/s, in the following years: 1976 – 566 m^3/s; 1982 – 720 m^3/s; 1993 – 549.2 m^3/s; 2000 – 750.84 m^3/s; 2008 – 562 m^3/s; 2012 – 505 m^3/s. The exponential law is the most suitable for an arid region, giving frequent flows close to those calculated by the various empirical laws. This is a major factor in hydrological studies, which are subsequently used to estimate recurrence probabilities for different return periods. The values of the estimated maximum daily frequency point flows are close only to those calculated by the Sokolovsky formula. Furthermore, the development and management of soil and water resources in catchment areas in arid zones requires knowledge of the hydrology of arid systems, unlike the predictive relationships concerning the behavior of catchment areas in the more populated humid temperate zone. In the studied region, after the floods of 10/19/2007, the water resources department of the Naâma district carried out several works to protect the banks in the most vulnerable areas with retaining walls and bank stability against erosion and possible overflowing of the banks. With regard to the watershed, adequate instrumentation more suited to the size and surface area of the basin, such as the reinforcement by setting up hydrometric stations at wadi level (Breïdj, Sfissifa and Torkount), the use of flood forecasting programs can rely on satellite meteorological data and the use of information technology.

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