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Assessment of Torrential Correction Thresholds on Ourika Sub-Watershed of the Tensift Watershed (High Atlas of Marrakech, Morocco)

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ABSTRACT

The Ourika sub-watershed is composed of about twenty different watersheds with diverse lithology, slope, and structural organization. In order to better characterize the basin, we inventoried and extensively assessed the different types of thresholds implemented in each micro-watershed. The present study focused on the area located between Meltsen and Sidi Ali Oufarés faults, which includes several micro-watersheds that have been modified by the installation of structures. We selected 12 micro-watersheds from the main tributaries draining this zone, based on the level of risk: four micro-watersheds on the right bank from upstream to downstream (Wigrane and Walighane, Tachmacht, and Touggalkhir), and eight micro-watersheds on the left bank from upstream to downstream (Imintaddarte, Oussane, Tikhfert, Tighazrit, Igri Foudene, Asni, Taljarft, and Tarzaza). The results of our study allowed us to detect and inventory 545 erosion protection structures made of masonry, gabions, and dry stone. However, the majority of these structures were damaged in several micro-watersheds due to steep slopes, torrential rainfall, and especially the solid sediment load resulting from the erosion of easily erodible old alluvial cones. This study serves as a warning to various stakeholders and decision-makers to ensure proper management in this mountainous system. The distribution of these thresholds is as follows: 62 masonry thresholds, accounting for 13.37%; 247 gabion thresholds, accounting for 45.32%; and 236 dry stone thresholds, accounting for 43.30%. The assessment of these structures revealed anomalies such as the loss of 17.43% of embankment structures and the destruction of certain thresholds.

Keywords: erosion, anti-erosion structures, evaluation, operational anomalies.

INTRODUCTION

Soil degradation is a major concern of the last century, being a global, irreversible, and devastating phenomenon, especially in arid and semi-arid areas, where fertile lands are severely depleted. Globally, soil losses are estimated to be around 6 million hectares per year (GTZ, 1998), while forest and agro-silvopastoral cover losses are estimated between 30 to 60 thousand hectares per year (Sabir et al., 1999).

The contribution of water erosion to this phenomenon is increasingly significant (Bou Kheir et al., 2001). This degradation is closely linked to intensive and imprudent exploitation of agricultural land. In fact, up to 3 × 106 hectares of arable land disappear each year worldwide, giving way to completely depleted skeletal lands (Ben Mansour et al., 2006). Gully erosion represents one of the most spectacular forms of land degradation (Valentin et al., 2005). Consequently, numerous studies on water erosion have emphasized the quantitative and qualitative aspects of its sometimes-dramatic consequences, which can affect the durability of hydraulic structures both upstream and downstream (Poesen et al., 2003). For example, in Italy, soil losses caused by gullies can reach 100 to 200 tons per hectare per year (Torri et al., 1994), and can rapidly rise to 800 tons per hectare per year in Haute Provence, France (Mathys et al., 2003). Therefore, gullies are often a major source of erosion in small

Mediterranean watersheds (Poesen et al., 2003). Due to its geographical location, belonging to the Mediterranean context, and its predominantly arid to semi-arid climate, Morocco is not exempt from this issue. The problem of sedimentation in reservoirs is particularly acute and has significant implications for both the state and scientists. The annual total sedimentation volume is estimated at 75 million m^3, which corresponds to 0.4% per year. In response to this situation, the Kingdom of Morocco, in collaboration with international organizations and the participation of all relevant national stakeholders, developed a National Watershed Management Plan between 1990 and 1996. This plan establishes intervention priorities and incorporates actions within a long-term and socioeconomic context to ensure their effectiveness.

The Tensift watershed is one of the highest mountainous areas in north Africa (Toubkal 4165 m) (El Alaoui El Fels, 2018). This geographical area is characterized, on one hand, by its complex morphology and diverse lithology with erosive tendencies, such as sedimentary rocks (clay, sandstone, shale, limestone, etc.), and on the other hand, by its resistant tendencies, such as magmatic rocks (granite, andesite, gneiss, etc.) (Proust, 1961). Additionally, the microclimate in this area leads to a wide biodiversity, but also causes violent and sudden thunderstorms and rainfall, which explains the magnitude and aggressiveness of floods that wreak havoc without warning (e.g., the deadliest flood in the summer of 1995). These repetitive tragedies, particularly affecting the Ourika sub-watershed known for its tourist and agricultural values, have prompted the Moroccan government to urgently launch promising projects aimed at reducing the damage caused by such natural phenomena.

