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Research article

Flash Floods Generation Processes in Arid and Semi-Arid Basins: A Case Study of the Aouerga Watershed, Morocco

Processos de geração de enchentes repentinas em bacias áridas e semiáridas: um estudo de caso da bacia hidrográfica de Aouerga, Marrocos

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Abstract: This article seeks to understand and interpret the mechanisms, impacts, and management strategies of flash floods in arid and semi-arid watersheds, with a focus on the downstream Aouerga watershed. This area is considered one of the most vulnerable zones on the left bank of the Souss watershed. The research addresses the issue of recurrent flash floods that cause severe material damage, as observed during major events in 2014 and 2018. The main objective is to identify the natural and anthropogenic factors that intensify flood risks and to propose sustainable mitigation measures. The study adopts an integrated methodological approach combining remote sensing, GIS-based spatial analysis, field observations, and hydrological data interpretation. The main results are as follows: first, land degradation and unplanned urbanization amplify runoff and peak discharge; second, the lack of efficient drainage infrastructure increases local vulnerability; and finally, spatial modeling identifies critical flood-prone areas. The findings highlight the need for integrated management measures both upstream in the Aouerga watershed and downstream in the Ouled Dahou Center.

Keywords: Flash Flood Risk; Management Measures; Aouerga Watershed; Ouled Dahou commune.

Resumo: Este artigo visa compreender e interpretar os mecanismos, impactos e estratégias de gestão relacionados às enchentes repentinas em bacias áridas e semiáridas, com foco particular na bacia do Baixo Aouerga. Essa área é considerada uma das zonas mais vulneráveis da margem esquerda da bacia do Souss. A pesquisa aborda a questão das enchentes repentinas recorrentes, que causam graves danos materiais, conforme observado em grandes eventos ocorridos em 2014 e 2018. O objetivo principal é identificar os fatores naturais e antropogênicos que intensificam os riscos de inundação e propor medidas de mitigação sustentáveis. O estudo utiliza uma abordagem metodológica integrada que combina sensoriamento remoto, análise espacial baseada em SIG, observações de campo e a interpretação de dados hidrológicos. As principais conclusões são: primeiro, a degradação do solo e a urbanização não planejada amplificam o escoamento superficial e a vazão de pico; segundo, a falta de infraestrutura de drenagem eficiente aumenta a vulnerabilidade local; e, finalmente, a modelagem espacial identifica áreas críticas suscetíveis a inundações. Os resultados destacam a necessidade de medidas de gestão integrada tanto a montante, na bacia do Aouerga, quanto a jusante, no centro de Ouled Dahou.

Palavras-chave: Risco de enchentes repentinas; Medidas de gestão; Bacia hidrográfica de Aouerga; município de Ouled Dahou.

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1. Introduction

At the onset of the third millennium, the world has witnessed a significant rise in the frequency and intensity of natural hazards, particularly floods, which constitute one of the most devastating hydrological phenomena. Floods are one of the most common weather-related natural hazards, causing devastating impacts worldwide, including fatalities (Liu *et al.*, 2022). Flood on the global scale is the most devastating catastrophe and is the cause of the highest mortality and destruction (Javadinejad *et al.*, 2019). However, river flooding has emerged as a significant problem worldwide, impacting vast areas and affecting millions of people annually (Jatin Anand *et al.*, 2024). In recent years, the severity and frequency of floods have generally worsened (Arrault *et al.*, 2016; Gripp *et al.*, 2014; Soomro *et al.*, 2024). According to reports by the United Nations, floods alone have affected approximately 2.3 billion people globally over the past two decades (Wahlstrom & Guha-Sapir, 2015). Moreover, 1.47 billion people, or 19 percent of the world population, are directly exposed to substantial risks during 1-in-100 year flood events. Natural disasters are estimated to cause an average of over $300 billion in direct asset losses every year (Rentschler & Salhab, 2020).

A flood is, in fact, an increase in the water level of the river and the overflow of water from it and the occupation of a part of the plains of the river boundary that can lead to flooding of the area, causing damage to public buildings and human and animal casualties (Benettin *et al.*, 2015). River floods are often due to heavy rainfall, which in some cases is associated with snow melting (Bowden *et al.*, 2001). Flash floods are rapid, short-lived events with high peak discharges, typically occurring within four to six hours of rainfall and confined to small watersheds of a few hundred square kilometers (Murray, 2023). A flood that is flowing in the river without a preliminary warning or advance warning is called a flash flood (Bronstert *et al.*, 2017). The casualties of this rapid flood occurring in small areas are generally higher than the death tolls of large river floods (Javadinejad, 2022). Flash flood disasters arise from the interplay of multiple drivers, including climatic triggers (e.g., extreme rainfall, rapid snowmelt), surface conditions (e.g., slope, soil moisture, land cover), and anthropogenic disturbances (e.g., engineering failures, unregulated development near rivers) (Terry *et al.*, 2023; Brázdil *et al.*, 2024). The interaction of flood flow with obstructed floodplains, often due to anthropogenic activities, is a crucial factor influencing the frequency, extent, and severity of flooding events. These impacts are especially severe in arid and semi-arid regions, where ecological fragility and limited adaptive capacity heighten vulnerability.

In Morocco, floods represent the most significant natural hazard, affecting both urban and rural territories (OCDE, 2016). The country's exposure results from a combination of physical factors—such as irregular rainfall patterns, steep slopes, and alternating wet and dry periods—and human-induced factors, including rapid population growth, unplanned and uncontrolled urbanization, and the degradation of natural drainage systems. Floods also generate considerable socio-economic and environmental impacts, thereby requiring significant efforts to reconstruct and protect areas vulnerable to such hazards.

Within this national context, flooding in the Souss River Basin has been examined in several studies (Saidi, 1994; El Mehdad, 2003; ABHSMD, 2013; Aghenda *et al.*, 2025). However, most of these investigations have focused on isolated aspects of the issue rather than adopting an integrated analytical perspective. In contrast, the present study adopts a comprehensive, multifactorial approach to analyze the dynamics of flooding within the basin. This integrated perspective aims to enhance the understanding of flood risk in the study area and to propose sustainable development strategies for mitigating its adverse impacts.

The present study aims to understand and interpret flash flood dynamics in the downstream section of the Aouerga watershed (Anti-Atlas Mountains) (Figure 1), with a particular focus on the Ouled Dahou Center—one of the most flood-prone zones on the left bank of the Souss watershed. Using a multidisciplinary methodological framework that combines hydrological modeling, geomorphological analysis, remote sensing, GIS-based spatial analysis, and field observations, this research seeks to identify the principal natural and anthropogenic factors driving flash floods and to propose sustainable management and mitigation measures. Ultimately, the study aspires to contribute to a comprehensive understanding of flood risk in semi-arid Morocco and to support the development of integrated strategies for regional resilience and sustainable watershed management.

