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Digital Elevation Model-Derived Morphometric Indices for Physical Characterization of the Issen Basin (Western High Atlas of Morocco)

Mohamed Ait Haddou[1*], Abderrahmane Wanaim[1], Mustapha Ikirri[1], Ali Aydda[1], Youssef Bouchriti[1], Mohamed Abioui[1], Belkacem Kabbachi[1]

[1] Department of Earth Sciences, Faculty of Sciences, Ibn Zohr University, Agadir 80000, Marocco
* Corresponding author's email: mohamed.aithaddou@edu.uiz.ac.ma

ABSTRACT

This study attempts to describe the physical characteristics of the Issen basin (western High Atlas of Morocco) in order to highlight the factors affecting water flow and volume that may increase water erosion risk. By using ALOS-DEM of moderate spatial resolution (12.5 m) and GIS platform, it was possible to provide a joint set of morphometric indices of the study area. The obtained results reveal that the relief of the study basin is of mountainous symptom indicating its maturity. The contrasting topography (625 m to 3528 m), with a specific unevenness of the order of 612 m, highlights a strong relief. 94% of the watershed area has a slope of over 3%. The mean elongation of the basin is 1.74, with a fairly long water concentration time of about 7.5 hours and an average drainage density of 0.85 km^{-1}. The tectonics, lithology, and external geodynamics characterstics indicate a strongly contrasted morphology characterizing the Issen basin. Overall, these morphometric characteristics can increase the shallow water flows and sediments mobilized by the Issen Wadi, which can increase the soil loss and flooding risks in the basin.

Keywords: watershed, morphometric indices, topography, GIS, Wadi Issen, Argana corridor, Morocco.

INTRODUCTION

A watershed is a geographical area drained by a hierarchical river system including the main river and its tributaries. The processes of erosion, sediment transport, and deposition are the factors that shape the riverine landscapes [Julien, 2010]. The extent of water erosion depends primarily on the physical characteristics of the basin, including geometry, lithology, and climate [Bouras et al. 2010; Kovacs et al. 2012; Nitheshnirmal, 2019]. In general, the morphometry of mountain river systems is different from that of the plain, which plays an important role in watershed hydrological behavior [Sajadi et al. 2020]. Moreover, the watershed dynamics depend essentially on many environmental conditions, such as climate, geology, land use, and control variables related to liquid flow (Ql) and solid (Qs) flow [Rollet, 2007].

In the literature, the water erosion of soils is viewed as the primary cause of soil damage in Morocco [Mohameden et al. 2022]. The whole mountain range of the western High Atlas suffers from efficient erosion that in general reaches high values in terms of soil loss by year [El Mouden et al. 2017; Markhi et al. 2019]. In this context, it is necessary to find appropriate solutions to conserve water and soil resources in this area. In fact, determining the physical characteristics of the watersheds is essential and crucial to highlight the morphometric factors aggravating water erosion, especially in arid zones suffering from stormy and unstable rainfall.

The Issen basin, located in the western High Atlas of Morocco, suffers from aridity and is occasionally hitted at by infrequent and heavy rain that causes several damages (such as soil silting, etc). In general, among the other basins in the western High Atlas, the Issen basin is more affected by the pedoclimatic hazards and the atmospheric disturbances due to the fragility of its environment

[Ait Haddou et al. 2020b]. Protecting this basin from erosion was identified as a priority [Ait Haddou et al. 2022]. In this context, this study anticipated to characterizing the dynamics and behavior of this complex system. This study aims to detect the physical characteristics of the Issen basin and to highlight the morphometric parameter that aggravates water erosion.

STUDY AREA DESCRIPTION

Geographic Setting

The Issen basin is located 50 km north-east of Agadir, between 30°.64 and 31°.07 of North latitude and between 8.72° and 9.31° of West longitude. This basin covers an area of 1300 km² and belongs to the downstream section of the Souss wadi [Ait Haddou et al. 2020a]. The length and width of this basin are 60 km and 35 km, respectively, following NE-SW orientation and including almost the entire permotriassic sedimentary basin of the Argana corridor (Fig. 1). The Issen basin straddles the boundaries of four provinces: Agadir Ida-Ou-Tanane to the southwest, Taroudant to the south and southeast, Chichaoua to the north and Essaouira to the northwest.

Geomorphologic setting

Geomorphologically, the Issen basin is a result of erosion by the Assif Ait-Moussa River (Issen Wadi). This basin is subjected to eustatic fluctuations and subsidence and vertical tectonics [Chacrone et al., 2005] that exposed the Permian and Triassic layers [Kent et al., 2021]. The topographic feature of the mountainous compartment corresponds to the following units:

- the two ancient blocks of Ida-où-Mahmoud and Ida-où-Zal to the east and south east. These are the main elements of relief where the crests culminate at altitudes that exceed 3500 m.
- the cuestas of Ida-Ou-Bouzia and Ida-Ou-Tanane in the west form respectively northern and southern plateaus of average altitude of 1600 m.

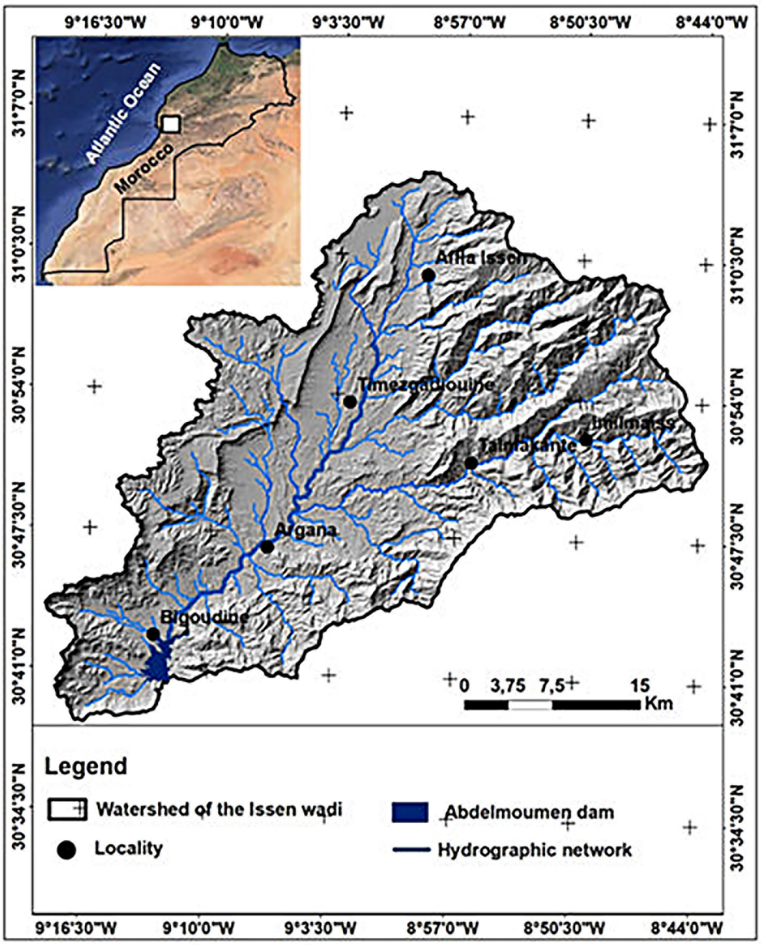


Figure 1. Map shows the location of the Issen basin

- the broad depression of the Triassic corridor of Argana, about 65 km long in the center of the Issen basin, does not generally exceed 1000 m in altitude. It is formed by a series of sub-basins more or less separated by monoclinal sandstone ridges. From the north of the basin to the south, there are the following sub-basins: Aglegal, Timezgadiouine, Argana, Bigoudine and Tassademt cuvettes.

