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Analyzing the Influence of Morphometric Characteristics on Hydrological Response: A Case Study from Morocco

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Abstract

This article focuses on analyzing the relationship between the hydrological response and the morphometric characteristics of the Tamri watershed, located in the Western High Atlas of Morocco. The research seeks to answer a key question: how do the Tamri watershed's geometric and topographic features influence its hydrological behavior? Given the arid and semi-arid nature of the region, understanding these interactions is essential for effective water resource management and flood risk mitigation. The study utilizes a quantitative approach, integrating Geographic Information Systems (GIS) and remote sensing techniques to analyze morphometric parameters such as drainage density, basin shape, slope, and stream network. These analyses are based on a Digital Elevation Model (DEM), topographical maps, and relevant hydrological and climatic datasets. Additionally, a geographical approach is adopted to describe and interpret the relationships between the morphometric characteristics of the watershed and its hydrological response. The main results reveal that the hydrological response of the Tamri watershed is primarily influenced by the interaction between its geometric and topographic characteristics. High drainage density and steep slopes contribute to rapid runoff and increased flood risk. Furthermore, effective spatial management of arid and semi-arid watersheds depends on regulating surface water flow and optimizing the connection between upstream and downstream areas. These insights highlight the importance of integrating morphometric analysis into watershed management strategies to enhance resilience against extreme hydrological events in similar environments.

1. Introduction

Flood risk in the Mediterranean Basin is one of the most significant natural hazards, causing human and material losses as well as environmental degradation. This hazard ranks second only to earthquakes in terms of frequency [1-4]. In 2023, floods accounted for 32.4% of frequently occurring hazards in many regions worldwide [5]. Floods are among the major natural disasters occurring worldwide [6], and they remain one of the most pressing challenges faced by numerous countries across the globe.

Flash floods are one of the most exceptional hydrological phenomena. They are linked to the geographical location, the nature of the hydrographic basin, and the path of atmospheric disturbances [7]. Flash floods are also among the most significant hydroclimatic events that frequently recur in arid and semi-arid regions due to a combination of multiple factors. The nature of a flood depends on the region's topography, economic and industrial activities, and water storage methods [8].

Most studies [9-11] confirm that these hydroclimatic events cause significant losses, the magnitude of which varies from one country to another. Losses resulting from floods are equally high in both developed and developing countries [12] Flood exposure includes assets and valuables in flood-prone areas, ranging from land cover and land use to human lives, livestock, and both residential and agricultural interests [13-14]. Climate change, alterations and degradations occurring in river basins, adverse interventions in stream beds and flood control structures, the use of flood-prone areas for various purposes, unplanned urbanization, road and railway networks, and inadequately designed infrastructure structures are among the main factors that exacerbate flood disasters and their impacts [15]. According to climate modeling by Arnell and Gosling in 2016, it is predicted that 450 million people will be at risk of flooding in 2025, and the flood risk ratio will increase to 187% [16].

In this regard, Morocco, due to its geographical location in the southern Mediterranean basin and its turbulent climatic characteristics, has become known for its high frequency of natural hazards associated with extreme hydrological conditions [17]. This location results in significant rainfall that is concentrated both temporally and spatially, contributing to rapid surface runoff and a consequent rise in the water level of the oueds in the basins. Moreover, Morocco experiences variations in both the quantity and quality of rainfall from one region to another, a situation that can lead to prolonged droughts and an increased frequency of flash floods [18-21].

Extreme climatic events (droughts, floods) have always been part of Morocco's history, with an increasing frequency since the 1980s. In this context, Morocco entered a new and exceptional climatic situation in September 2008, which continues to this day with significant and sometimes increasing intensity [22]. Between 1960 and 2020, several regions in Morocco experienced severe flash floods. Among the most violent were those recorded in 1963 in the Gharb Plain; in 1965 in the Ziz in Errachidia; in 1995 in the Ourika region of Marrakesh; and in 1997 in El Hajeb. In addition, notable floods occurred in Settat and Mohammedia in 2002; in Tan-Tan, Nador, Al Hoceima, and Khenifra in 2003; and in Casablanca in 2010. Moreover, the southern regions of the country were struck by floods in 2014 (affecting areas such as Guelmim, Tiznit, and Taroudant), and the Tizirt floods occurred in the Imi Ntiart commune in Taroudant province in September 2019.

Several studies indicate that the frequency of floods in Morocco has increased significantly. Between the years 1999 and 2009, the country experienced 15 major floods, which left 1068 dead and affected more than 146,400 people. The damage caused by these floods was very considerable [23]. Additionally, the southern regions of Morocco have been classified among the fifty areas most threatened by flash floods due to a combination of environmental and climatic factors that heighten the risk [24].

The underlying causes of flash floods are diverse [25]. However, the morphometric characteristics of hydrographic basins combined with climatic factors are among the most important elements controlling the acceleration of surface runoff in catchments. These characteristics differ from one basin to another due to variations in the rocky substrate and bioclimatic conditions, as well as differences in the geomorphological and topographical features of the watercourse. Analyzing drainage basins through morphometric parameters is essential for effective watershed planning. It offers insights into basin slope, topography, soil conditions, runoff behavior, and surface water potential [26].

Therefore, the study of the physiographic characteristics of watersheds is of great interest to hydrologists and geomorphologists due to their influence on hydrological behavior. Moreover, the relationship between watershed physiography and flow characteristics makes it essential to understand watershed morphology prior to any hydrological study [27]. The morphometric characteristics of basins directly influence the hydrological response of watercourses. In addition, various microenvironments that change with elevation affect climatic elements and accelerate runoff concentration in foothills [28].

This study provides an understanding of the hydrological and morphological characteristics of the Tamri watershed in the Western High Atlas of Morocco by highlighting the importance of analyzing the basin's morphometric parameters. Morphometric analysis is an effective approach for understanding the interaction between different geographical features within a region [29-30]. Furthermore, the morphometric analysis of watersheds in arid regions is an important topic that can reduce the risks associated with flooding and integrated water resources management [31-32]. The analysis of morphometric parameters provides an accurate scenario of the hydrological behavior of a watershed, especially in ungauged watersheds [33-34].