The Ourika sub-watershed (SBVO) is subject to disastrous floods, notorious for their destructive and deadly effects, with the most detrimental being the 1995 flood. In order to mitigate this phenomenon, the government has long implemented a range of water and soil conservation techniques, including fruit tree DRS (fruit tree development projects), soil protection reforestation, and torrential correction works, with the main objective of attenuating the frequent floods (Doukkali, 2003). However, the effectiveness of these anti-erosion measures in mitigating the flood risks that threaten this region remains uncertain, as these structures unfortunately suffer from difficulties and malfunctions. In this context, the present study aims to analyze and evaluate the impact of all these implemented measures in the Ourika sub-watershed, highlighting not only their effectiveness but also any undesirable deficiencies. The research focuses on the evaluation of state-sponsored flood protection measures in the Ourika watershed. For this purpose, the study area chosen is the perimeter located between the Meltsen fault and the Sidi Ali Oufarés fault, which contains several micro watersheds modified by the installation of various structures. The analysis and evaluation of the effectiveness of these measures are based on:

1. The geological context of the studied intervention.
2. A geomorphological analysis of the construction site area.
3. Determination of flood-prone areas.
4. Environmental impact assessment of the structure in question.
5. Mapping of the inventoried thresholds.

MATERIALS AND METHODS

The main objective of this study is to conduct a comprehensive survey of the current state of mechanical gully corrections implemented by the Oued Ourika watershed development project. In order to have a general idea of their effectiveness while considering the needs of the population and the specific characteristics of the area. The methodological approach used revolves around three main axes:

1. To fully understand the problem, a literature review is conducted to highlight the factors exacerbating the situation in the Ourika watershed on one hand, and the methods used to mitigate this issue on the other hand. To achieve the aforementioned objectives, data from four stations with the most complete data series were used.
2. Several inventory campaigns, mapping, and surveys of the current state of the structures and major sedimentation thresholds were carried out to cover the study area as extensively as possible.
3. Processing and analysis of the collected field data and evaluation of the current state of the thresholds, primarily involving the development of maps that spatially represent each type of threshold using ArcGIS and ERDAS software, integrating spatial remote sensing data and geographic information systems. Statistical data analysis was also conducted, particularly for return period laws, using the hyfran-plus software from INRS-Eau Canada version 2002.

STUDY AREA

Geographical framework

The study area is located 60 km southeast of Marrakech, on the northern slope of the Atlas of Marrakech (Oued Ourika sub-watershed) (Moret, 1931). Covering an area of 1071 km², the Ourika sub-watershed is part of the hydraulic system of the Tensift River in its Haouz Mejjate section, which includes several sub-watersheds. The studied sub-watershed is bordered to the east by the Zat sub-watershed, to the south by the High Atlas Mountains, to the northeast by the Tensift River, and to the west by the Issyl and Rherhaya sub-watersheds. It is a fairly rugged and dynamic area within the Tensift watershed (Fig. 1)

Geological framework

The Ourika sub-watershed is composed of a rigid basement formed by Paleozoic and Precambrian rocks in the south, consisting of crystalline outcrops (granitoids) and volcanic rocks (andesites and rhyolites), as well as Mesozoic cover series (detrital sediments: sandstones and red clays, carbonates: marls and limestones). The Cenozoic formations are developed towards the north and northeast (Fig. 2). This mountainous area is characterized by outcrops ranging from precambrian to quaternary, and the manifestation of several orogenies. These factors, along with the climate, have played a significant role in shaping the ancient and current morphology of the region. From a structural point of view, Moret (1930), Proust (1961), and Biron (1982) divided the region into four structural domains separated by major faults (Fig. 2).

Geomorphological characterization and delimitation of the Ourika sub-watershed

Geomorphological characterization

The arrangement of the hydrographic network is largely related to the evolution of structural phenomena that have affected the region over time. These factors can be classified as internal (geology: lithology and tectonic structures), external (climate, vegetation cover, and human activities), or composite (topography, hydrological factors, etc.). As for the hydrological regime, it depends on the density of drainage, confluence ratios, and length ratios. The Ourika sub-watershed is characterized by a dense and branching hydrographic network. The tributaries form a homogeneous dendritic network, and significant hydrological consequences are observed at its outlet during periods of high-water flow.