Geological setting

The Argana basin is considered as the western extension of the Essaouira basin, where it's separated from it due to the Alpine orogeny [Hofmann et al. 2000]. From a structural point of view, it is limited to the north by the reverse fault of Ichemraren-Imin'Tanout and the south by the fault of El Mnizla which marks the morphological contact between the Western High Atlas and the plain of Souss [Medina et al. 2001]. It is still affected by recent Plio-quaternary tectonic activity reflected by flexures, folds, and faults [Mridekh, 2002]. The main lithological facies outcropping are those attributed to the major geological formations of the study area. Herein, the lithological facies are identified from the geological map of Argana drawn by Tixeront [1974]. Figure 2 resumes the main lithological facies in the study area.

Climate and vegetation

The Issen basin is part of the arid to semi-arid Mediterranean vegetation stage [Ait Haddou et al. 2020b]. It is dominated by the Argan trees that are very tolerant to water stress, hence their extension to continental areas with an arid climate [Chakhchar et al. 2017].

Rainfall is irregular varying between 194 mm and 480 mm over the entire basin. The average annual temperature is 21.85 °C, it ranges from 1.5 °C to 41.8 °C with 26 days of frost in Argana. The evaporation determined in the Colorado tank for the Abdelmomen dam is 2278 mm/year.

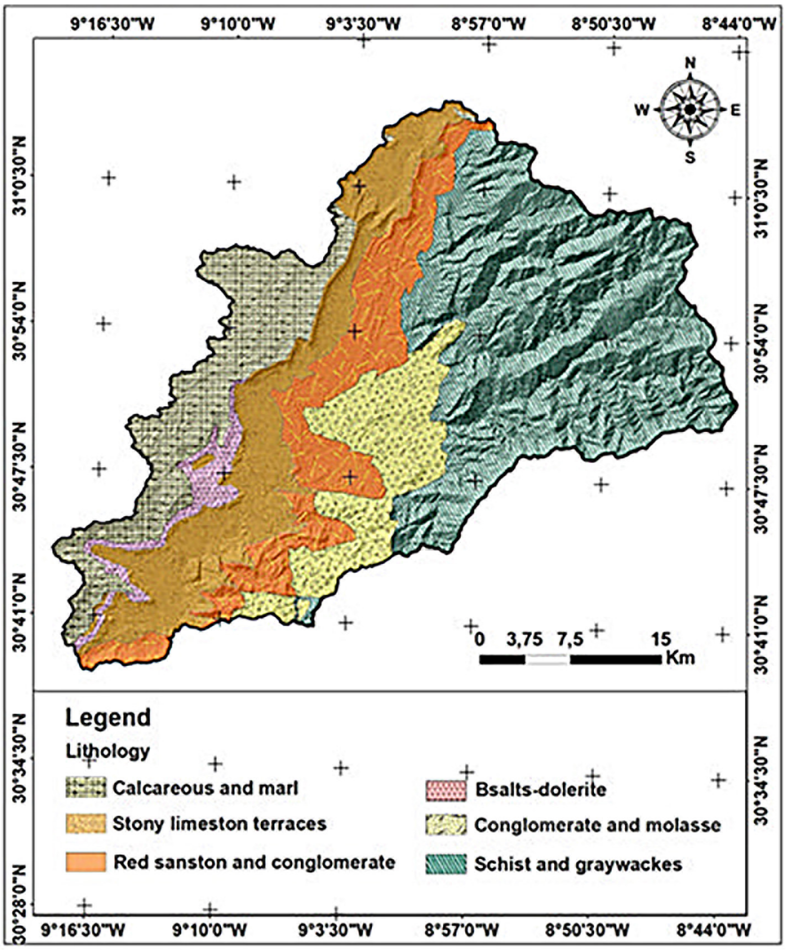


Figure 2. Lithological map of the Issen basin

Table 1. Morphometric and geomorphic parameters formulas used for the physical analysis

Morphometric parameters	Formula/Definition	References
Perimetre (*P*)	Length of the watershed boundary (km)	Jobin et al., 2010
Compactness index (*KG*)	$KG \approx 0.28.\ P/\sqrt{A}$ where: A = watershed area in km²; P = perimeter (km)	Bendjoudi & Hubert, 2002
Average lengthening of the pelvis (*C*)	$C = E/\sqrt{A}$ where: E = the longest path of water	Bendjoudi & Hubert, 2002
Basin length (*Lb*)	Maximum length of the watershed measured parallel to the main drainage line (km)	Jobin et al., 2010
Length (*L*) and width (*l*) of the equivalent rectangle (km)	$L = (KG\ \sqrt{A})/1.12*[1+\sqrt{(1-(1.12/KG)^2)}]$ (Dimensionless) $l = (KG\ \sqrt{A})/1.12*[1-\sqrt{(1-(1.12/KG)^2)}]$	Roch, 1963
Average gradient of water catchment (m/km)	$S = 2h_a/L$, where: h_a = the average altitude of the basin (m), L = the length of the longest talweg (km)	Amaya, 2015
Overall slope index (*Ig*) in m/km (‰)	$Ig = D/Leq = (H_{5\%} - H_{95\%})/L$ 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)	Hamed & Bouanani, 2016
Specific elevation gain (*Ds*)	$Ds = Ig.\sqrt{A}$, where: Ig = overall slope index (m/km)	Dubreuil et al., 1975
Slope index (*Ip*) in %	$Ip = 1.10\sqrt{(Ig/1000)}$	Dubreuil et al., 1975
Average slope of the watercourse. (S_a) in %	$S_a = \Delta H/L = (H_{max}-H_{min})/L$ *where* ΔH = the maximum height difference (m); L = Length of main stream (m)	Gericke & Du Plessis, 2012
Stream order (*Nu*)	Hierarchical order	Strahler, 1964
Stream length (*Lu*)	Length of the stream (km)	Horton, 1945
Stream number (*Ni*)	Number of stream segment of all orders	Horton, 1945
Drainage density (*Dd*)	$Dd = Lu/A$, where: Lu = total length of stream	Genchi et al., 2016
Stream frequency (*Fs*) (km^{-2})	Fs = Nu/A where: Nu = total number of stream; A = area of basin	Genchi et al., 2016
Drainage basin asymmetry (*Af*)	$Af = ((Ar/At) \times 100)$, where: Ar = area of the basin to the right side of the major river; At = total area of the drainage basin	Vijith et al., 2017
Gradient ratio (*Rg*)	$Rg = Es - Em/Lb$, where: Es is the elevation at the source, *Em* is the elevation at the mouth (Dimensionless)	Sreedevi et al., 2004
Time of concentration of water (*Tc*) in hours	$Tc = 4\sqrt{A}+1.5L/0.8\sqrt{H_a}$, where: L = length of the longest thalweg (km); H_a = average altitude (m)	Giandotti,1934
Sinuosity factor (*Sin*)	$Sin = L_{ms}/L_b$, where: Lb = basin length (Max. distance) (km), L_{ms} = main stream length (km), l = real length	Genchi et al., 2016
Confluence Report (*Rc*)	$Rc = N^n/N^{n+1}$ where N^n = number of thalwegs of order n N^{n+1} = number of higher order troughs (n + 1)	Tucker et al., 2001
Torrentiality coefficient	$CT = Dd \cdot F1$ where $F1$= density of elementary thalwegs	Gómez-Villar et al., 2006