The objective of this paper is to study ungauged watersheds, determine their hydrological response to rainfall events, and identify the most suitable areas for installing hydraulic structures and water storage systems to reduce the risk of flooding.

Thus, numerous papers have been conducted on morphometric analysis using remote sensing and GIS approaches, which have been applied in various geographical environments [35-37]. However, our study area is arid, where rainfall and runoff are not measured. Understanding the hydrological behavior of watercourses is essential for better water management during periods of both scarcity and abundance. Therefore, in this study, we relied on the analysis of the basin's morphological characteristics using remote sensing tools and GIS approaches to estimate the hydrological response of watercourses.

In this regard, an integrated study of the basin's geometric and topographical characteristics can provide valuable insights into its evolution in relation to hydrodynamic, climatic, and structural factors. This approach helps determine the basin's capacity to receive, store, and discharge water, with the aim of mitigating the risk of flash floods in the area.

2. Method

A comprehensive hydraulic study necessitates a systematic analysis and integration of fundamental parameters such as spatial geometry, flow discharge, and boundary conditions, to construct an effective hydraulic model [38]. In the field of geomorphology, morphometric indices serve as the primary metrics for evaluating the hydrological potential of watersheds and for comparing their morphological features [39]. Streamflow response to rainfall is influenced by various characteristics of the watershed [40].

2.1. Study area description

The Tamri watershed covers an area of 1,747.11 km^2 and is situated in the western High Atlas, north of Agadir.

It is located between 30°40’ to 31°06’ N latitude and 9°09’ to 9°50’ W longitude. The Tamri hydrographic system drains all the water falling on the slopes of the western High Atlas Mountains. It comprises two sub-basins: Oued Aouegar, which covers an area of approximately 1,243.81 km², and Oued Amalou, which extends over an area of about 410.43 km². The elevation in the Tamri watershed ranges from 0 m downstream at the Atlantic Ocean to 1,791 m upstream in the basin. About 80% of the area consists of mountains covered with diverse plants and agricultural activities, particularly banana and vegetable cultivation, which is concentrated in the lower areas along river terraces (Figure 1).

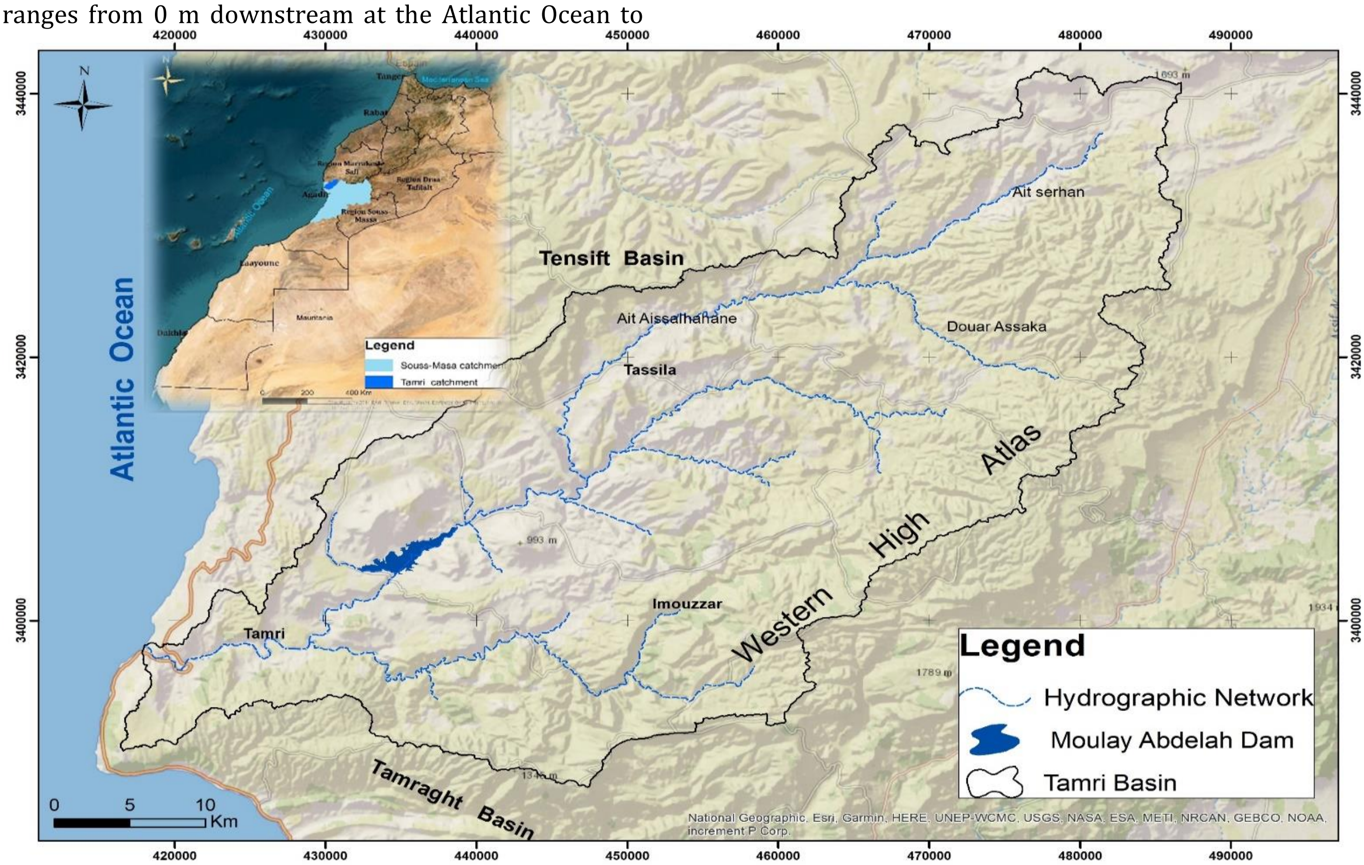

Figure 1. Geographical location of the Tamri watershed

The Tamri Basin is characterized by a semi-humid climate. This area experiences strong seasonal contrasts and significant irregularities in precipitation. The average daily temperature in the Tamri watershed is 21.2°C, and the average annual rainfall is approximately 493 mm. winters are relatively cool, with maximum rainfall occurring in October and November. The Tamri streams flow from northeast to southwest, eventually reaching the Atlantic Ocean.