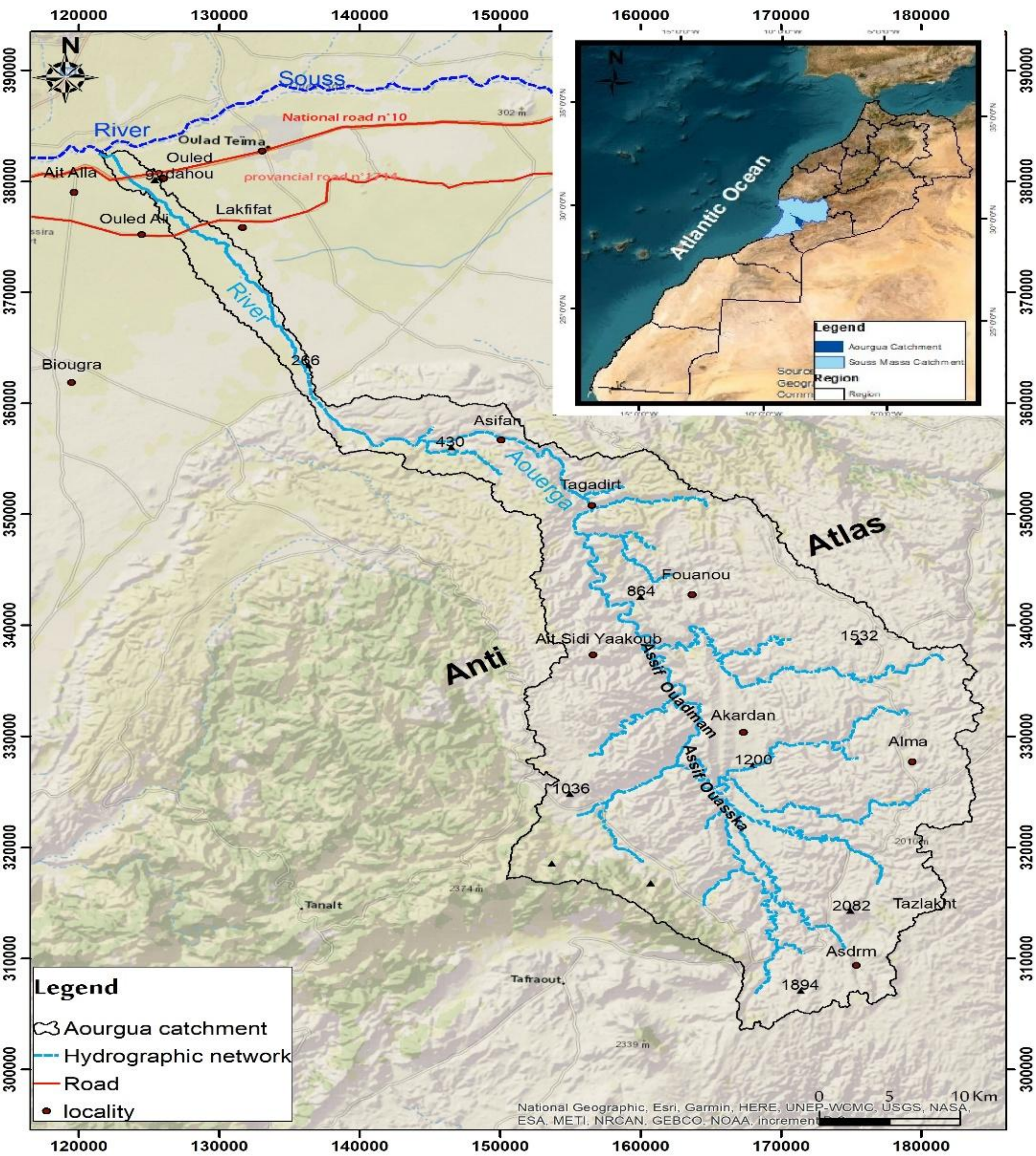

Figure 1. Location of the study area (Aourgua watershed).

Figura 1. Localização da área de estudo (bacia do rio Aourgua).

2. Study Area

The Aouerga watershed covers an area of approximately 1283.52 km², representing about 10% of the total area of the Souss basin. It extends between 29°42' and 30°24' N latitude and 8°40' and 9°02' W longitude. The Aouerga hydrographic system drains all the water falling on the slopes of the western Anti-Atlas Mountains. It comprises two sub-basins: the Ouska river, which covers an area of approximately 467.33 km², and the Ouedmane river, which extends over an area of about 709.14 km². The elevation in the Aouerga watershed ranges from 93 m downstream at the Souss plain to 2378 m upstream in the basin.

The study area corresponds to the downstream section of the Aouerga watershed, especially in the Ouled Dahou commune, which covers an area of 88 km². According to the High Commission for Planning (HCP, 2024), it has a population of 15697 inhabitants, resulting in a population density of approximately 178,3 h/km^2. The commune comprises 15 villages (douars) distributed mainly along the 17 km course of the Aouerga river, a direct tributary of the Souss river.

The study area is located on the left bank of the Souss river and lies on Quaternary detrital formations that constitute part of the alluvial fans of the northern slopes of the Anti-Atlas Mountains (Hssaisoune *et al.*, 2017). The geographical landscape is characterized by agricultural land use and the built-up areas of the Ouled Dahou commune. From an economic perspective, the commune is predominantly agricultural. Over the past few decades, agricultural activity has expanded through the adoption of modern land cultivation and livestock farming techniques, leading to the development of several large-scale modern farms. These farms rely on covered crop production (greenhouse cultivation) and advanced irrigation systems such as drip irrigation.

3. Materials and Methods

3.1 Documentation, data, tools and software

In this study, we investigate the morphometric characteristics of watersheds located in an arid zone using a Geographic Information System (GIS) to analyze and identify the various features of the Aouerga watershed.

These characteristics were selected for their ability to represent watershed morphometry and their influence on hydrological responses. Digital Terrain Model (DTM) data with a 30-meter spatial resolution were used to delineate the basins and generate various thematic maps, including slope, hypsometric, and hydrographic maps. Data processing was carried out using a specialized set of tools integrated within the ArcGIS software. In this study, ArcGIS version 10.3 was employed. Arc Hydro utility allowed us to perform several operations such as delineating and characterizing watersheds in raster and vector formats, defining and analyzing the geometric hydro network, managing time series data, and exporting data to digital models (ESRI, 2011).

To identify the characteristics of the study area, detailed field surveys were conducted to collect information on previous flood events that affected the region. It was observed that the emergence and intensification of flood risk result from the interaction of several natural and anthropogenic factors. Therefore, the study was based on the analysis of a set of documents, information, and data obtained from administrative institutions (Souss Massa Hydraulic Basin Agency, Ouled Dahou Commune, etc.), as well as from previous references and studies.

3.2 Watershed characteristics formulas

Morphometric analysis of watersheds is essential for comprehending the complex interplay among the relief, linear, and areal characteristics of a given watershed (Shekar & Mathew, 2024). The sub-parameters include stream order, number of streams, stream length, bifurcation ratio, drainage density, stream frequency, relief ratio, basin shape, circularity ratio, elongation ratio, and length of overland flow. The morphometric characterization of the Aouerga watershed, in terms of linear, areal, and relief aspects, was calculated using the formulas presented in Table 1.

Table 1. Morphometric parameter formulas used in this study.

Tabela 1. Fórmulas dos parâmetros morfométricos utilizados neste estudo.

Morphometric parameters	Formulas and description	References
Gravelius compactness index *KG*	$KG \approx 0.28.\ P/\sqrt{A}$ where: A = watershed area in km²; P = perimeter (km)	(Bendjoudi & Hubert, 2002)
Length (L) and width (W) of the equivalent rectangle (km)	$Leq = (KG\ \sqrt{A})/1.12x[1+\sqrt{(1-(1.12/KG)^2)}]$ $Weq = (KG\ \sqrt{A})/1.12x[1-\sqrt{(1-(1.12/KG\ )^2)}]$	(Roche, 1963)
Overall slope index *IG* in m/km	$IG = (H5\% - H95\%)/L$ where: H 5% = altitude corresponding to 5% of the watershed (m); H 95% = altitude corresponding to 95% of the watershed (m); L = length of the equivalent rectangle (km)	(Bouguerra *et al.*, 2016)
Specific elevation *Ds*	$Ds = Ig.\sqrt{A}$ where: *Ig* = overall slope index (m/km) ; A = watershed area in km²;	(Dubreuil, 1974).
Average slope of the main river (S_a) in m/m	**S avg =(Hmax-Hmin)/L** where: Hmax = Maximum altitude (m); Hmin = Minimum altitude (m); L = Length of the longest talweg (m).	(Gericke & Du Plessis, 2012)
Stream order *Nu*	**Hierarchical order:** The smallest permanent streams are called "first order". Two first-order streams join to form a larger, second-order stream; two second-order streams join to form a third-order, and so on. Smaller streams entering a higher-ordered stream do not change its order number	(Strahler, 1957)
Drainage density *Dd(km/km²)*	$Dd = \Sigma L/A$ where: L = total length of stream (km); A = watershed area in km²	(Horton, 1945)
Stream frequency Fs (N/km2)	$Fs = \Sigma N/A$ where: N = total number of stream; A = watershed area in km²	(Horton, 1945)
Time of concentration of water *Tc* (hours)	$Tc = 60\ (4\sqrt{A}+1.5xL/0.8\sqrt{H_{moy}-H_{min}})$ where: L = length of the longest thalweg (km); H_{moy} = average altitude (m) H_{min}= minimal altitude (m)	(Chow, 1959)
flood flow estimation	$QT = (4xN\ /300)\ (1 + a \log T)\ (A0,8 + 8/3\ A0.5)$ Where: QT: Peak flow in m³/s of return period T years; A: Catchment area in km²; N: Coefficient generally taken equal to 80 in the lowlands and 100 in the mountains; a: Coefficient ranging from 0.7 to 1.7 and may exceed 2 in arid regions.	(Bouziane, 1997; Ouarda *et al.*, 2001)