DATA AND METHODS

In geomorphology, the morphometric indices are the first measures investigated to quantify the potential hydrological behavior of watersheds and to compare their morphological characteristics [Jobin et al. 2010]. The response of streamflow to precipitation depends on watershed parameters [Snelder et al. 2009]. Thus, the speed of the flow and its rapid concentration is essentially linked to the combined effect of the slope system, the organization of the talweg networks and the shape of the watersheds [Douvinet, 2008].

In this study, the morphometric analysis of the studied basin was carried out from Digital Elevation Models (DEM) (12.5 m of resolution) of ALOS (Advanced Land Observing Satellite) (https://search.asf.alaska.edu/#/). In general, DEMs represent georeferenced digital grid files where each point corresponds to the ground elevation (z) at the (x, y) coordinate point. The processing (visualization, analysis and mapping) of these DEMs was investigated in the ArcMap platform of ArcGIS 10.5 software (ESRI). This platform allows us to determine several descriptive parameters of the shape, relief and hydrographic network (watershed contours, network shape, slopes, hypsometry, hydrography). Table 1 lists the quantitative and analytical morphometric parameters investigated in this study.

RESULTS AND DISCUSSION

Basic geometric descriptors

The Issen basin covers an area of 1300 km², which represents about 8% of the total area of the Souss watershed (16000 km²). The fan shape of this basin (Fig. 3) is characterized by a compactness index of 1.69 which is close to that of Rdat, N'fis and Tifnout basins [Ait Melouk, 2020; Amaya, 2015; Tairi, 2021], and an average elongation of 1.74. The elongated form of the hydraulic networks of this basin indicates that it is less strong and less rapid than a compact basin. The drainage basin asymmetry (Af) calculated for Issen Watershed shows a value below the 50% cutoff, indicating degree of asymmetry with a general northwesterly tilt. The length of hydraulic networks is 51 km with a time of concentration of the water quite long of 7 h 50 min, indicating that the study basin has the lowest peak flows. The hydrographic network of this basin is of dendritic type with an average drainage density of 0.85 km^{-1}. These values are very similar to those of the N'fis watershed [Amaya, 2015]. The main stream of the Issen basin appears with the order 5. The overall slope index is 17 m/km, while the slope index is 14.32% with a specific gradient of about 612 m. This highlights a strong relief according to the ORSTOM classification, indicating that most zones of this watershed are exposed to water erosion risk.

Table 2 summarizing the morphometric indices to characterize the Issen basin at the Abdelmomen dam station.

Table 2. The results of the calculation of morphometric and geomorphic characteristics in the Issen basin

Morphometric indexes		Value
Shape index	Surface (km²)	1300 km²
	Perimeter (km)	218.17
	Compactness index	1.69
	Average pelvis lengthening	1.74
	Basin length (km)	55
	Length of the main river (km)	63
	Length of equivalent rectangle (km)	94.31
	Width of equivalent rectangle (km)	15 .04
Volume index	Maximum altitude (m)	3528 (Jbel Awlim)
	Minimum altitude (m)	625 (Abdelmomen dam)
	Altimeter range (m)	2903
	Average altitude (m)	1332
	Median altitude (m)	1500
	Overall slope index (m/km)	16.96
	Slope index (%)	14.32
	Specific elevation gain (m)	611.97
Indices and characteristics of hydrographic network	Type of hydrographic network	dendritic
	Watershed order	5
	Path length's hydraulic (m)	51029 m
	Drainage density (km^{-l})	0.85
	Drainage basin asymmetry (%)	43 %
	Gradient ratio	0.016
	Water concentration time (h)	7.5 hours
	Sinuosity factor	1.11 (sinuous)
	Confluence report	1.77 (poorly prioritized)
	Torrentiality coefficient	0.34

Topographic index

Altitude and hypsometric curve

The hypsometric map obtained reveals that the total basin is a mountainous zone with an altitudinal average of 1332 m. The altitude of 800–1600 m remains the most frequent, where it covers 66% of the total study area (Fig. 3). The eastern and northeastern parts of the basin are characterized by high altitudes exceeding 3500 m in the ancient massif of Id-ou-Mahmoud. In contrast, the south-western part of the basin, which corresponds to the distal segment of the Argana corridor, where the altitude reaches 625 m at the outlet of the Wadi Issen. Rieke-Zapp and Nearing [2005] highlighted that differences in erosion and soil loss depend on the morphology of the land. Thus, in the highly elevated terrain, erosion and soil loss occur more. In addition, the terrain topography affects the convergence and the divergence of flow, which leads to non-uniform distribution of the size and effectiveness of gullies and ravines. Also, heavy and rapid runoff in highly elevated terrain attacks the deep and the banks of the wadis, causing land degradation.

The hypsometric curve of the study area presents a concave slender shape (Fig. 4). This shape reflects the state of maturity and the aging trend. This result reveals a progressive reduction of the surface of the altimetric zones and a great extension of the middle altitudes in the study area in response to geomorphological and tectonic evolution.

The analysis of the longitudinal profiles of the Wadi Issen (Fig. 5) reveals a gentle slope with an average of 1.6%, progressively decreasing from upstream to the downstream zone. The slope varies from 5% to 2% in upstream zone, characterizing mountainous relief and indicating the unevenness of the terrain that reaches 1500m of elevation at the northern edge to the confluence of Ida or Ida-ou-Mahmoud in the center of the Argana corridor. At the distal end of the Issen valley, the slope is 0.8% over a distance of 15 km near the outlet, where the relief is relatively flattened. The average slope of the main beds is 4%.