2.2. Tools and software

Hydrological modeling plays a crucial role in understanding the complex relationships between rainfall and runoff processes, enabling accurate assessments of surface runoff [41]. This study aims to analyze the morphometric parameters of watersheds located in an arid region by using a Geographic Information System (GIS) to identify various watershed characteristics. The selected parameters represent watershed morphology and impact hydrological response. We utilized a 30-meter resolution Digital Elevation Model (DEM) of the 12.5 North zone to create slope, hypsometric, and hydrographic maps. Data processing was conducted with Arc Hydro, a set of tools integrated within the GIS software.

The Arc Hydro utility enabled us to perform multiple operations, such as delineating and characterizing watersheds in both raster and vector formats, defining and analyzing the geometric hydro network, managing time series data, and exporting data to digital models. Additionally, we used topographic maps of Imouzare, Taghazout, and Tamanar at a 1:100,000 scale, along with the geological map of Morocco at the same scale. These tools allowed us to determine the area, perimeter, Gravelius compactness index, equivalent rectangle, slope, and specific altitude.

2.3. Watershed characteristics

The watershed is a natural hydrological unit, a topographically defined area drained by a stream system, from which runoff resulting from precipitation flows past from a point into a single stream [42]. The size of a watershed and the length of its stream drainage are important factors in hydrology and geomorphology [43]. (Table 1)

Table 1. Morphometric parameters formulas used in this study

Morphometric parameters	Formulas and description	References
Watershed area **A (km^2)**	A = Lx l where: L : Length of the bassin (km); l : width of the bassin (km)	[39]
Watershed Perimeter **P (km)**	P = (L+l)x2 where: L : Length of the bassin (km); l : width of the bassin (km)	[39]
Gravelius compactness index ***KG***	$KG \approx 0.28.\ P/\sqrt{A}$ where: A = watershed area in km^2; P = perimeter (km)	[44]
Length (*L*) and width (*W*) of the equivalent rectangle (km)	$Leq = (KG\sqrt{A})/1.12x[1+\sqrt{(1-(1.12/KG)^2)}]$ $Weq = (KG\sqrt{A})/1.12x[1-\sqrt{(1-(1.12/KG)^2)}]$	[45]
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 corresponds to 95% of the watershed (m); L = length of the equivalent rectangle (km)	[46]
Specific elevation ***Ds***	$Ds = Ig.\sqrt{A}$ where: Ig = overall slope index (m/km) ; A = watershed area in km^2;	[47]
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).	[48]
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	[49]
Drainage density ***Dd(km/km²)***	$Dd = \Sigma L/A$ where: L = total length of stream (km); A = watershed area in km^2	[50]
Stream frequency **Fs (N/km2)**	$Fs = \Sigma N/A$ where: N = total number of stream; A = watershed area in km^2	[50]
Cumulative indicator **(Ci)**	$Ci=Nx/Nx+1$ where: Nx: Number of watercourses of rank x Nx+1: Number of watercourses of rank x+1	[50]
Longitude Indicator **(Li)**	$Li=Lx+1\ /Lx$ where: Lx+1 Average length of 1+X watercourses Lx: Average length of X grade watercourses	[50]
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)	[51]

3. Results and discussion

3.1. Geometric characteristics

The geometric characteristics of a watershed are crucial for analyzing and understanding hydrological risks. These features influence water flow behavior, which is also determined by the basin's geological formations, climatic conditions, topographic characteristics, and land use. Basins with a circular shape tend to have irregular flow over time and high drainage rates that decrease rapidly from upstream to downstream. In contrast, longitudinal catchments are characterized by flow that is more consistent over time and lower drainage rates, allowing for greater water loss due to infiltration and evaporation, as well as the successive arrival of water from it branch along the watercourse. Surface water runoff is closely related to the geometric characteristics of the watershed and it sub-basins. Therefore, identifying these characteristics plays an important role in studying and interpreting hydrological risks. Thus, the area, perimeter, and shape of the basin play a crucial role in determining the hydrological response of basins and in guiding the behavior of surface water flow during extreme hydrological events. In order to create a hydrological model in this study, hydrological parameters are needed. Calculating these hydrological parameters is possible by determining hydrological soil groups, classifying the land, and creating a digital elevation model [52].

A watershed is the area of land where all the water that falls within it and drains from it converges to a common outlet. The area and shape of a watershed play a pivotal role in determining its hydrological response during flash floods. The catchment perimeter is the length of the outer boundary that encircles a catchment area, measured along the drainage divide between adjacent watersheds. The Tamri basin covers an area of 1747, 11 km^2, with a perimeter of approximately at 284, 34 km. (Table 2).

This parameter is valuable for assessing the shape and size of a catchment. By analyzing the perimeter length, hydrologists and geomorphologists gain insights into the form and characteristics of a catchment. The perimeter offers information on the extent and boundaries of the catchment area, facilitating a better understanding of its spatial distribution.

Table 2. Results of the calculation the morphometric characteristics of the Tamri watershed

Morphometric characteristics	Value
Watershed Area A (km^2)	1747,11
Watershed Perimeter P (km)	284,34
Gravelius compactness index (KG)	1,9
Length of the equivalent rectangle (L (km))	128,93
Width of the equivalent rectangle (l (km))	13,55
Length of the main watercourse (km)	54,03

The index recommended by hydrologists to characterize the shape of watershed is the Gravelius compactness index KG [27, 53]. KG index is allow to characterizing the geometrical configuration and the shape of the watershed. The Gravelius compactness index allows for hydrological interpretations and provides insight into the shape of watersheds. It indicates how close the basin is to a circular shape. When the value of this index is closer to 1, the catchment takes a circular form, meaning it is compact or clustered, with a rapid response during runoff events and a short time for water concentration. Conversely, if the index value is farther from 1, the basin assumes an elongated shape, resulting in a slower response. This configuration influences the surface runoff representing the response of the watershed to the rainfall it receives. This index allows for comparing the basin's perimeter to that of a circle with the same area [45]. Thus, the identification of this indicator in hydrological studies of hydrographic basins helps to anticipate the valleys' hydrological behavior and to employ it in the development of integrated geosynthesis programs for these basins.