3.3. Steps and procedures for field work

The fieldwork conducted in the downstream part of the Aouerga watershed, aimed at studying the impact of floods on human activities, included several key steps. These involved carrying out a reconnaissance survey to identify observation points along both banks of the valley, measuring water flow heights during floods and assessing channel characteristics, collecting data on land use patterns in the downstream area, identifying flood-inundated points using the Global Positioning System (GPS), and conducting interviews with affected residents to explore their perceptions of flash flood risks and to document their historical memory of such events.

4. Results

4.1 Morphometric and topographic characteristics

The study and interpretation of hydrological hazards are made possible by analyzing the geometric characteristics of a basin, which play a crucial role in determining its hydrological response. This response is closely related to the nature of the geological formations, the prevailing climatic conditions within the basin, and the type and characteristics of the landforms.

Watershed geometry and morphometric parameters are essential for understanding runoff processes and assessing hydrological hazards (Horton, 1945; Strahler, 1957). These characteristics allow for the determination of the compactness and shape indices, as well as the equivalent rectangle length and width. Furthermore, their analysis reveals the drainage patterns of the watershed. Therefore, this information is essential for understanding hydrological processes, predicting surface runoff patterns, identifying flood-prone areas, and developing appropriate water resources management strategies (Mathew & Shekar, 2023).

The Gravelius compactness index allows for hydrological interpretations and provides insight into the shape of watersheds (Amrani & El-Amrani, 2025). According to the shape parameters, the Aouerga basin is shaped longitudinally and has a general direction of southeast-northwest (Tab.2).

Table 2. Morphometric parameters of the Aourgua watershed.

Tabela 2. Parâmetros morfométricos da bacia de Aourgua.

Geomorphic parameters	Results
Area (A) km^2	1283.52
Perimeter (P) km	311.75
Compactness index (K_G)	2.43
Length of the equivalent rectangle (L) km	146.81
Width of the equivalent rectangle (l) km	8.74
Maximum altitude (H max) m	2345
Minimum altitude (H min) m	93
Average altitude (H moy) m	1282.54
Altitude corresponding to 5% (H5%) m	2180
Altitude corresponding to 95% (H95%) m	650
Specific elevation (Ds) m	373,3
Overall slope index (I g) m/km	10,42

Source: ASTER DEM 30 m

Circular basins are characterized by irregular water flow in both time and space, whereas elongated (longitudinal) basins exhibit more regular flow patterns over time, typically with lower peak discharges. This is due to water losses from infiltration and evaporation as water moves from upstream to downstream, as well as the successive contribution of inflows from tributaries.

Topographic characteristics play a crucial role in understanding the nature of basin terrain and its degree of geomorphological evolution, as they directly influence hydrological responses. Basin elevation, slope steepness, and slope orientation control the speed and direction of surface runoff. In addition, steep terrain in the upper basin accelerates water flow and increases the risk of flash floods in downstream areas. Therefore, analyzing these characteristics is essential for identifying elevation variations and assessing slope intensity and orientation, as hydrological hazards arise from the combined effects of multiple topographic factors rather than any single factor.

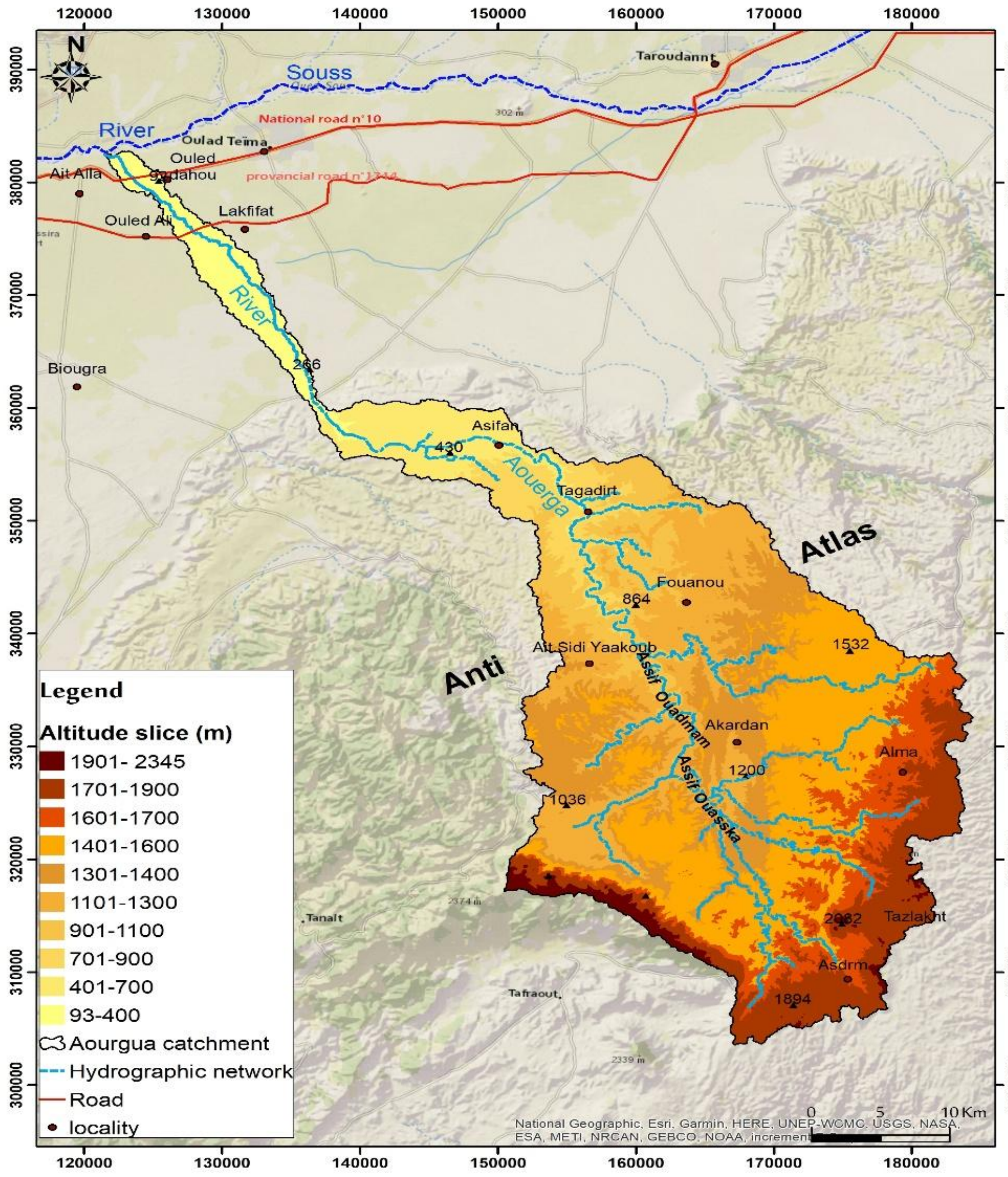

Figure 2. Hypsometric map of the Aouerga watershed (DEM 30 m).