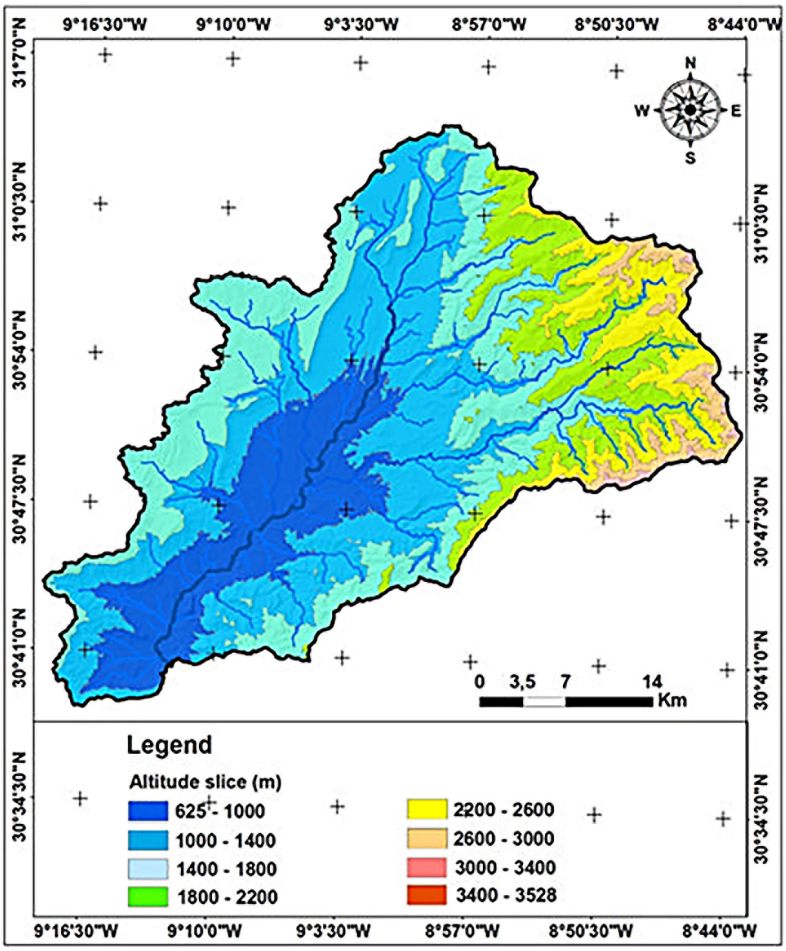
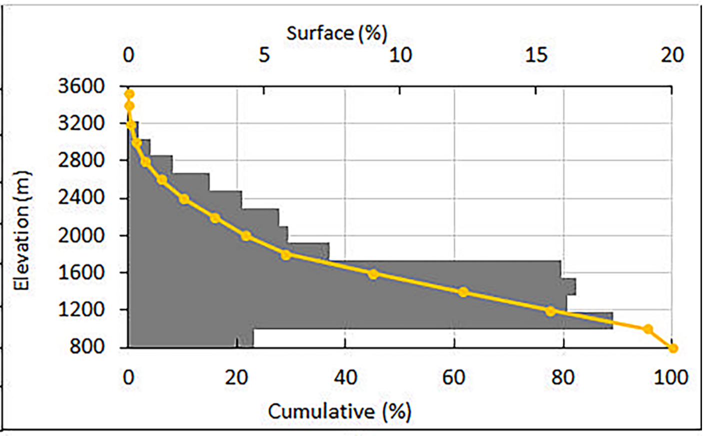


Figure 3. Hypsometric map

Elevation (m)	Area (Km²)	Simple (%)	Cumulative (%)
625-1000	292.45	22.45	100.00
1000-1400	424.85	32.61	77.55
1400-1800	303.87	23.33	44.94
1800-2200	148.47	11.39	21.61
2200-2600	94.15	7.22	10.22
2600-3000	32.6	2.51	3.00
3000-3400	6.15	0.48	0.49
3400-3528	0.09	0.01	0.01

(a)



(b)

Figure 4. Elevation classes (a) and hypsometric curve (b)

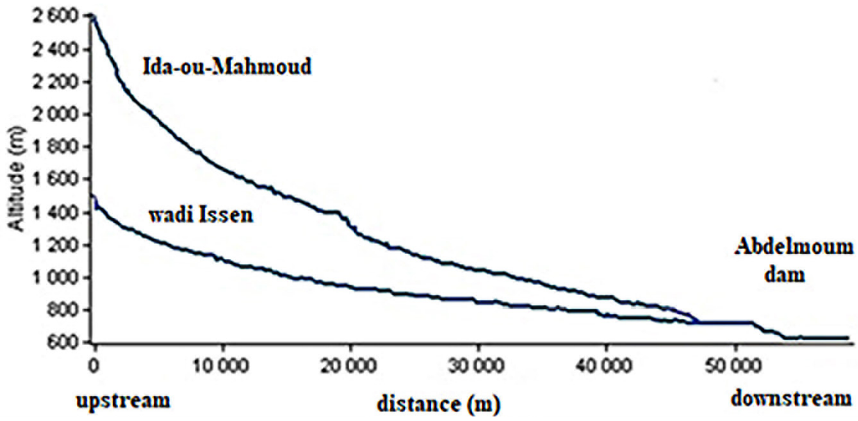


Figure 5. Longitudinal profiles of the Wadi Issen and its main tributary Ida-ou-Mahmoud

Slope

Figure 6 shows the obtained slope map and its classification depending on slope effects on erosion. Except for the Argana corridor and the extreme northwest zone (Blad Demsira), the terrain of the entire watershed is relatively steep, with an average slope of about 23%. In general, the study terrain shows a very uneven landscape, where main reliefs are correspond to the ancient massif dissected by the tributaries of Ait Driss, Ouargioun, Ait Chaib, and Ait Bkhayr that reaches 3528 m of altitude and slopes ranging from 60% to 150%, and to the glacis levels of the Quaternary that outcrop on the Jurassic plateaus (slopes > 70%). These reliefs from the alluvial and colluvial lands that are highly susceptible to ablation and transport, which could even undergo a landslide of red clay-silts and Permo-Triassic arenolutites. According to [UNEP/MAP/PAP, 2000], the erosion can be active on slopes greater than 3%. Consequently, 94% of the total study basin is susceptible to erosion.

Characteristic indexes of fluvial systems

Hydrographic network

The hydrographic network of the Issen basin is of dendritic type (Fig. 7). Hortons [1945] reported that the stream order of the Mountain Rivers ranges from 1 to 4. The main watercourse of the study area is of stream order 5. This watercourse receives on its right bank five major tributaries that parent the Jurassic plateaus of Ida-ou-Bouzia to the northwest and Ida-ou-Tanan and Ida-ou-Souar to the southwest draining the Permo-Triassic red terrain. On the other hand, this watercourse is more branched on its left bank which receives the main tributaries of Wadi Issen originating from the culminating crests of the ancient snowy massif of western High Atlas. Their axes are parallel and oriented NE-SW and are the following: Ait Bkhayr, Ait Chaaib, Ait Tourner, and Ida-ou-Mahmoud. The latter is the largest tributary of the Wadi Issen (L = 50 km). In general, these large tributaries of