This watershed has an area of approximately 562 km² and a high drainage density of about 3.1 km/km². It has a slightly elongated shape with a compactness index of 1.3 (Table 1). The main

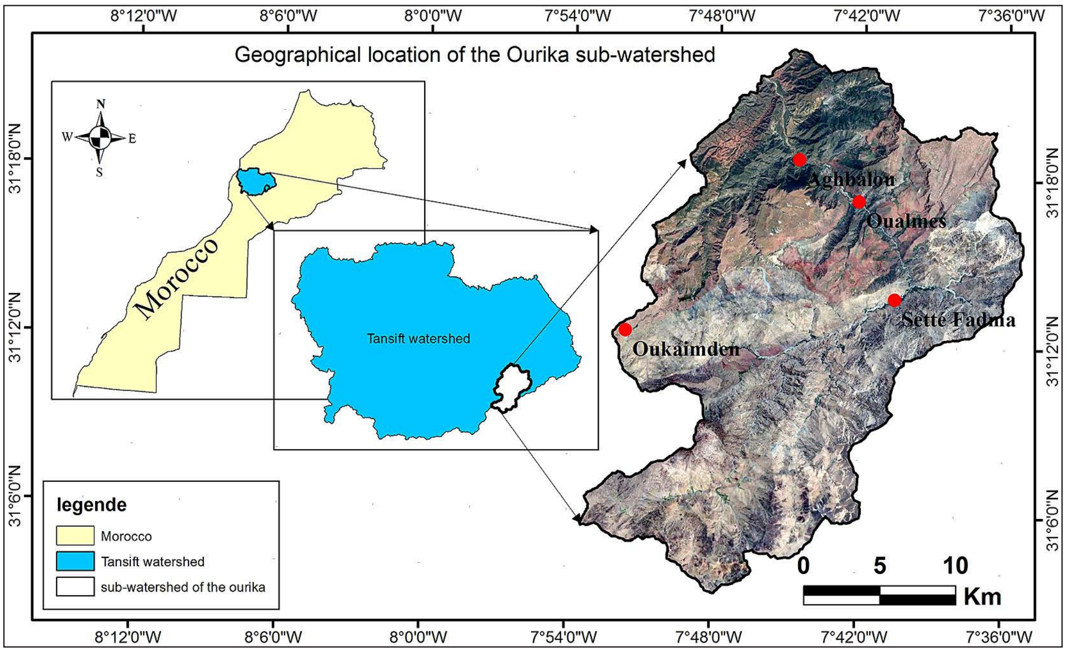

Figure 1. Geographical location of the Ourika sub-watershed

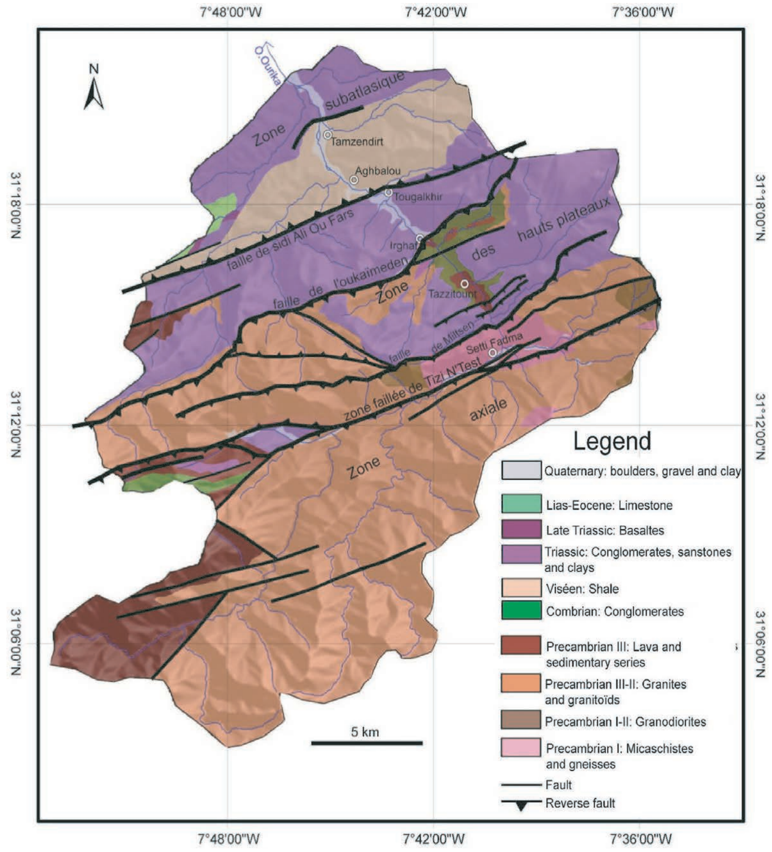

Figure 2. Geological map of the Ourika sub-watershed (Namous M. 2012)

river, with a length of 53 km, flows towards the northeast and then northwest. The hydrographic network of the watershed is particularly dense and well-hierarchized (Saidi et al., 2010). The main river reaches the 6th order at the outlet and flows through a long, narrow valley, towards which a succession of valleys and tributary gullies converge on both sides. Thus, the flood waves of the Oued Ourika increase downstream as they are fed by the tributaries.