Figura 2. Mapa hipsométrico da bacia de Aourgua (MDE de 30 m).

The study of elevation differences within a watershed is of great importance in hydrological analysis, as it provides valuable information about the basin's topography and offers indications regarding the time of surface runoff concentration. Its impact is also reflected in the peak discharge during rainfall events: the steeper the slopes, the faster the flow and the shorter the time of water concentration in the basin.

Table 3: Distribution of Elevation Classes in the Aouegra Watershed.

Tabela 3: Distribuição das classes de altitude na bacia de Aourega.

Elevation Class (m)	Partial Area (km²)	Partial Area (%)	Cumulative Area (km²)	Cumulative Area (%)
1801–2345	22.06	1.71	22.06	1.7
1601–1800	138.85	10.81	160.90	12.51
1401–1600	110.86	8.63	271.77	21.15
1201–1400	289.14	22.52	560.91	43.68
1001–1200	192.53	15.0	753.44	58.68
801–1000	211.97	16.51	965.41	75.19
601–800	105.15	8.19	1070.54	83.36
401–600	66.56	5.18	1137.10	88.55
201–400	79.36	6.18	1216.50	94.73
93–200	67.05	5.22	1283.52	100
Total	1283.52	100	-----	-----

Source: ASTER DEM 30 m

Based on topographic analysis, the distribution of elevation classes within the Aouerga watershed is uneven. Elevations ranging from 1201 to 2345 m are the most widespread, covering over 43% of the basin's total area. This elevation class is primarily concentrated in the upper part of the basin and along its southeastern and western boundaries (Figure 3 and Table 3).

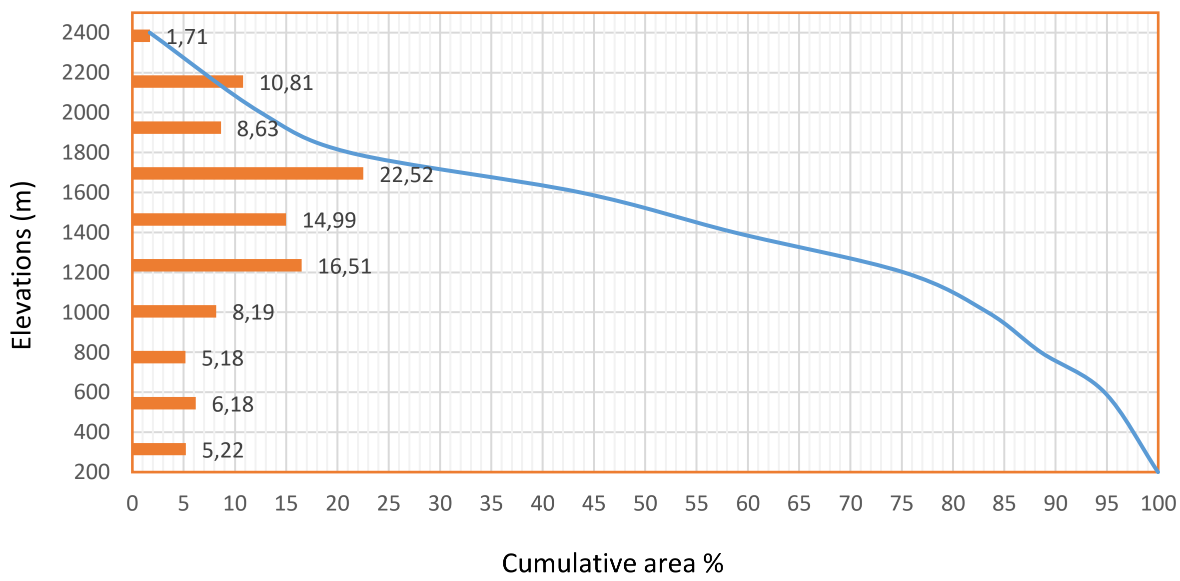

Figure 3: Hypsometric curve of the Aourega watershed (DEM 30 m).

Figura 3: Curva hipsométrica da bacia de Aourega (MDE de 30 m).

The hypsometric curve of the Aourega watershed illustrates the relationship between area and elevation. The basin is characterized by a large internal area, suggesting that it is still in the youthful stage of development due to ongoing and intense erosion (Figure 3).

Analyzing and classifying slopes are important in hydrogeomorphological studies. This process allows for the interpretation of the intensity and velocity of surface runoff, as well as the time required for water to accumulate within a basin from higher to lower elevations (Laborde, 2000). Steeper slopes shorten the time needed for water to reach tributaries, resulting in rapid, near-instantaneous runoff that may develop into sudden and violent surges (Amrani *et al.*, 2021).

4.2 Geological and soil factors

The characteristics of geological formations are among the most important factors explaining the nature and patterns of water flow, as the hydrological response of a basin during rainfall events is closely related to the type and spatial distribution of rock formations. Consequently, morphostructural analysis of drainage basins is essential for understanding how geological and geomorphological factors contribute to the acceleration of surface runoff and the generation of floods.

Geological features are an essential factor in watershed studies. Thus, the surface runoff will be higher, and the intensity of water flow and flooding events will increase as the underlying geological formations become more impermeable, which in turn increases the intensity.

Numerous studies conducted in the southern regions in general, and in the Souss basin in particular (Dresch, 1941; Roche, 1963; Ambroggi, 1963; Oliva, 1972; Weisrock, 1980; Bouzalim, 1987; Ouahman, 1993; Ait Hssaine, 1994; 2000; Saidi, 1994; Chakir, 1997; El Mehdad, 2003; Charif *et al.*, 2014), confirm that geological studies focus on determining the nature, structure, permeability, and structural position of rock formations.

In terms of structure, the Aouerga watershed falls within the western Anti-Atlas and is primarily made up of Precambrian geological formations, with calcareous and dolomitic rocks from lower Adoudounian age making up 43.83% of the catchment area. Other dolomitic, calcareous and violet-shelled formations of Taliwinian age occupy 13.85% of the surface (Charif *et al.*, 2014).

From a hydrological point of view, the Aouerga River is deeply incised into formations that constitute a softer level within the calcareous–dolomitic massif, forming a drainage system and a vast, elongated basin (Saidi, 1995). Despite the fact that the main rock units of this catchment are characterized by high permeability, this does not prevent rapid surface runoff, particularly in areas with low vegetation cover and the presence of steep slopes. The intensity of surface runoff in these areas increases when rainfall persists for several days (more than two days) or when intense thunderstorms occur, often leading to devastating floods. This is supported by data from meteorological stations and records of floods that have affected the region, notably in 2010, 2014, 2018, and 2026.