The hydrographic basin of Oued Tamri is characterized by an elongated shape, as indicated by a compactness index exceeding 1, estimated at 1.9. Based on this index, the basin exhibits a weak hydrological response to rainfall. Similarly, the shape coefficient is low, estimated at 9.51. Therefore, analyzing the topographic characteristics of the basin is of great importance for interpreting its hydrological response.

This indicator is used to transform the hydrographic basin into an equivalent geometric form, typically a rectangle. Its significance lies in enabling comparisons between hydrographic basins to assess how their properties influence surface runoff [45]. The length of the rectangular equivalent of the Tamri watershed is estimated to be 128.93 km, while its width is approximately 13.47 km.

3.2. Topographical characteristics

Topography is an important component of resource inventory of a watershed [54]. Relief refers to the variation in elevation within a catchment area, defined as the difference between its highest and lowest points. This topographic aspect significantly influences the slope characteristics of a basin. Examining the hypsometric features of hydrographic basins offers valuable insights into the region's topography and the nature of its landforms. The analysis of topographical characteristics is essential for providing a comprehensive understanding of the basin's topography and the degree of its geomorphological development. Determining the elevations, slopes, and their orientation within the basin plays a crucial role in shaping its hydrological behavior and drainage system.

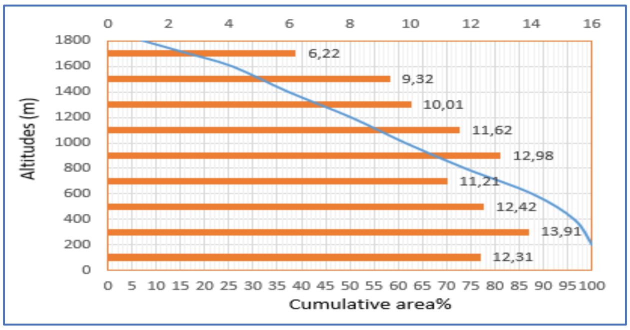

Figure 2. Hypsometric curve of the Tamri watershed

Table 3. Altitude classes

Altitude classes	Partial Area		Cumulative Area	
	Km^2	%	Km^2	%
1601-1791	108,71	6,22	108,71	6,22
1401-1600	162,78	9,32	271,49	15,54
1201-1400	174,85	10,01	446,34	25,55
1001-1200	202,96	11,62	649,3	37,17
801-1000	226,81	12,98	876,11	50,15
601-800	195,85	11,21	1071,96	61,36
401-600	216,97	12,42	1288,93	73,78
201-400	243,02	13,91	1531,95	87,69
0-200	201	12,31	1747,19	100
Total	1747,19	100	----	----

The hypsometric curve provides a comprehensive perspective on basin regression, serving as an important tool for comparing basins to identify similarities and differences. Constructing this curve involves plotting the basin's area on the X-axis and the altitudes categories on the Y-axis [49]. Hypsometric analysis describes the distribution of ground surface area, or horizontal cross-sectional area, of a landmass at different elevations [55-57]. The hypsometric curve or hypsometric integral facilitate estimation of hypsometric characteristics of the region/basin [55]. (Figure 2) and (Table 3).

Table 4. Topographical features of the Tamri Watershed

Topographical features	Value
Maximum altitude (H max (m))	1791
Average altitude (H avg (m))	882,11
Medianheight50%	1000
Minimum altitude (H min (m))	0
Altitude corresponding to 5%	1735
Altitude corresponding to95%	400
Overall slope index IG in m/km	10,35
Average slope of the main river (Sa) in %	13,51
Specific elevation Ds	432,61

Following the analysis of the Tamri Basin's characteristics, it has a significant internal area, indicating strong erosion activity and suggesting that the basin is still in its youthful phase. The hypsometric curve provides valuable insights, revealing the highest elevation within the study area at 1791 m in the northern part of the basin, and the lowest elevation at 0 m at its downstream outlet into the Atlantic Ocean. The altitude corresponding to 95% of the basin's area is 400 meters, while the altitude corresponding to 5% of the basin's area is 1735 m (Table 4).