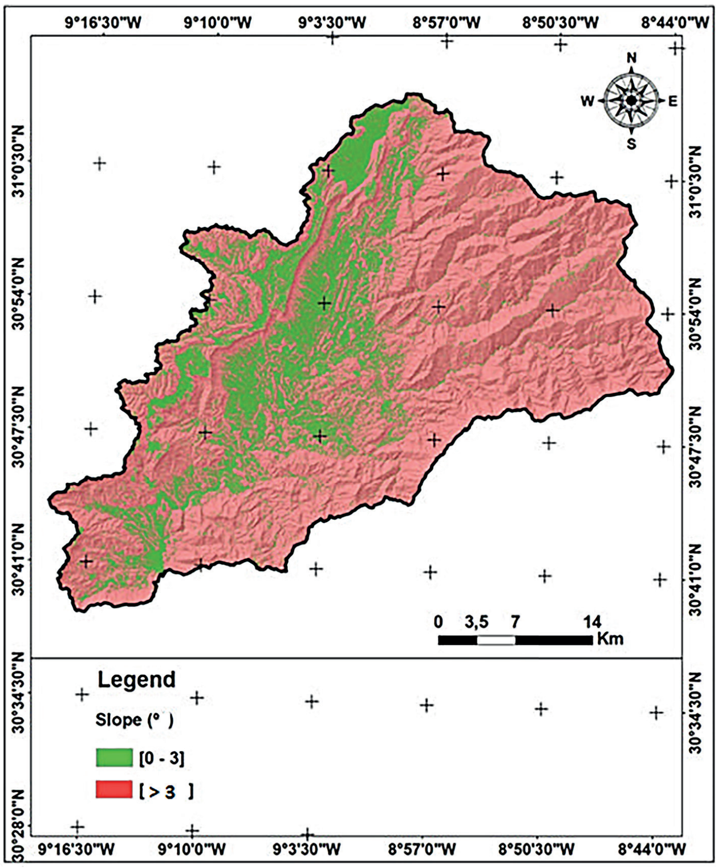


Figure 6. Slope map and slope classes according to their effect on erosion

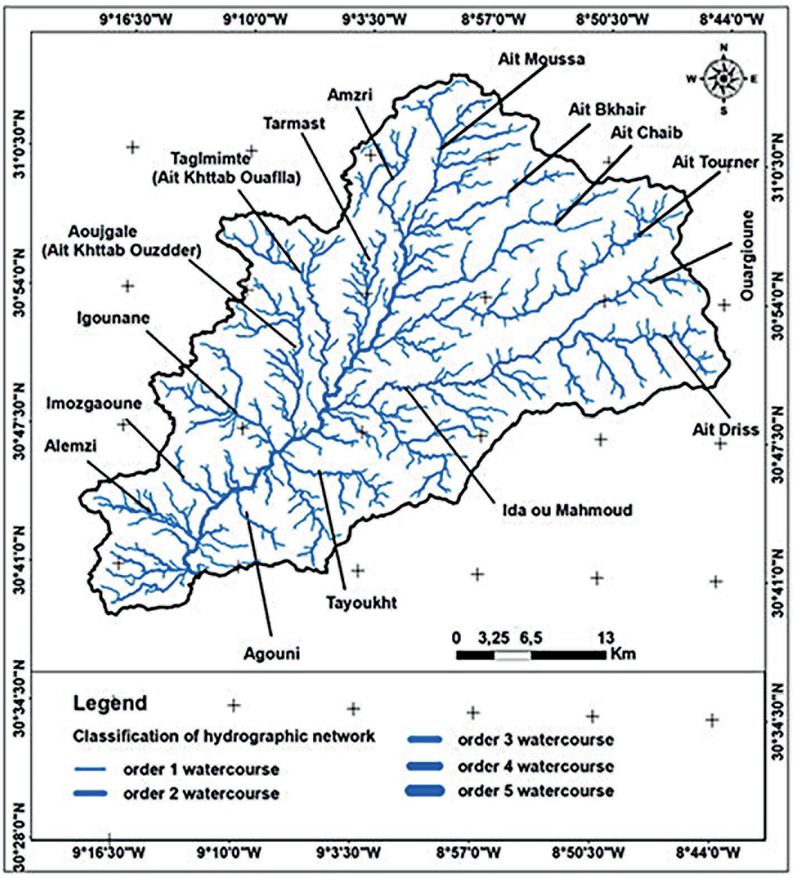


Figure 7. Hydrographic network map according to the Horton - Strahler system

the Wadi Issen cross the western slopes of the ancient massif towards the Argana corridor, producing an exclusively endoreic drainage system. This system is of a high-energy erosive which can be affected quickly by large-scale events (single peak floods).

Stream frequency, drainage density and flow directions

The density of drainage is low, averaging 0.85 km/km². It exceeds this value for certain sub-basins where the flow is very branched in a particular topographic and litho-climatic context, undoubtedly favoring the development of hydrographic networks. The Stream frequency is average ranging from 0 to 7 km^{-2} (Fig. 8). However, the density of the hydrographic network and its ramification are especially important from 1200 m altitude on the marl-limestone and schist-sandstone friable mountain slopes framing the Argana corridor. In general, the sectors with high drainage and hydrographic density are often concentrated in the ancient massif and the Jurassic plateaus with mountainous relief and less permeable bedrock and less dense vegetation cover. In addition to physiographic characteristics, the response of stream flow to precipitation also depends on the underlying geology, vegetation cover, intensity and frequency of precipitation.

Figure 9 shows the obtained flow direction map. The flow is in all directions to the heterogeneity of the relief and the contrast of the topography and lithology on both sides of the Argana corridor. We note a slight dominance of flows directed to the northeast in relation with the layout of the relief of the Hercynian central massif. The Issen basin is fed from 14 main tributaries forming five hydrological sub-basins with endoreic character and which feed the great depression of Tassadamt closed by the Abdelmomen dam. Each of these sub-basins is either, crossed by a main tributary of Issen, or linked to several tributaries occupying its proximal section. The most important of these sub-basins are those of Igounane and Agouni, Ait Driss, and Ait Moussa Wadis.