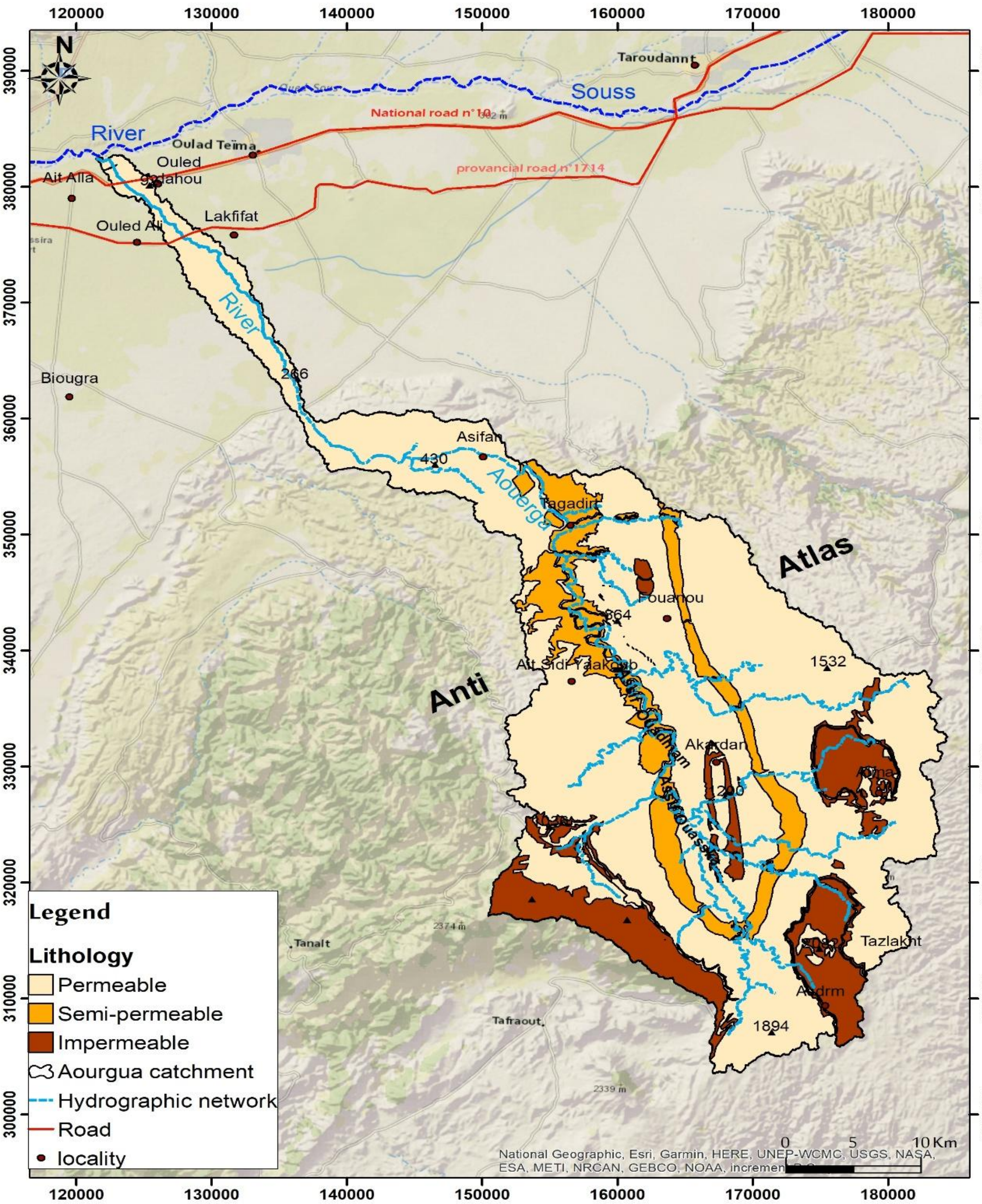

Figure 4. Lithological map of the Aourgua basin.

Figura 4. Mapa litológico da bacia de Aourgua.

4.3 Hydrographic network characteristics

The importance of studying the hydrographic network lies in its ability to facilitate comparisons between drainage basins by identifying all tributaries of the main hydrographic network. It also helps to clarify the relationships among the different components of the network (Laborde, 2000). Determining the characteristics of a basin's hydrographic network involves calculating a set of indicators, primarily related to drainage density and stream frequency (hydrographic density), as well as assessing the network's structure, degree of development, and flow coefficient.

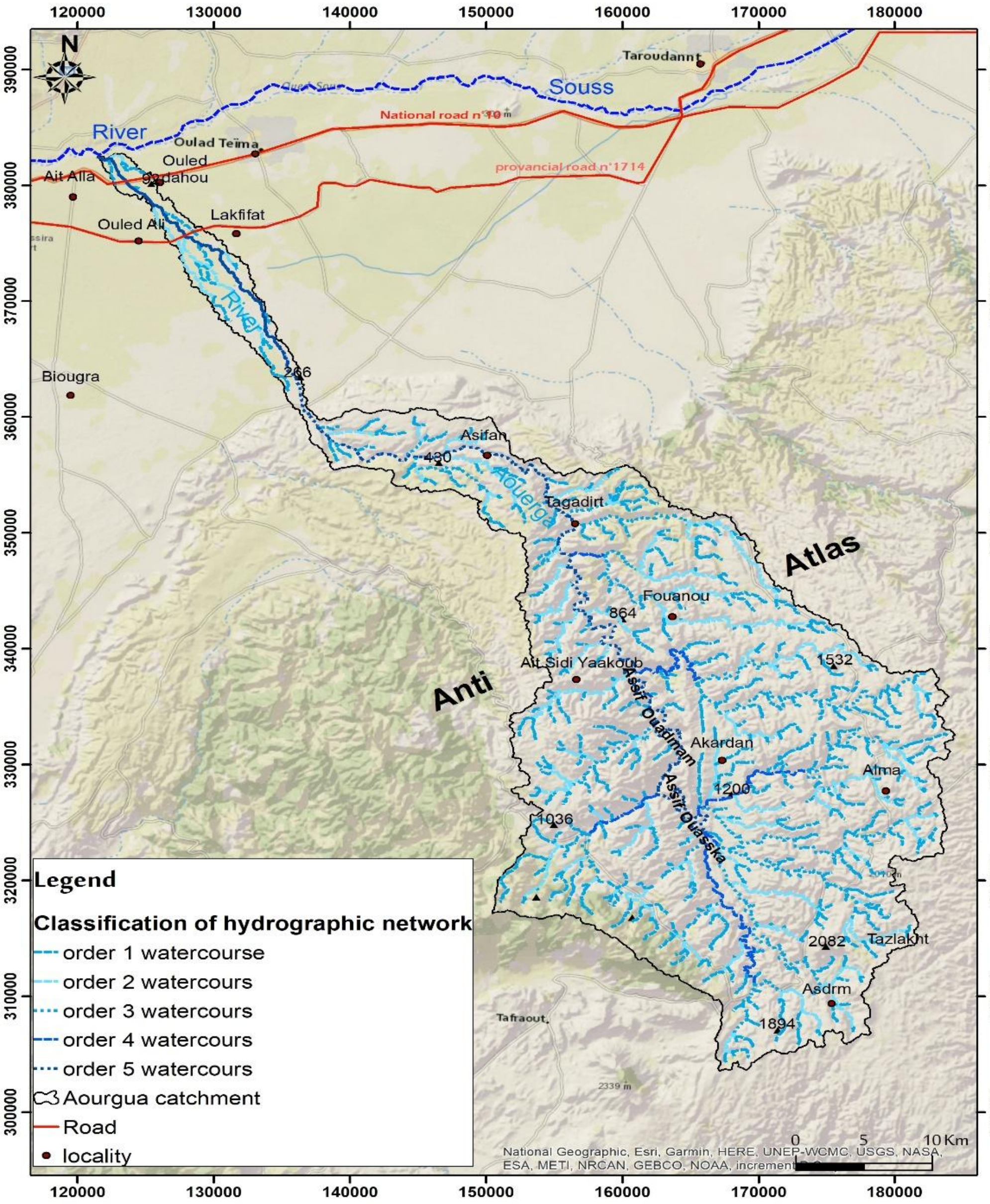

Figure 5. Hydrographic network map according to the Horton-Strahler system (DEM 30 m).

Figura 5. Mapa da rede hidrográfica segundo o sistema de Horton-Strahler (MDE de 30 m).