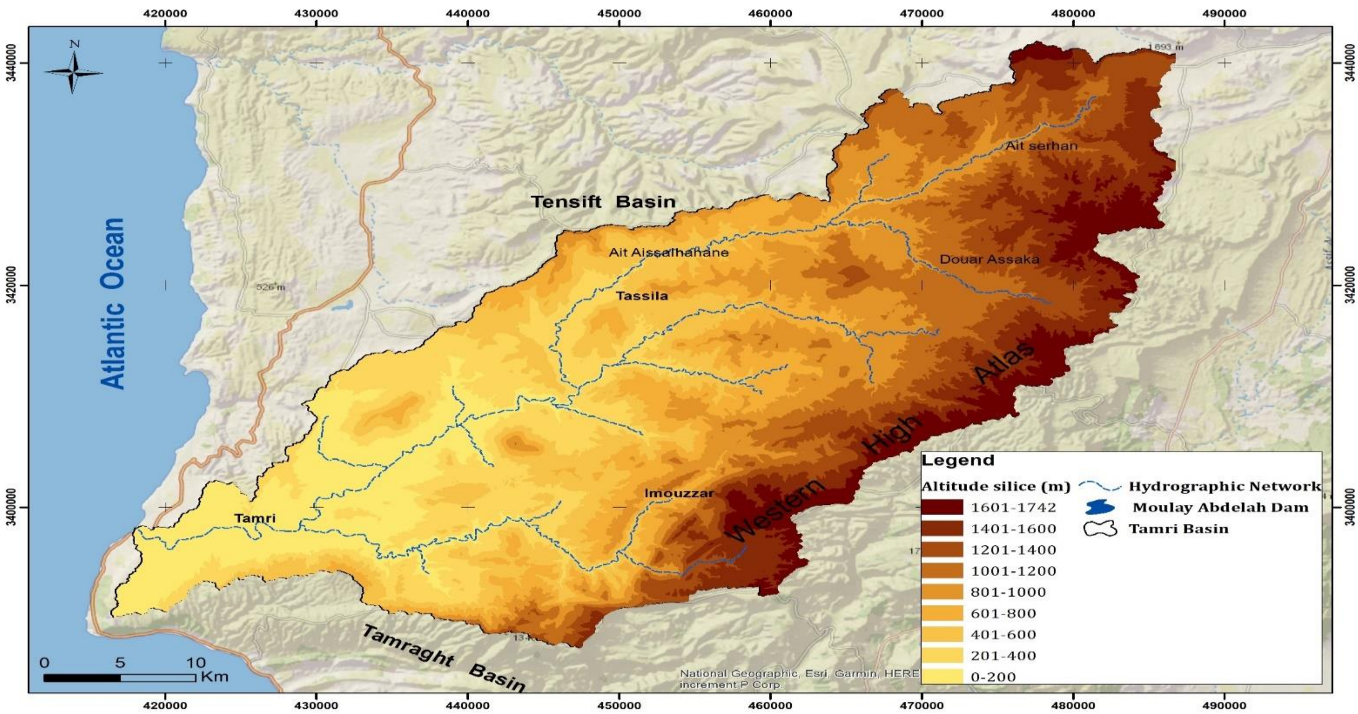

Figure 3. Hypsometric map in the Tamri watershed (DEM 30m)

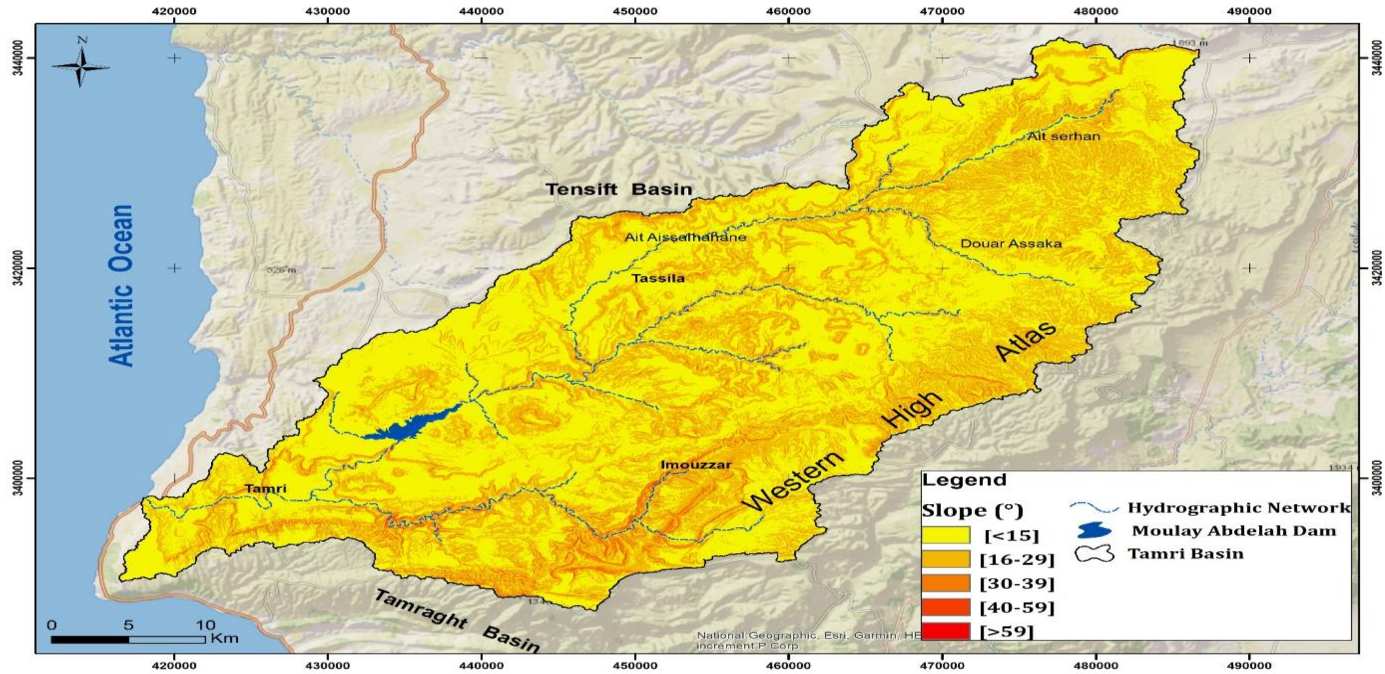

Figure 4. Slopes map in the Tamri watershed (DEM 30m)

Studying variations in hydrographic basin altitudes is crucial for hydrological analysis, as it provides valuable information about the basin's topography, indicates the time of runoff concentration, and highlights its impact on peak flow during rainfall events. Steeper slopes lead to faster runoff and shorter water concentration times within the basin (Figures 3 and 4).

Since soil groups can affect infiltration in different ways, they are an important factor influencing flood susceptibility [58]. In this context, analyzing the lithological formations and land use in the Oued Tamri watershed is crucial for understanding their hydrological response. Watersheds dominated by impermeable rocks are characterized by a predominance of surface runoff, whereas those composed of rocks that allow infiltration tend to exhibit reduced surface runoff. In the Tamri basin, permeable rocks—mainly limestone and dolomite—constitute 64.2% of the total area and are primarily concentrated in the northeastern and southeastern parts. Semi-permeable rocks, including sandstone, account for 28.6% of the basin and are mainly found in the western and northwestern parts. Impermeable rocks, such as clay and shale, extend across the central portion of the basin, covering more than 7.2% of its area. These spatial variations in rock permeability significantly influence the hydrological response of the Tamri basin, particularly during the wettest periods of the year.