Table 1. Morphometric characteristics of the Ourika sub-watershed (extracted from Arc Gis)

Area (km²)	562
Perimeter (km)	132
Maximum altitude (m)	4054
Average altitude (m)	2600
Minimum altitude (m)	945
Length of the main river (km)	53
Gravelius compactness index (KG)	1.6
Drainage density	2.25
Length of the equivalent rectangle (km)	39.2
Width of the equivalent rectangle (km)	12.8
Average slope of the main river	2.15%
Average slope of the main tributaries	9.35%
Average slope of all slopes in the watershed	35%

Slope

In general, the slopes in the Ourika sub-watershed are dominated by steep gradients, reaching up to 81° in the axial zone, which is characterized by the crystalline massif and high plateau cliffs. However, the slopes decrease to 0° and 15° in the high plateaus and also in the Oukaïmeden area. The remaining parts are characterized by varying slopes (Fig. 3).

Aspect

In terms of morphology, the area consists of a succession of stepped reliefs that increase in elevation towards the south. Additionally, the exposure of slopes to disrupted flow and the effects of slope orientation also play an important role in the aridity of the soils and their ability to retain moisture for long periods (Fig. 4). The orientation of the slopes towards the south or north affects the duration of sunlight exposure and, consequently,

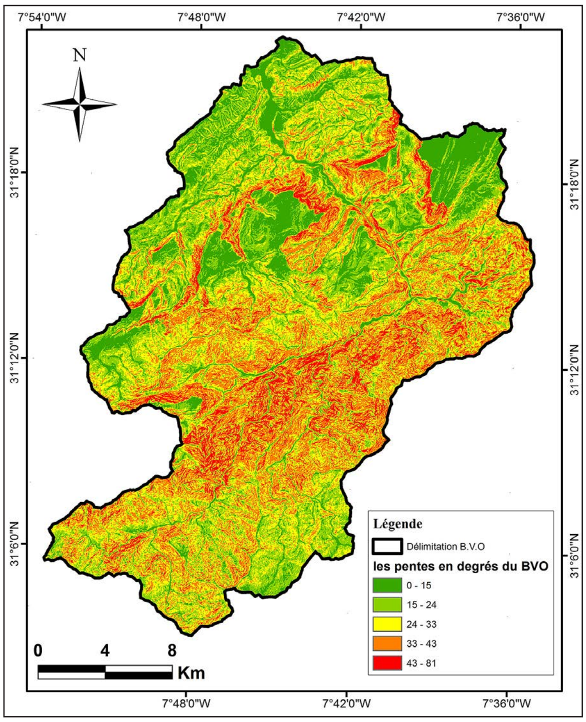

Figure 3. Map of slopes in the Ourika sub-watershed (extracted from ARC-GIS)

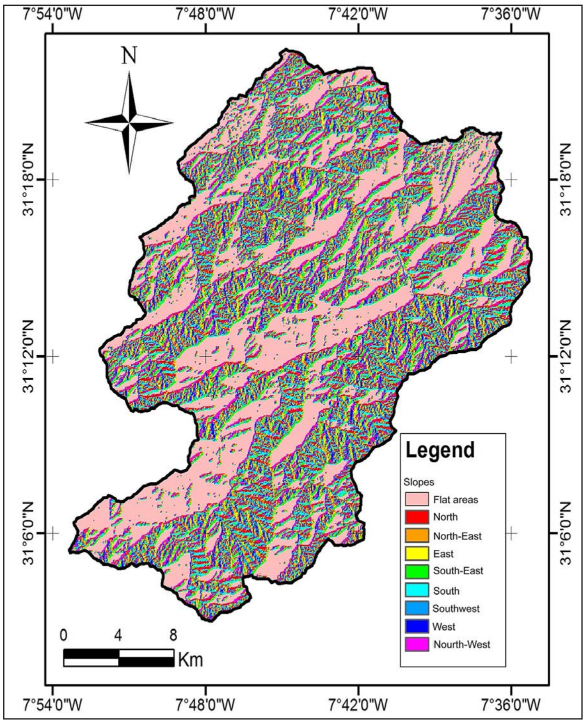

Figure 4. Aspect map of the Ourika sub-watershed (extracted from ARC-GIS)

the intensity of solar radiation received on the ground per unit surface area. This effect is more pronounced when the slopes are steep, as is the case in the Ourika watershed, where the valleys are deep, and the slopes are mostly oriented towards the north or northwest.

Hydrographic network

The hydrographic network of the Ourika sub-watershed (Fig. 5) is well-developed in the upstream part of the basin due to the impermeability of the Precambrian basement rocks (gneiss, granite, granodiorite, etc.), limited vegetation cover, and rugged terrain. In the downstream part, the network is less developed due to the presence of less resistant and less permeable formations, more moderate relief, and a denser vegetation cover compared to the upstream area. The drainage density represents the total length of the hydrographic network per unit surface area of the watershed. It is influenced by the evolution of structural phenomena that have affected the region over time.