The hydrographic network of the Aouerga Basin is of the dendritic type (Figure5). The main watercourse in the study area is fifth order. The principal stream of the Oued Aouerga watershed extends for 101 km from its headwaters to the outlet and is characterized by a sinuosity coefficient of 2.43, indicating the presence of pronounced meanders.

Furthermore, the basin's morphometric indicators, such as mean gradient, total gradient index, and specific elevation, show high values, indicating widespread steep terrain. In particular, the specific elevation index reaches 373,3 m. According to the ORSTOM classification, these characteristics place the Aouerga watershed in class six, which is reserved for rugged terrain.

Table 4: Distribution of Hydrographic Network Features in the Aouerga Basin.

Tabela 4: Distribuição das características da rede hidrográfica na bacia de Aouerga.

Hydrographic network parameters	Results
Area (km^2)	1283,52
Total number of watercourses	479
Total length of water network (km)	1254,4
Drainage density (Dd) km/km^2	0.97
Stream frequency (Fs) (km^{-2})	0.37
Stream order	5
Water concentration time (h)	10.68h
Runoff speed V (m/s)	2.62
Flow coefficient	0.27

Source: ASTER DEM 30 m

The average drainage density is relatively low at 0.97 km^{-1}. However, this value is higher in specific sub-basins characterized by highly branched flow patterns. These patterns are driven by topographic and litho-climatic conditions that favor the development of hydrographic networks. The stream frequency is moderate, averaging 0.37 km^{-2}. (Table 4).

Picture1: The Aouerga's main channel at its lowest point following the drainage of floodwaters.

Foto 1: O canal principal do Aouerga em seu ponto mais baixo, após o escoamento das águas de cheia.

Watershed hydromorphometric indices play a significant role in controlling their hydrological behavior. The drainage and hydrographic density are low due to its geological characteristics, which are represented by the presence of permeable carbonate rocks, especially dolomite. However, the water flow in this catchment is characterized by a runoff speed and concentration time of 2.62 m/s and 10.68 h, respectively. The mainstream and its tributaries' generally sloped nature, as well as the degradation of vegetation cover in most of the watershed area, cause this problem (Picture1).

4.4 Climate (rainfall) factor

Rainfall is an important factor in the functioning of watersheds. In order to study the distribution of annual and monthly rainfall over time and space, this study was based on data provided by NASA, due to the absence of measuring stations in the area under study. We recall that NASA's digital platform only provides monthly and annual data; for this, we were obliged to use the data from the Sfa station, near the Aouerga basin, which provides daily recordings.

The climate in the region changes from arid downstream to semi-arid upstream, as indicated by De Martonne's climate data and aridity index (Mohamed, 2025). The annual average rainfall in the Aouerga basin 219.8 mm. For a period of 31 years (1987-2018), annual maximum rainfall was recorded in 1995, 2009, and 2010, reaching more than 440 mm. While the lowest rainfall was recorded in two years, 2011 and 2017, reaching, respectively, 57.7 and 75.2 mm (Figure 6). The results of the analysis showed that the quantities recorded during the 32 years in Sfa were below the annual average, compared to only 15 years where rainfall was above the average.

Figure 6 shows that November recorded the highest monthly average over the period from 1981 to 2019, with a value of 46.45 mm, followed by December with a value of 42.61 mm.

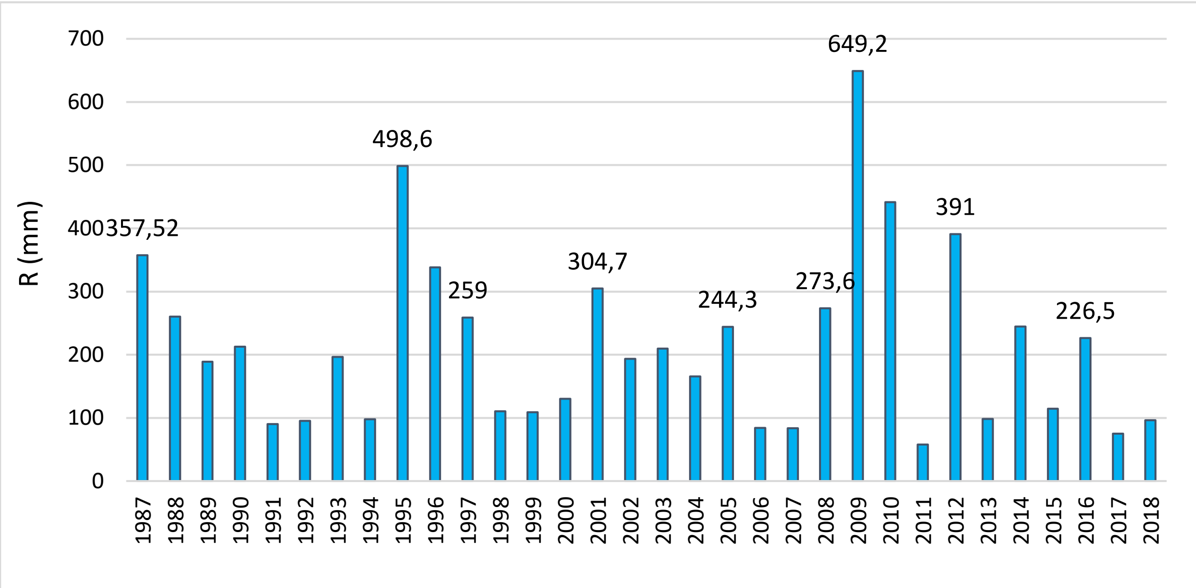

Figure 6: Annual rainfall recorded in the SFA station between 1987 and 2018.

Figura 6: Precipitação anual registrada na estação SFA entre 1987 e 2018.

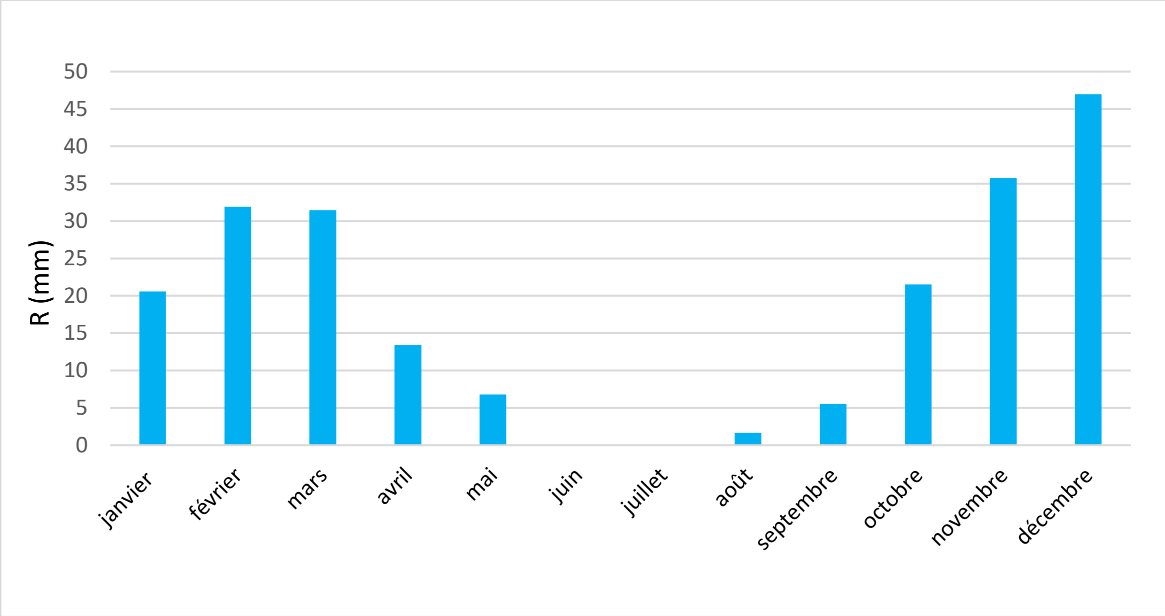

Figure 7: Average monthly rainfall recorded in the SFA station between 1987 and 2018.
Figura 7: Precipitação mensal média registrada na estação SFA entre 1987 e 2018

For daily maximum rainfall, we relied on data from the extended period of 1977 to 2019 for the weather station of Amaghouz located southwest of the Aouerga watershed, due to the quality of its data and the almost total absence of gaps in relation to the two neighboring stations (Ahl Souss Dam and N'Guerf).