3.3. Hydrological Response

The response of streamflow to precipitation is greatly influenced by watershed parameters [40]. The flow velocity and its rapid concentration are primarily determined by the combined effects of the slope system, the structure of the talweg network, and the shape of the watershed [59].

The analysis of the structure and hierarchy of a hydrographic network forms the foundation for understanding the geomorphological evolution of valleys. Classifying watercourses by rank provides insight into the development of the network and the drainage density. Typically, higher-order streams are fewer in number, while lower-order streams are more abundant. Mid-level streams are often found in areas with moderate to steep slopes, whereas first- and second-order streams are prevalent in steep terrains. These lower-order streams are characterized by high water velocities and short water concentration times, reflecting the rapid flow of water in such regions.

The Tamri Valley is distinguished by its channel, which progressively widens as it flows from the upstream toward the downstream. The Tamri Basin, along with its tributaries, includes several significant sub-hydrographic basins. On the right bank of the Tamri River lies the Ouekar Basin, originating in the highlands of Ait Daoud and flowing downstream, covering over 71% of the basin's total area (1,243.81 km²). In contrast, the Amalo Basin, located on the left bank of the Tamri River, extends approximately 410.43 km², representing 23.5% of the total basin area.

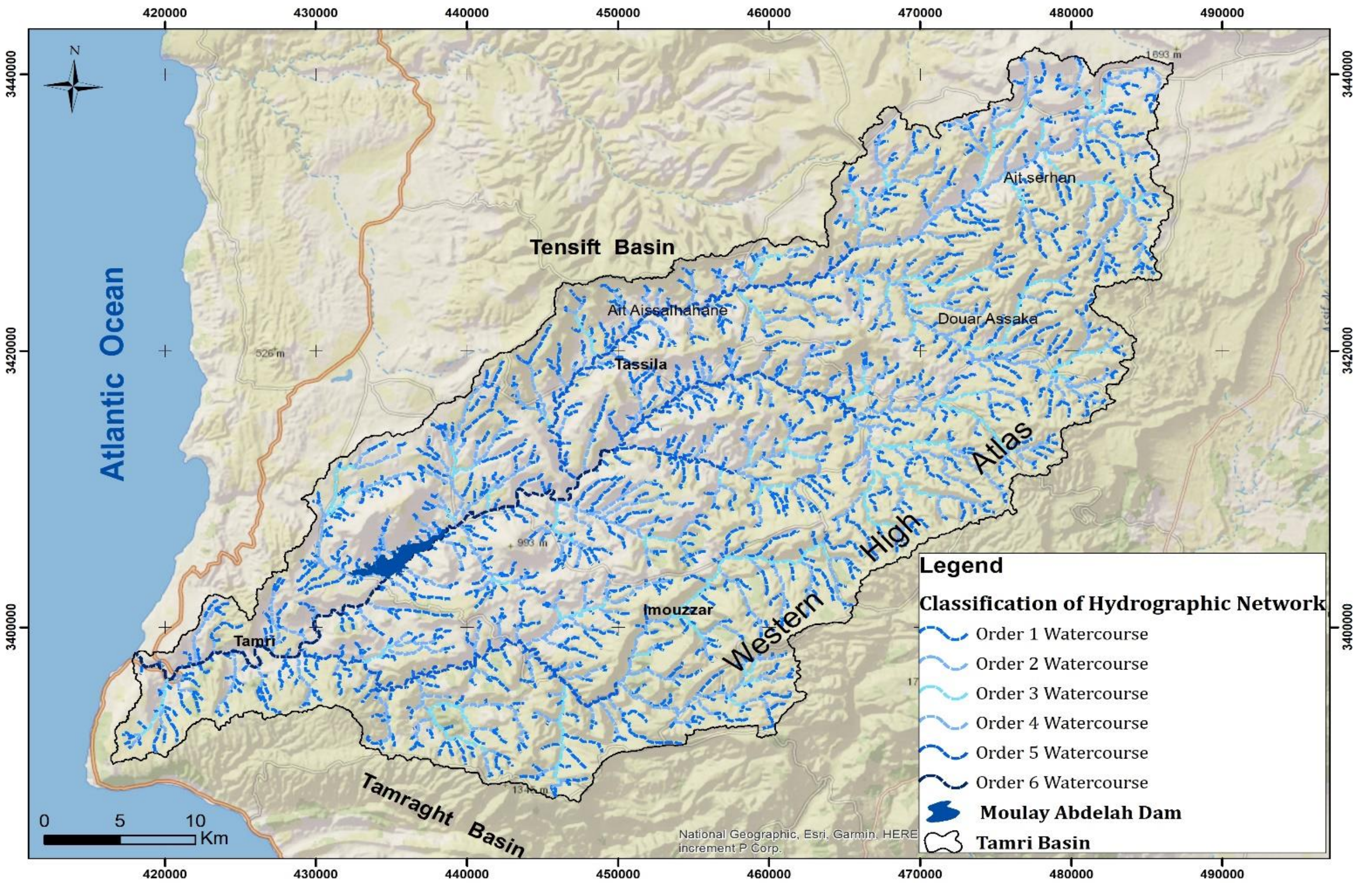

Figure 5. Hydrographic network classification map of the Tamri watershed (DEM 30m)

The concept of stream order, introduced by Strahler in 1957, is a fundamental tool for analyzing the geomorphology of drainage basins. This method evaluates the hierarchical structure of stream networks within a watershed. In the Strahler system, tributaries are classified by their order, starting with the smallest and most upstream streams, known as first-order streams, which are assigned an order of 1. When two first-order streams converge, they form a second-order stream. Similarly, the junction of two second-order streams creates a third-order stream. This hierarchical pattern continues, with higher-order streams forming as tributaries of the same order combine (Figure 5).

The morphometric analysis of the drainage basin and channel network play an important role in understanding the geo-hydrological behavior of drainage basin and expresses the prevailing climate, geology, geomorphology, structural antecedents of the catchment [60]. Thus, the analysis of hydrographic network ranks and lengths involves examining the gradient of tributaries within the basin, from the upstream to the downstream regions. The Tamri watershed is classified as a sixth-order basin, indicating that its main channel collects substantial amounts of surface water from its tributaries.