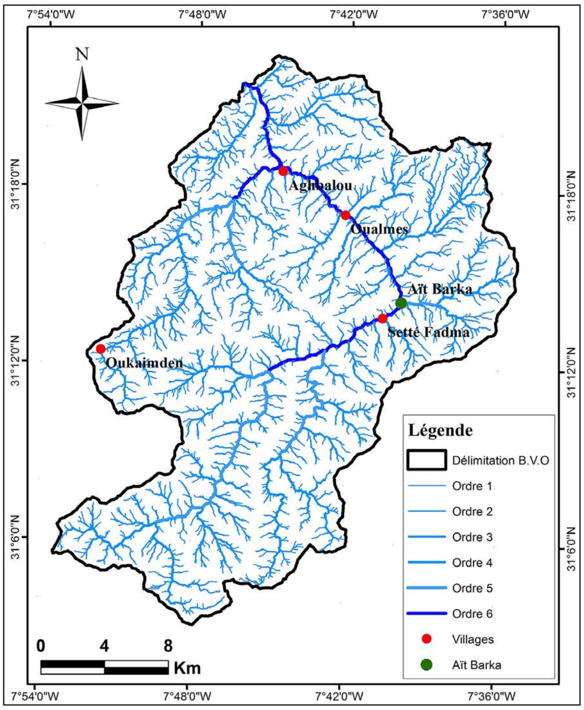

Figure 5. Hydrographic network classification map of the Ourika sub-watershed (extracted from ARC-GIS)

Hypsometry

The relief of the Ourika watershed features a high mountain landscape, with the peak in the axial zone reaching approximately 4054 m. The average altitude of the slopes varies between 1600 and 2800 m, and the outlet altitude is 945 m (extracted from ARC-GIS). 75% of the surface area of the basin lies at altitudes between 1600 and 3200 m, with an average altitude exceeding 2500 m (Fig. 6). These significant altitudes have allowed the basin to benefit from substantial rainfall. By referring to the rainfall gradient of the northern slopes of the High Atlas, calculated based on pluviometric and altimetric data from stations in the region, it is possible to estimate the probable precipitation amounts upstream of the basin.

Vegetation and land use

Vegetation plays a key-role in trapping and retaining a portion of the eroded sediments within a watershed (Viles, 1990). Van Dijk et al. (1996) demonstrated the filtering effect of flow through vegetation. These flows deposit sediments as their transport energy decreases. Deposits have been observed upstream of vegetative barriers (Sanchez and Puigdefabregas, 1994) on steeper slopes than those without vegetation (Bochet et al., 2000). These deposits can be retained permanently if they are colonized by plants, which trap the sediments through root development. As a result, large amounts of eroded sediments are trapped within watersheds and do not reach the outlet of the basins (Beuselinck et al., 2000., Rey F. 2001). Vegetation also helps combat erosion by soil fixation through root systems (Handel et al., 1997). Plants improve soil cohesion and enhance their mechanical properties (O'Loughlin et al., 1986).

According to Ouhammou (1991), Ilmen (2004), and Affobiao (2015), the main vegetation formations found in the Ourika watershed include Tetraclinis (*Tetraclinis articulata* L.) associated with Juniper (*Juniperus phoenicea* L.) and *Quercus rotundifolia Lam* oak woodlands, Juniper (*Juniperus phoenicea* L.) formations in the internal areas, shrubby Genista formations, *Quercus rotundifolia Lam* oak woodlands, Thuriferaie (*Juniperus thurifera* L.), xerophytic formations with spiny vegetation, and high-altitude grasslands.

The land use map was created using the supervised classification method on ERDAS, based on the image (SENTINEL2A_20180626-111803-971_L2A_T29RPQ_D_V1-8) covering the watershed (Fig. 7). The obtained results are represented as follows in the watershed (Fig. 8).

Climatology

Due to its combination of semi-arid, mountainous, and even continental climates, the climate of the Ourika watershed is complex, resulting