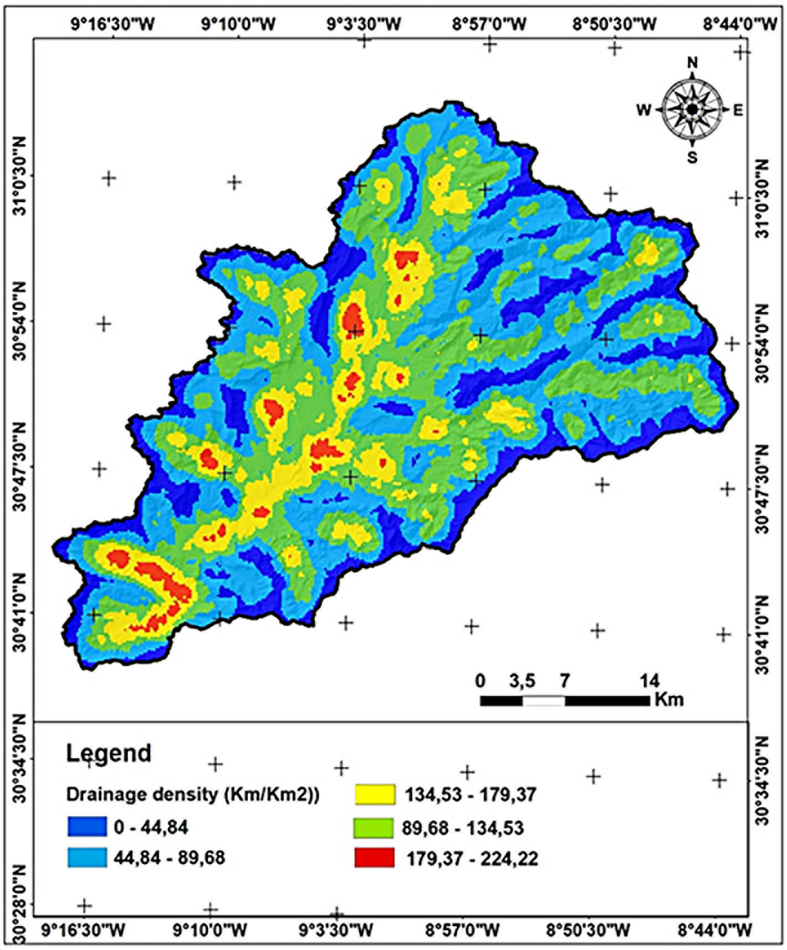


Figure 8. Stream frequency map

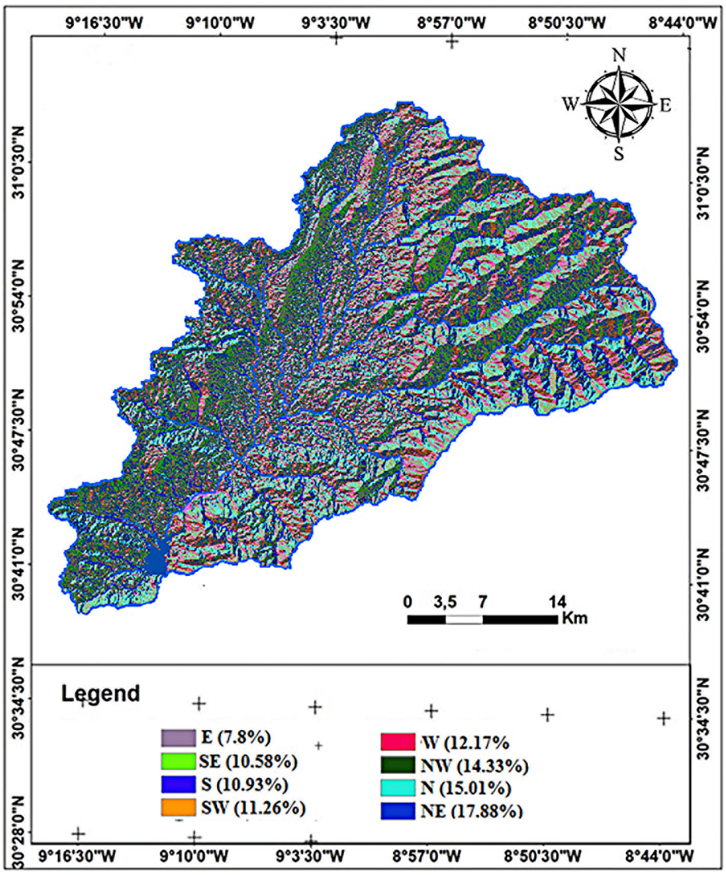


Figure 9. Flow directions map

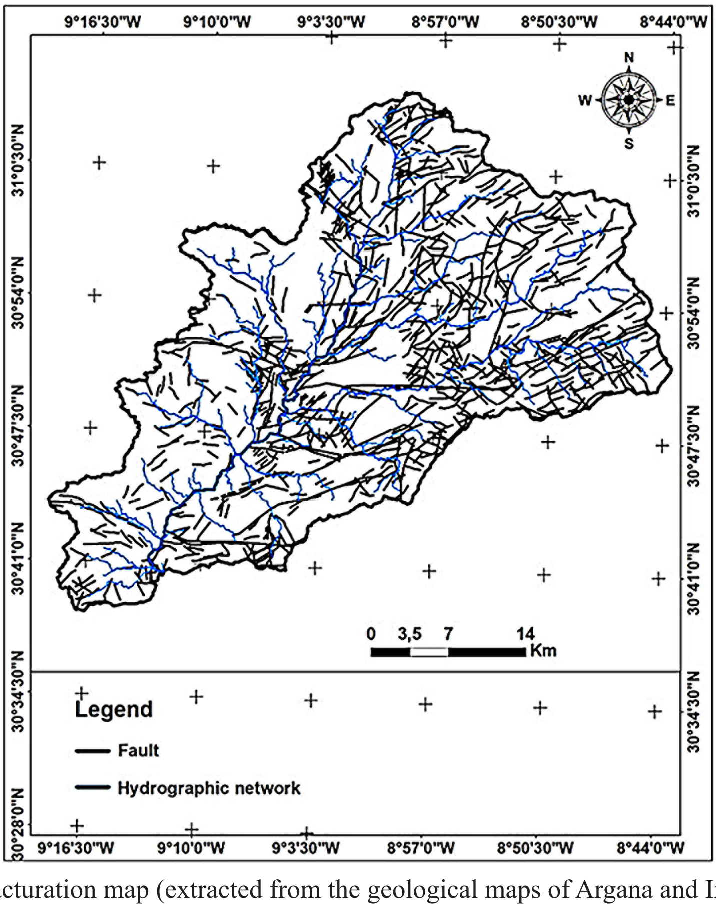


Figure 10. Fracturation map (extracted from the geological maps of Argana and Imi N' Tanout)

Tectonics: a significant factor in morphogenesis

Tectonics is a factor that acts in two ways; either directly by influencing alluvial fans through slopes, or indirectly by affecting the rate of erosion. The Argana basin is considered as the western extension of the Essaouira basin and is separated from it due to the Alpine orogeny [Hofmann et al., 2000]. Structurally, it is limited to the north by the reverse fault of Ichemraren-Imin'Tanout and to the south by the fault of El Mnizla which marks the morphological contact between the Western High Atlas and the plain of Souss [Medina et al. 2000]. It is located at the meeting of two structural directions; the first one is of Hercynian orogeny with NNE-SSW direction, and the second one is of Atlasic orogeny with ENE-WSW direction. Michard et al. [2011] reported that some faults with ENE-WSW, NE-SW, and WNW-ESE directions are active until the present (Fig. 10). The sedimentary filling of this basin is contemporary with the opening of the central Atlantic in a synrift context largely governed by tectonic constraints materialized by a system of distensive faults. The Triassic sedimentary activity was most probably controlled along the Argana Basin by a series of horsts and grabens in the East-West direction (Brown, 1980). This tectonics played a primary role in landform formation [Harvey, 1989].

In 1993, the Hydraulic Basin Agency (ABHSM) conducted a study for mapping the seismic hazard of the Abdelmoumen Dam. This study showed that the right outlet of the Issen basin recorded maximum horizontal accelerations of 0.35 g and 0.2 g. Similarly, the seismic zoning map of Morocco classified the southwestern Atlantic part of the country, where the study basin is part of it, as a strong seismic zone (Zone III) [ONE, 2011].