This shows that rainfall in the region is characterized by year-over-year irregularities due to the impact of two types of influences: north and northwest influences on one side, south and southeast on the other side (Quarro *et al.*, 2011). The climate of the region is also influenced by other important factors, namely topography and slope exposure. The north and northwest slopes receive the humid winds of the Atlantic Ocean, while the south and southeast slopes are exposed to the dry winds of the desert (Chergui).

The average monthly rainfall is unevenly distributed from month to month. In general, two different periods can be distinguished: the wet period extends from October to April, and the very low rainfall and sometimes dry period from May to September, as shown in Figure 7.

The average maximum daily rainfall is about 44.8 mm. The results of the analysis showed that in the last 18 years (2002-2019), some years have recorded exceptional amounts well above the annual average. This gives a general trend of increase, and also explains the very extreme floods that occurred during this period, in particular, the 2002, 2010, 2014 and 2018 floods, which recorded 89.8, 66.8, 155.3 and 57.1 mm respectively (Figure 8).

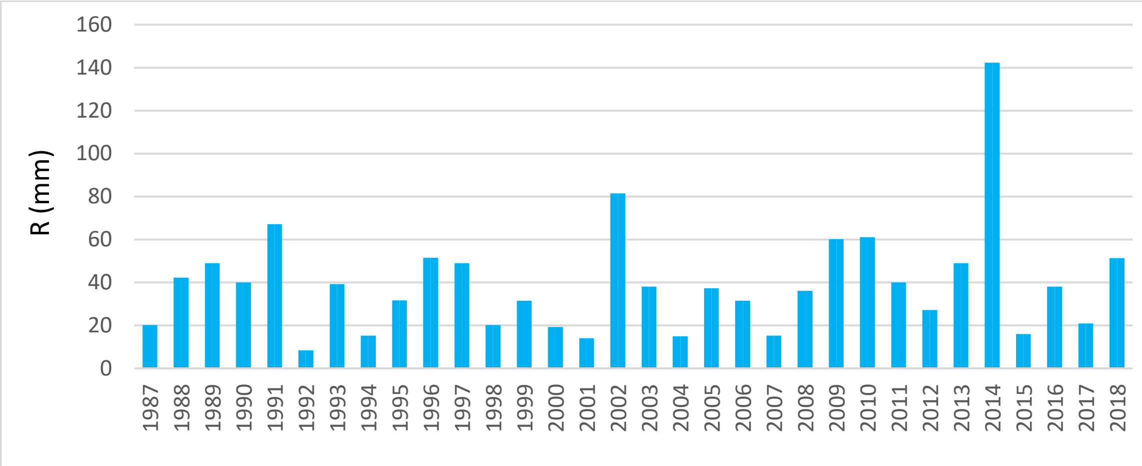

Figure 8: Maximum daily rainfall at the SFA station between 1987 and 2018.

Figura 8: Precipitação diária máxima na estação SFA entre 1987 e 2018.

It seems that the maximum daily rainfall, which exceeded the annual average for 43 years, occurred 19 times, compared to 24 times below the average. These maximum rains are unevenly distributed over the months, and concentrated mainly in the months of November, January and February. Therefore, most devastating floods known in the region occur during the three months mentioned, due to extreme daily rainfall that sometimes reaches more than 155 mm in a few hours.

Return periods or return times (Meylan & Musy, 1999) of maximum daily rainfall, according to the Ln-normal law, are indicated in Table 5.

Table 5: Return period of maximum daily rainfall according to the Ln-normal law.

Tabela 5: Período de retorno da precipitação diária máxima segundo a Lei Ln-normal.

Frequency	1 /2	1 /5	1/10	1/20	1/50	1/100
Return Period (years)	2	5	10	20	50	100
Daily Max Rain	33.1	54.9	71.7	89.2	114.2	134.7

Source: Sfa Station, ABHSM

4.5 Impact of torrential flood on the commune of Ouled Dahou

The Aouerga flows in a south-east-northwest direction for approximately 24km from the outlet at the foot of the northern slope of the Anti-Atlas at Tagounite to the Souss River. Before entering the Souss River, it passes through three rural communes (Imi Mqourn, Ahl Reml, and Lakfifat) and finally reaches the commune of Ouled Dahou. During its discharge, it traverses a landscape that is divided into agricultural land and farmland, including provincial road n°1714 and national road n°10 (Picture 2).

Picture 2. Extensive flooding in Ouled Dahou during the 2018 flood, where water inundated residential areas and neighborhoods almost completely. It reflects the intensity of the hydrological event and the limited drainage capacity of the area in the face of extreme rainfall (a). Significant damage to infrastructure, particularly roads, as a result of flooding, which disrupted transportation within the area. It also shows the impact on local economic activities due to interrupted mobility and reduced access to services and facilities (b). (Source: Technical Department of the Territorial Commune)

Foto 2. Inundações extensas em Ouled Dahou durante o evento de cheia de 2018, quando a água cobriu quase totalmente áreas residenciais e bairros. Isso reflete a intensidade do evento hidrológico e a capacidade de drenagem limitada da área diante de chuvas extremas (a). As inundações causaram danos significativos à infraestrutura — particularmente às vias —, interrompendo o transporte local. O episódio também ilustra o impacto nas atividades econômicas locais decorrente da interrupção da mobilidade e do acesso limitado a serviços e instalações (b). (Fonte: Departamento Técnico da Comuna Territorial).

Due to its superficial bed and the absence of protective walls, the Aouerga river loses its course in the northwest of the Lakfifat commune. This distance is almost 2km before reaching provincial road n° 1714, at a distance of about 6,8km, to extend over large areas, especially when large floods occur with high flow.

Downstream, the Aouerga river is shaped like a cone of waste consisting of very calcareous silty deposits (Watteeuw, 1964). This situation allows the appearance of diffuse surface runoff during floods; this makes rural centers (Ouléd Dahou and Lakfifat) and agricultural areas exposed to the floods of the Aouerga river.

The spatial distribution of flood risk within the Aouerga basin is classified into high, moderate, and low-risk zones. High-risk areas (red) are mainly concentrated along the central drainage channels and near several settlements, indicating strong exposure to runoff accumulation and possible flash flooding. Moderate-risk zones (orange) surround the main channels, while low-risk areas (yellow) are generally located on the basin margins and elevated terrain (Figure 9). The distribution of risk clearly follows the hydrological network, showing the important influence of topography and water flow on hazard intensity. This map is useful for identifying vulnerable areas and supporting land-use planning and flood management strategies.