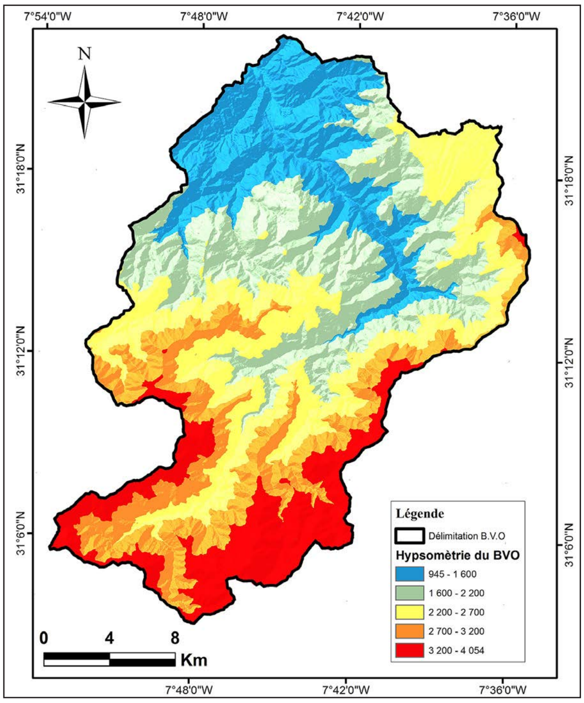

Figure 6. Hypsometric map and characteristic altitudes of the Ourika sub-watershed (extracted from ARC-GIS)

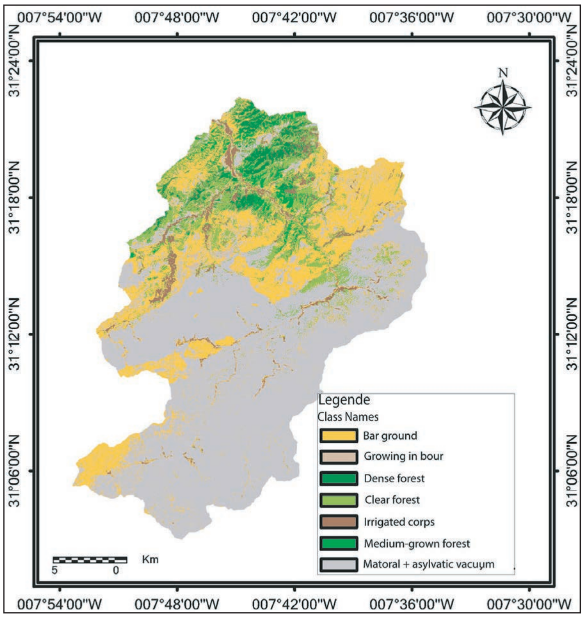

Figure 7. The land cover map produced on ERDAS using the supervised image classification method (SENTINEL2A_20180626-111803-971_L2A_T29RPQ_D_V1-8) covering the BV

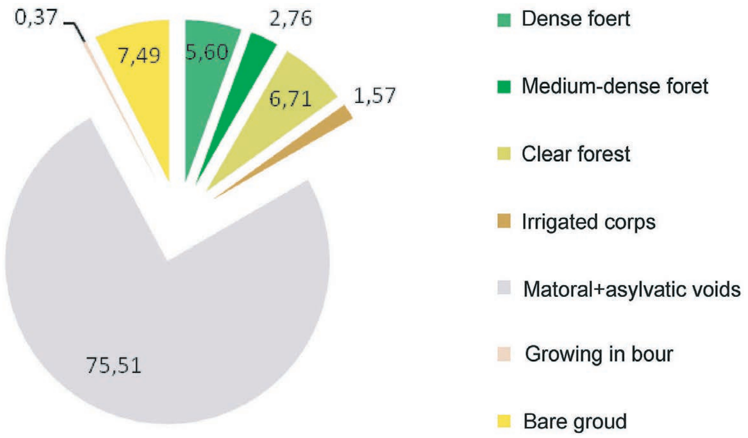

Figure 8. Graph showing the percentage distribution of land use

from the interference of several factors. The winter snowfall in the upstream area, which can last for more than one-third of the year, indicates a mountainous climatic aspect. However, the significant variation in temperature amplitude (15°) (Namous M, 2012), derived from the average temperature ratio between July and January, contributes to a continental aspect of the climate. Nevertheless, the summer drought and the interannual irregularity of precipitation are characteristic signs of a Mediterranean climate. Moreover, several aridity indices classify our study area as a semi-arid zone with a subhumid tendency, where oceanic (disturbances from the northwest), continental, and mountainous influences intersect (Namous M, 2012). The Ourika watershed is characterized by spatiotemporal variability of precipitation and relative irregularity of surface runoff in wadis (Saidi, 1994). The position of the mountain range under study, with its northeast-southwest orientation, is crucial. Perturbations from the south to southwest, caused by tropical air masses, primarily affect the southern and southwestern slopes. Altitude-related disturbances, particularly localized in high peaks, result in predominantly summer thunderstorms (Delannoy, 1981). This convective activity is the primary factor causing devastating floods in the Ourika area, with the most destructive flood occurring on August 17, 1995. The results on rainfall dynamics in the Ourika watershed show that convective rainfall is concentrated between the Meltsen fault and the Sidi Ali Oufares fault (isohyets of 390 mm/year and 510 mm/year) (Fig. 9).