A Comparison of the morphometric index estimated in this study, shows the similarity of the characteristics of intermittent streams of three other watersheds. The results based on GIS are shown in Table 3.

CONCLUSIONS

The characterization of the physical environment of a watershed by the various morphometric indices appeared necessary for the understanding of its hydrological functioning. Thus, the relationships between the physiographic and geomorphometric characteristics of the terrain and the surface flow of water responsible for the hazards and risks of erosion and flooding were approached. The use of a DEM and GIS allowed for providing a joint set of physical indices of the Issen basin. The elaboration of thematic maps of some volume and network indices offers the possibility of a prediction of the vulnerability of the lands to runoff. In conclusion, we

Table 3. Comparison of the morphometric characteristics of the High Atlas watersheds

Catchment attributes	Issen watershed	N'Fis watershed	Rdat watershed	Tifnoute watershed
Catchment area (km²)	1300	1442.72	540	1570
Perimeter (km)	218.17	238.68	134	218.40
Compactness index	1.69	1.76	1.6	1.5
Form	Extended			
Max. altitude (m)	3528	4070	3563	4057
Min. altitude (m)	625	640	693	732
Average altitude (m)	1332	2300	2115.2	1861
Slope (%)	23.1	41.6	37.99	23
Origin point	High Atlas	High Atlas	High Atlas	High Atlas & Anti Atlas
Outlet	Abdelmomen Dam	Lalla Takerkousst Dam	Sidi Rehal	Aoulouz Dam
Hydrographic network	Dendritic	Dendritic	Dendritic	Dendritic
Watershed order	5	5	5	5
Length of the main course (km)	51	110	50	70.24
Time of concentration of water	7h	6h	6h	---
References	This work	Amaya, 2015	Ait Melouk, 2020	Tairi, 2021

will retain the great spatial diversity with the following essential characters:

- The contrasting topography (625 m to 3528 m), with a specific difference in height of about 612 m highlights a strong relief,
- 94% of the basin surface has slopes greater than 3%,
- An average elongation of 1.74, with a fairly long water concentration time of about 8 hours and an average drainage density of 0.85 km^{-1},
- The conjunction of tectonics, lithology, and external geodynamics, indicates a strongly contrasted morphology characterizing the Issen basin.

This situation thus favors an increase in the volumes of water and contribution of sediments mobilized by the Wadi Issen which increases the risks of soil loss and flooding. In addition to these morphometric characteristics, the rainfall, the intensity, the soil cover and the previous rainfall accumulation during the rainy episode all have a significant effect on the hydrological response of the basin.

REFERENCES

1. Ait Haddou M., Kabbachi B., Aydda A., Bouchriti Y., Gougeni H., En-Naciry M., Aichi A. 2022. Traditional practices: A window for water erosion management in the Argana basin (Western High Atlas Morocco). E3S Web of Conferences, 337, 02002. https://doi.org/10.1051/e3sconf/202233702002
2. Ait Haddou M., Kabbachi B., Aydda A., Gougni H., Bouchriti Y. 2020b. Spatial and temporal rainfall variability and erosivity: Case of the Issen watershed, SW-Morocco. E3S Web of Conferences, 183, 02003. https://doi.org/10.1051/e3sconf/202018302003
3. Ait Haddou M., Kabbachi B., Labbaci A., Ezaidi S., Bouchriti Y. 2020a. Soil erosion prediction based on modelling and siltation at the watershed upstream of the Abdelmomen dam in Argana corridor (SW Morocco). Int. J. Sci. Res. Innov. Std., 2, 1. https://ijarimss.org/publications/volume2-issue1/
4. Ait Melouk M. 2020. Caractérisation d'un bassin versant en climat semi-aride: analyses sédimentologiques, cartographies des zones à risques naturels par SIG et télédétection cas du bassin versant de l'oued Rdat, Marrakech, Maroc. Ph.D Dissertation, Cadi Ayyad University.
5. Amaya A.D. 2015. Analyse sédimentaires, gestion et approche par Télédétection et SIG des risques naturels du bassin versant semi-aride de l'Oued N'fis, Maroc. Ph.D Dissertation, Cadi Ayyad University.
6. Bendjoudi H., Hubert P. 2002. The Gravelius compactness coefficient: critical analysis of a shape index for drainage basins. Hydrol Sci J, 47(6), 921–930. https://doi.org/10.1080/02626660209493000
7. Bouras F., Djebbar Y., Abida H. 2010. Estimation de l'envasement des Barrages: une approche non paramétrique. J Int Environ Manag Confl, 1(1), 114–119.
8. Chacrone C., Hamoumi N. 2005. L'Arenig–Llanvirn du Haut Atlas occidental et central (Maroc). Environnements sédimentaires, paléogéographie et contrôle de la sédimentation. CR Geosci, 337(12), 1026–1034. https://doi.org/10.1016/j.crte.2005.05.015
9. Chakhchar A., Haworth M., El Modafar C., Lauteri M., Mattioni C., Wahbi, S., Centritto M. 2017. An Assessment of Genetic Diversity and Drought Tolerance in Argan Tree (Argania spinosa) Populations: Potential for the Development of Improved Drought Tolerance. Front Plant Sci, 8, 276. https://doi.org/10.3389/fpls.2017.00276
10. Douvinet J., Delahaye D., Langlois P. 2008. Modélisation de la dynamique potentielle d'un bassin versant et mesure de son efficacité structurelle. Cybergeo Europ J Geogr, 412. https://doi.org/10.4000/cybergeo.16103
11. Dubreuil P., Morell M., Séchet P. 1975. Comportement et interactions des paramètres physiques des petits bassins versants semi-arides et intertropicaux. Cah. Orstom, Sér. Hydrol, 13(1), 13–36.
12. El Mouden A., Alahiane N., El Faskaoui M., El Morjani Z.E.A. 2017. Dams siltation and soil erosion in the Souss–Massa river basin. (In: Choukr-Allah R., Ragab R., Bouchaou L., Barceló D. (eds)). The Souss-Massa River Basin, Morocco, The Handbook of Environmental Chemistry. Springer International Publishing, Cham, 95–120. https://doi.org/10.1007/698_2016_70
13. Genchi S.A., Vitale A.J., Perillo G.M.E., Piccolo M.C. 2016. Geomorphometric assessment of drainage systems in a semi-arid region of Argentina using geospatial tools and multivariate statistics. Earth Sci Inform, 9(3), 309–324. https://doi.org/10.1007/s12145-016-0258-2
14. Gericke O.J., Du Plessis J.A. 2012. Catchment parameter analysis in flood hydrology using GIS applications. J S Afr Inst Civ Eng, 54(2), 15–26.
15. Giandotti M. 1934. Previsione delle piene e delle magre dei corsi d'acqua. Memorie e studi idrografici, 8, 107–117.
16. Gómez-Villar A., Álvarez-Martínez J., García-Ruiz J.M. 2006. Factors influencing the presence or absence of tributary-junction fans inthe Iberian Range, Spain. Geomorphology, 81(3-4), 252–264. https://