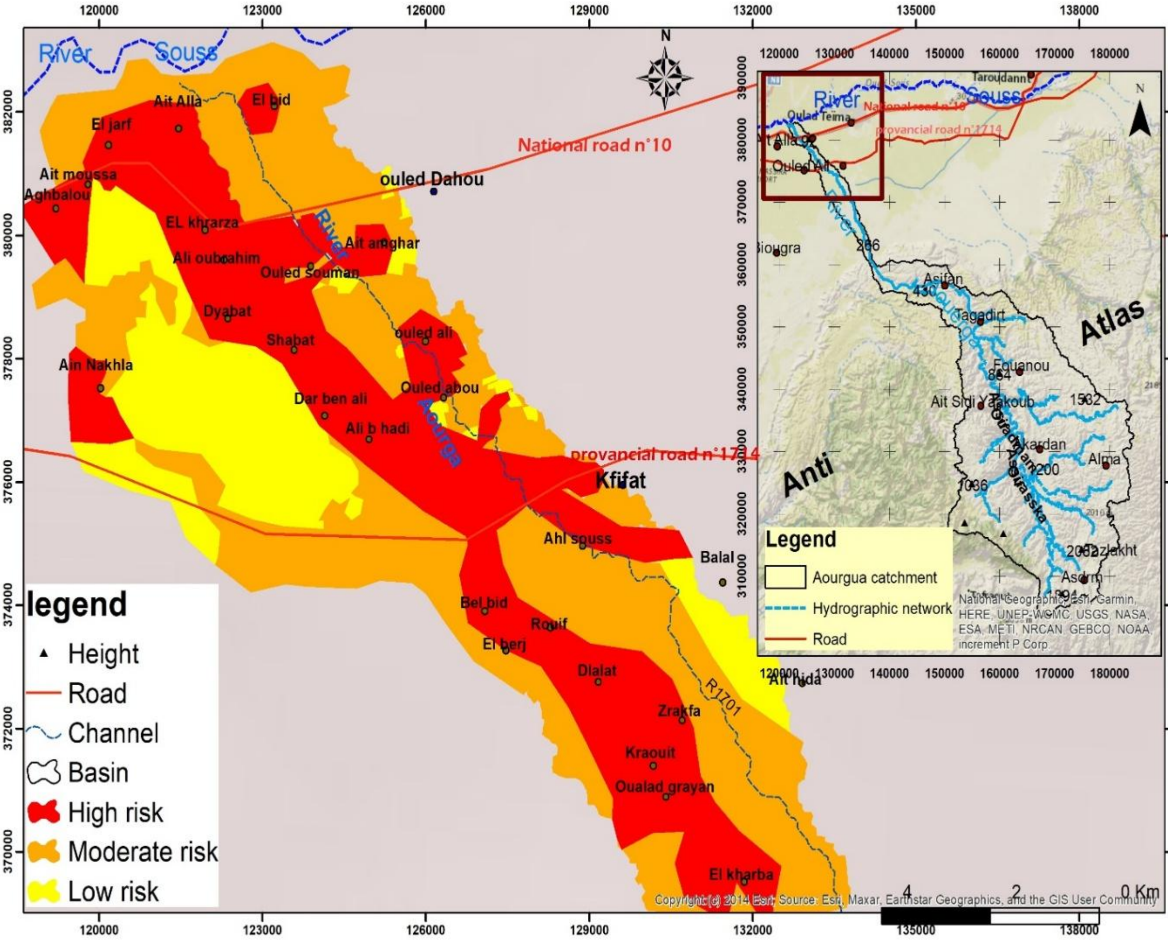

Figure 9: Flood risk areas in the Ouled Dahou commune.

Figura 9: Zonas de risco de inundação na comuna de Ouled Dahou.

5. Discussion

The morphometric characteristics of basins, along with their topographical features, directly influence the hydrological response of a watercourse. Several processes vary with elevation, including climatic factors and the rate at which runoff concentrates on slopes. In this context, analyzing morphometric characteristics in combination with topographic attributes helps clarify the conditions of basin evolution in relation to hydrodynamic, climatic, and structural factors. Such analysis also enables the assessment of a basin’s capacity for water intake and storage, as well as its discharge potential—key elements that contribute to the formation of flash floods.

Looking at the shape and physical characteristics of a watershed is really important to understand how it affects the risk of flooding. Watersheds with features and steep slopes near the top tend to make water run off the surface quickly, which can cause really bad flooding in the areas downstream. Usually, the more of a watershed that's high up, the more likely it is to have problems with water, like flooding, as shown by El-Amrani *et al.* (2021). Watersheds with a lot of ground are just more prone to flooding. These conditions result from the interaction of several factors, including geological structure and climatic conditions, which govern geomorphological processes and ultimately shape the development, topography, and morphological characteristics of hydrographic basins.

This phenomenon can be attributed to the accumulation of water within the narrow, closed sub-basins in the upstream area, followed by its rapid discharge toward residential zones located in the middle and lower parts of the basin. This accelerated flow often results in significant social and economic impacts on these vulnerable areas.

Based on the results, we are proposing two key projects to reduce and mitigate the effects of devastating torrential floods.

- ✓ **Develop the upstream to protect the downstream:** The upstream development works aim at reducing the flow rate of surface water, including the construction of small drainage dams or flood-break dams, the achievement of thresholds at the main tributaries of the Aouerga river, the construction of a large dam on the main watercourse to benefit from it for water supply, reforestation of degraded bare slopes and steep slopes, as well as raising awareness of the importance of vegetation cover for soil erosion and degradation control, and for the sustainability and balance of ecosystems.
- ✓ **Downstream protection work:** Downstream protection works require the construction of a main canal or artificial stream to divert the flow from the Ouled Dahou Ued outside the Ouled Dahou center to its mouth at the Souss river. Road crossings and bridges must also be constructed to standards and dimensions that allow for the passage and flow of large flood volumes (rare and exceptional floods), with return periods of 20 to 50 years or more. These types of floods can be considered as reference or project floods.

6. Conclusion

From the above discussion, the study demonstrates that the Aouerga watershed possesses a set of highly interconnected physical and anthropogenic characteristics that create favorable conditions for the development of intense surface runoff and the occurrence of devastating flash floods. The arid and semi-arid climatic context, marked by irregular but highly concentrated rainfall events, combined with steep slopes, fragile lithological formations, weak vegetation cover, and intense erosion processes, significantly accelerates the hydrological response of the basin. These natural factors are further aggravated by human activities such as deforestation, inappropriate land use, expansion of settlements in flood-prone areas, and insufficient hydraulic infrastructure, all of which contribute to increasing the destructive power of flood events within the watershed.

The analysis carried out in this study confirms that flash floods in the Aouerga basin cannot be explained by a single factor, but rather by the interaction of several geomorphological, climatic, hydrological, and socio-economic processes. The combination of these elements increases both the vulnerability of the territory and the degree of exposure of local populations, agricultural lands, transportation networks, and infrastructure to flood hazards. As a result, even short-duration rainfall events can generate rapid and violent floods capable of causing significant human, material, and environmental losses. This situation highlights the urgent need to better understand the mechanisms governing flood generation in arid and semi-arid environments in order to improve prevention and mitigation strategies.

Furthermore, the study underlines the importance of integrating watershed-scale management into flood-risk reduction policies. Effective protection against torrential floods in the Aouerga watershed requires interventions not only at the level of the downstream communes affected by flooding, but also throughout the upstream catchment areas where runoff processes originate. Soil conservation measures, reforestation programs, slope stabilization, and erosion control strategies should therefore be considered essential components of any sustainable flood-management plan. These actions would contribute to reducing runoff velocity, improving water infiltration, and limiting sediment transport during extreme rainfall events.

At the same time, local planning and infrastructure development must be adapted to the hydrological realities of the basin. The improvement of drainage systems, the rehabilitation and maintenance of river channels, the construction of protective hydraulic structures, and the regulation of urban expansion in vulnerable zones are all necessary measures to facilitate the safe conveyance of floodwaters and minimize damages. In addition, strengthening early-warning systems, raising public awareness, and improving emergency preparedness can play a crucial role in reducing the impacts of future flood events on local communities.

Ultimately, this research emphasizes that flood-risk management in arid and semi-arid basins such as the Aouerga watershed must adopt an integrated and multidisciplinary perspective that combines environmental management, territorial planning, and socio-economic development. Considering the increasing pressures associated with climate variability and human activities, the implementation of sustainable and coordinated management strategies has become indispensable for enhancing the resilience of local populations and reducing the devastating consequences of flash floods in the region.

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