Table 5. Bifurcation ratio and streamlength ratio of Tamriwatershed

Steam order	Number of stream	Length of oueds (km)	Bifurcation Ratio (Rb)	Average length (km)	Stream length ratio (Rl)
1	1112	1066,16	---	0.95	1.97
2	276	520,89	4.02	1.88	1.83
3	60	207,05	4.6	3.45	2.39
4	15	124,08	4	8.27	3.40
5	4	112,79	3.75	28.19	1.85
6	1	52,41	4	52.41	----
Total	1468	2083,4	Average =4,074	----	----

The Tamri Basin comprises 1,468 streams distributed across six orders, with a total length of 2,083.4 km. The sixth order represents the main channel of the basin, stretching 52.41 km, while first-order streams constitute 75.74% of the total number of streams, with a combined length of approximately 1,066.16 km. These first-order streams are characterized by shallow surface flow and converge directly at the center of Tamri, contributing to the occurrence of sudden flash floods that inundate the banks of the main channel and encroach on certain human settlements (Table 5). Thus, in the risk assessment of flooding is crucial particularly in the mountainous area where the floods are mostly flash floods [61].

Drainage density refers to the total length of streams across all orders within a specific geographical area. This parameter offers valuable insights into the distribution and extent of the stream network within a watershed, enabling a detailed assessment of its hydrological characteristics. Typically, regions with low relief and dense vegetation exhibit low drainage density values. In contrast, high drainage density is often associated with weak, impermeable underlying materials, sparse vegetation, and mountainous terrains [62].

Table 6. Indices and characteristics of hydrographic network

Indices	values
Type of hydrographic network	dendritic
Stream order *Nu*	6
Total length of the water network (km)	2083,4
Total number of waterways	1468
Drainage density (Dd km/km²)	1,19
Stream frequency Fs (N/km2)	0,84
Time of concentration of water *Tc* (Hours)	10,44

Drainage density is a critical factor in shaping a basin's hydrological response. A high drainage density within the hydrographic network indicates a rapid runoff response, often leading to intense flooding (Table 6).

Hydrographic density refers to the ratio of the total number of watercourses in a basin to its total area. Stream frequency plays a critical role in the hydrological response of oueds. A high stream frequency indicates a dense network of watercourses, which facilitates rapid surface runoff during rainfall events, potentially leading to a faster hydrological response and an increased risk of flash floods. Conversely, low stream frequency often implies fewer channels to convey water, allowing for greater infiltration into the soil and delayed runoff, which helps moderate flood risks. Additionally, stream frequency influences sediment transport and erosion processes, shaping valley morphology and affecting water flow patterns.

In particular, the Tamri watershed exhibits a high drainage density of 1.19 km/km², attributed to the nature of the basin's carbonate rock formations and the influence of steep slopes. Regarding hydrographic density, the value for the Tamri watershed is 0.84 streams per km².

The bifurcation ratio (Rb) is defined as the ratio of the number of streams (Nμ) of a given order to the number of streams in the next higher order (Nμ+1) [56, 63]. The bifurcation ratio is influenced by the hierarchy of the hydrographic network, the shape of the basin, and its structural characteristics. Its significance lies in identifying variations between drainage basins, allowing for the distinction between different hydrographic network patterns, such as narrow longitudinal, semi-longitudinal, and circular configurations. This makes it a valuable tool for understanding basin morphology and the dynamics of water flow within various drainage systems.

The stream length ratio is the ratio of the mean length (Lμ) of all stream segments of a given order (μ) to the mean length of all streams of the next lowest order (Lμ−1) [50, 63]. The stream length ratio provides valuable insights into the hydrological characteristics of a basin, helping to estimate surface flow discharge and assess the erosional stage of the basin.

The average bifurcation ratio (Rb) for the Tamri watershed is 4.07, which suggests a moderately hilly region with a moderate slope, high runoff, and moderately permeable rocks. In this watershed, the fourth-order stream exhibits the highest stream length ratio (3.40). This elevated value indicates that the area drained by the fourth-order stream has relatively high permeability and gentler slopes compared to areas drained by lower-order streams (Table 5).

The water flow concentration time (Tc) is the time it takes for water to move from the farthest point in a watershed to its outlet. This indicator is crucial for understanding the hydrological behavior of the basin, as it influences the timing of runoff and the potential for flooding. Tc is influenced by various factors, including the topography of the basin (e.g., slope and shape), land use, vegetation cover, soil type, and geological formations. Additionally, human activities such as urbanization and deforestation can alter natural flow patterns, affecting concentration time and the overall hydrological dynamics of the basin. In particular, the floods occur and negatively affect the hydrological balance in the river basins because of the intensive building stock and land use decisions taken to meet the needs of the growing population with the acceleration of urbanization and industrialization [64].

The average degradation of the catchment plays a crucial role in defining and highlighting the nature of the topography. This characteristic significantly influences the time it takes for water to reach downstream areas, impacting the concentration time and the potential for maximum flow during rainy periods [65].

The water concentration time of these basins is relatively high, exceeding 10 hours, indicating their significant length from upstream to downstream. The flow speed is also notable, reaching 1.43. The combination of high water concentration time and flow speed can be attributed to a mix of topographical, geological, and biological factors, as well as both deliberate and unintended human interventions.

Climatic characteristics have a significant impact on the hydrological response of watersheds. Increased rainfall in a basin directly influences surface runoff, often leading to a higher drainage volume, which can sometimes cause flooding. Floods have the power to greatly damage the living creatures and lands around the beds according to their flow rates [66]. Furthermore, analyzing the annual flow of oueds provides insight into the temporal distribution of hydrological behavior, enhancing our understanding of the basin's hydrological response over time. Monitoring and assessing flash floods and managing mitigation measures is a complex project that requires great effort and a relatively long period of time [67].