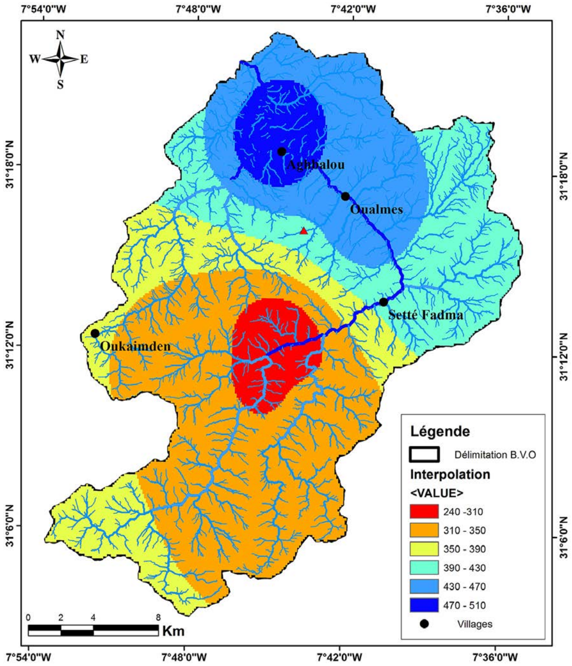

Figure 9. Map showing rainfall in the Ourika sub-Watershed (extracted from Arc-Gis)

Fitting laws to a sample of annual maximum instantaneous flows at the Aghbalou station. Estimating the return periods of extreme flow and rainfall values is one of the major challenges faced by designers of water management systems. For this purpose, a statistical analysis is performed on the observed time series of annual maximum instantaneous flows.

Our study focuses on fitting the annual maximum instantaneous flows in the Ourika Watershed (Aghbalou station) over a 46 – year observation period (1969/70–2013/2014). For data processing, we used the hyfran-plus software from INRS-Eau Canada version 2002. This allows for fitting various statistical distributions and comparing the fits using relevant criteria such as AIC (Akaike's Information Criterion) and BIC (Bayesian Information Criterion). The statistical distributions applied in this study are the Gumbel, log normal, inverse gamma, normal, and Pearson type 3 distributions. The goodness-of-fit test between empirical and theoretical distributions is performed using the chi-squared test. The AIC and BIC criteria are used to compare probabilistic models and select the best-fitting distribution. The distribution with the lowest AIC or BIC values is chosen. Table 2 provides details on these criteria. The appendix of Table 2 explains the use of hyfran in frequency analysis. The table presents a comparison test of statistical distributions based on the AIC and BIC criteria. The numerical fitting yielded return periods of 10, 20, 50, and 100, and the results are extracted from the frequency histogram (Fig. 10) (Table 2). The BIC and AIC criteria led to selecting the log normal distribution (maximum likelihood) as the best-fitting distribution for better estimation of annual maximum instantaneous flows.

RESULTS

The Moroccan authorities responsible for mountain prevention and hydraulic equipment have implemented various measures such as reforestation in high valleys, land improvement, torrent and ravine corrections, and terracing of cultivated lands on steep slopes. Mechanical structures (masonry thresholds, gabion thresholds, dry stone thresholds, terraces) and biological pastoral structures (reforestation) are among the measures currently applied in Moroccan watersheds.

Study of micro-watersheds in the Ourika sub-watershed

The Ourika sub-watershed consists of about twenty micro-watersheds that differ in terms of lithology, slope, and structural organization. In order to properly characterize the watershed, a detailed inventory and evaluation of the different types of thresholds implemented in each micro-watershed were conducted. These morphological characteristics are listed in Table 3. The study area is located between the Meltsen Fault and the Sidi Ali Ou Farés Fault, as these areas are influenced by various erosion factors related to geological, morphological, and climatic diversities. The analysis focused on 12 micro-watersheds, four of which are on the right bank from upstream to downstream (Wigrane, Walighane, Tachmacht, and Touggalkhir), and eight on the left bank from upstream to downstream (Imintaddarte, Oussane, Tikhfert, Tighazrit, Igri Foudene, Asni, Taljarft, and Tarzaza) (Namous et al., 2012) (Fig. 11).