doi.org/10.1016/j.geomorph.2006.04.011

17. Gravelius H. 1914. Grundriβ der gesamten Gewâsserkunde, Band 1: fluβkunde (Compendium of Hydrology, vol. 1: Rivers, in German). Goschen, Berlin, Germany.
18. Hamed K.B., Bouanani A. 2016. Caractérisation d'un bassin versant par l'analyse statistique des paramètres morphométriques : Cas du bassin versant de la Tafna. (Nord-ouest algérien). Geo-Eco-Trop, 40(4), 277–286.
19. Harvey A.M. 1989. The occurrence and role of arid zone alluvial fans. In: Thomas, D.S.G. (ed.), Arid Zone Geomorphology. Belhaven, London, 136–158.
20. Hofmann A., Tourani A., Gaupp R. 2000. Cyclicity of Triassic to Lower Jurassic continental red beds of the Argana Valley, Morocco: implications for palaeoclimate and basin evolution. Palaeogeogr Palaeoclimatol Palaeoecol, 161(1–2), 229–266. https://doi.org/10.1016/S0031-0182(00)00125-5
21. Horton R.E. 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geol Soc Am Bull, 56(3), 275–370. https://doi.org/10.1130/0016-7606(1945)56(275:EDOSAT)2.0.CO;2
22. Jobin T., Sabu J., Thrivikramaji K.P. 2010. Morphometric aspects of a small tropical mountain river system, the southern Western Ghats, India. Int J Digit Earth, 3(2), 135–156. https://doi.org/10.1080/17538940903464370
23. Julien P.Y. 2010. Erosion and sedimentation. Cambridge University Press, Cambridge.
24. Kent D.V., Olsen P.E., Muttoni G., Et-Touhami M. 2021. A Late Permian paleopole from the Ikakern Formation (Argana basin, Morocco) and the configuration of Pangea. Gondwana Res, 92, 266–278. https://doi.org/10.1016/j.gr.2021.02.009
25. Kovacs A.S., Fulop B., Honti M. 2012. Detection of hot spots of soil erosion and reservoir siltation in ungauged Mediterranean catchments. Energy Procedia, 18, 934–943. https://doi.org/10.1016/j.egypro.2012.05.108
26. Markhi A., Laftouhi N., Grusson Y., Soulaimani A. 2019. Assessment of potential soil erosion and sediment yield in the semi-arid N′ fis basin (High Atlas, Morocco) using the SWAT model. Acta Geophys, 67(1), 263–272.https://doi.org/10.1007/s11600-019-00251-z
27. Medina F., Vachard D., Colin J.P., Ouarhache D., Ahmamou M. 2001. Charophytes et ostracodes du niveau carbonaté de Taourirt Imzilen (Membre d'Aglegal, Trias d'Argana); implications stratigraphiques. Bull Inst Sci, 23, 21–26.
28. Michard A., Saddiqi O., Chalouan A., Rjimati E., Mouttaqi A. 2011. Nouveaux guides géologiques et miniers du Maroc. Notes Mém Serv Géol Maroc, 3, 558.
29. Mohameden A., Baghdad B., Chakiri S., El Hadi H., Hamoud A., Zoraa N., Zerdeb M.A., Moussa K. 2022. Quantification and evaluation of water erosion by RUSLE / GIS approach in the Ykem watershed (western Morocco). Ecol Eng Environ Tech (in Press).
30. Mridekh A. 2002. Géodynamique des bassins méso-cénozoïques de subsurface de l'offshore d'Agadir (Maroc sud occidental) : contribution à la reconnaissance de l'histoire atlasique d'un segment de la marge atlantique marocaine. Ph.D Dissertation, Ibn Tofail University.
31. Nitheshnirmal S., Thilagaraj P., Abdul Rahaman S., Jegankumar R. 2019. Erosion risk assessment through morphometric indices for prioritisation of Arjuna watershed using ALOS-PALSAR DEM. Model Earth Syst Environ, 5, 907–924. https://doi.org/10.1007/s40808-019-00578-y
32. ONE. 2011. Actualisation de l'étude d'impact sur l'environnement du projet de station de transfert d'énergie par pompage d'Abdelmoumen. Unpublished Report.
33. PNUE/PAM/PAP. 2000. Directives pour la gestion de programmes de contrôle d'érosion et de désertification, plus particulièrement destinées aux zones côtières méditerranéennes. Split, Programme d'actions prioritaires.
34. Rieke-Zapp D.H., Nearing M.A. 2005. Slope shape effects on erosion: a laboratory study. Soil Sci Soc Am J, 69(5), 1463–1471. https://doi.org/10.2136/sssaj2005.0015
35. Roche M. 1963. Hydrologie de surface. Gauthier-Villars Editeur, Paris.
36. Rollet A.J. 2007. Etude et gestion de la dynamique sédimentaire d'un tronçon fluvial à l'aval d'un barrage : le cas de la basse vallée de l'Ain. Géomorphologie. Ph.D Dissertation, Jean Moulin University. https://tel.archives-ouvertes.fr/tel-00221368
37. Sajadi P., Singh A., Mukherjee S., Sang Y.F., Chapi K., Salari M. 2020. Drainage network extraction and morphometric analysis in an Iranian basin using integrating factor analysis and geospatial techniques. Geocarto Int, 1–30. https://doi.org/10.1080/10106049.2020.1750060
38. Snelder T.H., Lamouroux N., Leathwick J.R., Pella H., Sauquet E., Shankar U. 2009. Predictive mapping of the natural flow regimes of France. J Hydrol, 373(1–2), 57–67. https://doi.org/10.1016/j.jhydrol.2009.04.011
39. Sreedevi P.D., Subrahmanyam K., and Ahmed S. 2004. The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain. Environmental Geology, 47, 412–420. https://doi.org/10.1007/s00254-004-1166-1

40. Strahler A.N. 1964. Quantitative geomorphology of drainage basin and channel networks. In: V.T. Chow (Ed.), Handbook of applied hydrology. McGraw Hill Book, New York, 40–74.
41. Tairi A. 2021. Application de la géomatique à la gestion des risques naturels en zones montagneuses: Modélisation des aléas des mouvements de terrain et d'érosion hydrique au niveau du bassin versant de Tifnoute (Atlas-Maroc). Ph.D Dissertation, Ibn Zohr University.
42. Tixeront M. 1974. Carte géologique et minéralisations du Couloir d'Argana, Haut Atlas occidental, 1/100 000. Notes Mém Serv Géol Maroc, 205.
43. Tucker G., Lancaster S., Gasparini N., Bras R. 2001. The Channel-Hillslope Integrated Landscape Development Model (CHILD). (In: Harmon, R.S., Doe, W.W. (eds)). Landscape Erosion and Evolution Modeling. Springer, Boston, MA, pp 349–388. https://doi.org/10.1007/978-1-4615-0575-4_12
44. Vijith H., Prasannakumar V., Sharath Mohan M.A., Ninu Krishnan M.V., Pratheesh P. 2017. River and basin morphometric indexes to detect tectonic activity: a case study of selected river basins in the South Indian Granulite Terrain (SIGT). Physical Geography, 38(4), 360–378. https://doi.org/10.1080/02723646.2017.1283478