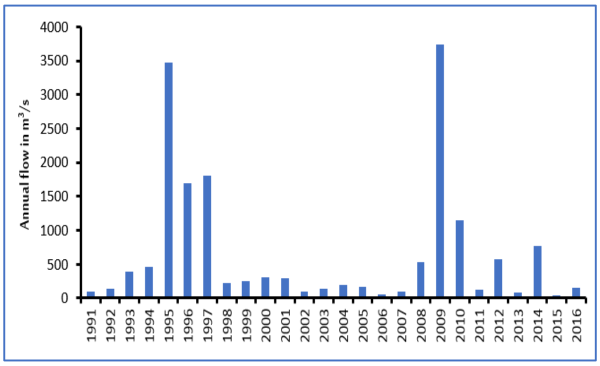

Figure 6. Maximum instantaneous annual flow at Tamri station in m3/s (1991-2016)

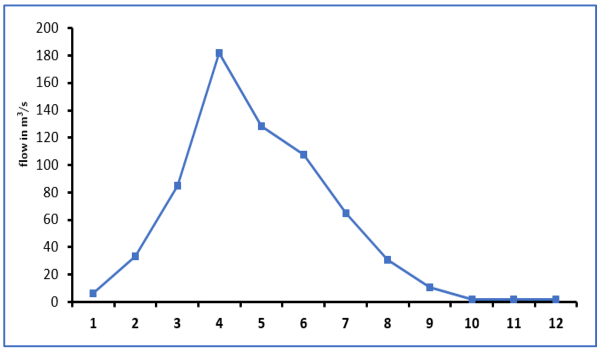

Figure 7. Average monthly flow at Tamri station (1991-2016)

The annual instantaneous flow in the Tamri watershed from 1991 to 2016 exhibits significant variability, with flow levels reaching high peaks in some years before quickly dropping to lower levels. During humid hydrological years, the average annual flow exceeds or equals 1 m^3/s, while in dry years, it falls below 1 m^3/s. The maximum annual flow at the Tamri station also shows irregularity, with the highest recorded value of 3500 m^3/s in 1995. In 1996, it reached 1690 m^3/s, and in 1997, it was 1805 m^3/s. However, in 2008, it decreased to 533 m^3/s, only to rise again to 3743.5 m^3/s in 2009, before reaching 773.9 m^3/s in 2014. These years correspond to the wettest periods in the basin, while other years, such as 2002, 2005, 1998, 1991, 2011, and 2015, were dry (Figure 6). This variability is reflected in the hydrological drainage of the hydrographic network, which leads to the concentration of human activities and the exploitation of marginal lands at the valley bottom. However, with increased rainfall and the corresponding rise in water flow in the tributaries, barriers are encountered that alter the flow's direction towards areas of human settlement.

The monthly average flow rates at the Tamri station (Figure 7) show notable variation and uneven distribution. Two distinct periods can be identified: the first corresponds to the wet season, spanning from October to May, with flow rates ranging between 50 and 225 m^3/s. The second period includes June and July, during which flow rates gradually decline, reflecting the drier conditions typical of this time of year.

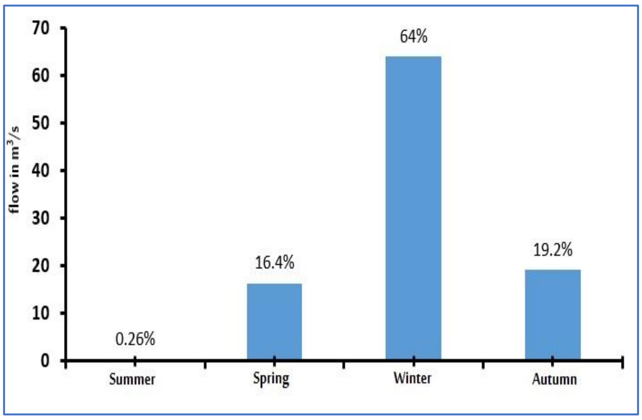

Figure 8. Distribution of seasonal flow at Tamri station (1991-2016)

The seasonal flow of Oued Tamri shows notable variation throughout the year. In winter, rainfall contributes to 64% of the oued's flow, followed by fall with 19.2%, and spring with 16.4%. The summer season contributes minimally, at just 0.26%. This seasonal variation is largely due to the hydrological system of Oued Tamri, which is a purely rainy system, receiving the majority of its precipitation during the fall and winter months (Figure 8).

4. Conclusion

In conclusion, this study makes a significant contribution to enhance that the morphometric analysis is a critical method for studying the physiological and quantitative characteristics of a watershed. Prioritizing sub-watersheds has proven effective in conserving natural resources. Geographic Information Systems (GIS) is an invaluable tool for analyzing these characteristics, particularly using digital elevation models. GIS helps to identify spatial variations and correlations within the morphometric features of a watershed, enabling more precise and informed assessments. Hydrological phenomena are closely linked to morphometric properties, particularly factors such as area, slope, and the compactness index. These parameters help estimate the relationship between lithological characteristics and hydrological response.

The Tamri watershed is dominated by significant mountainous terrain belonging to the Western High Atlas, which stretches in a general northeast-southwest direction. The mountain peaks in this region exceed 600m, covering approximately 80% of the area. Specifically, the Tamri Basin is characterized by steep foothill terrain, with an elevation difference of 432.61m. This places the basin within Group 5, which features rugged terrain with elevations ranging from 250 to 500m.This watershed is characterized by high drainage density, stream frequency, and drainage texture, which are indicative of moderately hilly terrain, rock strata with moderate permeability, increased surface runoff, and a limited potential for groundwater infiltration.

Based on the calculation of morphometric parameters and an extensive field survey, it has been determined that the Tamri basin has an elongated shape, a moderate to steep slope, and a moderate infiltration capacity.

The analysis of the morphometric characteristics of the Tamri catchment suggests that all tributaries of the main watercourse within the study basin should be prioritized for hydrological planning projects. This approach is essential to safeguard human activities and settlements from potential hydrological risks.

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Author contributions

Soukaina AMRANI: Writing-Original draft preparation, Conceptualization, Methodology, Software, Field study and Investigation

Abdelouahed EL-AMRANI: Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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