Diagnosis of erosion control structures in ravines

Mechanical corrections

The study area has undergone significant development by public authorities since 2001 to protect agricultural land and riverbeds. These anti-erosion structures cover approximately

Table 2. Numerical fitting of statistical laws (10 –, 20 –, 50 – and 100 – year periods) for maximum annual instantaneous flows at the Aghbalou station

Number of observation: 46															
Return period:	T = 10				T = 20			T = 50			T = 100				
Model	NB	Param,XT	P(Mi)	P (Mi/X)	Param,XT	P(Mi)	P (Mi/X)	Param,XT	P(Mi)	P (Mi/X)	Param,XT	P(Mi)	P (Mi/X)	BIC	AIC
Log normal (maximum likelihood)	2	499.418	20.00	69.67	768.079	20.00	69.67	1246.653	16.67	69.67	1246.653	16.67	69.67	584.75	581.092
Gamma (maximum likelihood)	2	460.604	20.00	30.33	601.218	20.00	30.33	787.424	16.67	30.27	787.424	16.67	30.27	586.413	582.756
Gumbel (maximum likelihood)	2	399.543	20.00	0.00	492.012	20.00	0.00	611.704	16.67	0.00	611.704	16.67	0.00	608.078	604.421
Normal (maximum likelihood)	2	488.131	20.00	0.00	570.251	20.00	0.00	662.65	16.67	0.00	662.65	16.67	0.00	635.858	632.201
Pearson type 3 (conditional maximum likelihood)	3	519.372	20.00	N/D	678.623	20.00	N/D	3889.963	16.67	N/D	3889.963	16.67	N/D	N/D	N/D
P(Mi): a priori probability															
P(Mi/x): a posteriori probability (method of Schwartz)															
BIC : Bayesian information criterion															
AIC: Akaike information criterion															
Ponderated mean of quantiles:	487.6457				717.4703			1119.4733			1507.808				

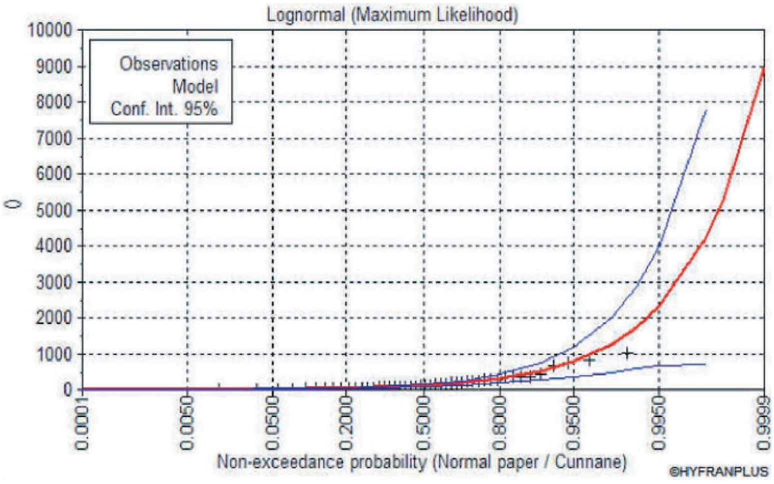

Figure 10. Graphical adjustment of annual instantaneous maximum flows at the Aghbalou station according to the log normal law

Table 3. Physiographic characteristics of the various micro-watersheds in the Ourika sub-watershed

Name of the micro basin	Surface area (km²)	Perimeter (km)	KG index	Shape	Slope average	Length (km)	Drainage density (km/km²)
Wigrane	7	12	1.27	Elongated	29.81	5.8	0.84
Walighane	31	27	1.36	Elongated	26	8.23	2.4
Tachmacht	11.62	19.4	1.6	Elongated	26.70	7.15	2.15
Touggalkhir	9.79	13.84	1.23	Elongated	31.84	5.8	2.09
Imintaddarte	6.16	11.46	1.30	Elongated	25.21	4.6	1.8
Tikhfert	1.51	6.48	1.48	Elongated	26	2.75	4.56
Oussane	7	15	1.6	Elongated	26	6.16	2.35
Tighazrit	16.43	11.21	0.77	Spherical	28.46	6	2.43
Igri Foudene	1.03	4.85	1.34	Elongated	34.86	1.8	0.79
Asni	1.23	5.72	0.44	Spherical	34.86	2 .42	2.75
Taljarft	1.58	6.78	1.5	Elongated	33.89	2.56	3.32
Tarzaza	109	56	1.52	Elongated	26.22	25	2.42
Total	203.35						

Table 4. Detailed status of weirs in the various micro-watersheds examined

Micro watershed	Threshold status												Nbr
	MT				GT				DST				
	U.M.T	M.D.M.T	H.D.M.T	SMTE	U.G.T	M.D.G.T	H.D.G.T	T.D.G.T	U.D.S.T	M.D.D.S.T	H.D.D.S.T	T.D.D.S.T	
Wigrane	0	3	3	1	0	0	0	10	11	4	6	0	38
Walighane	0	1	0	0	10	1	0	0	0	0	5	0	17
Tachmacht	2	0	0	1	0	6	1	4	0	0	0	0	14
Touggalkhir	0	3	0	0	0	0	0	9	9	0	0	0	21
Imintaddarte	1	0	0	0	0	0	0	11	0	20	8	11	51
Tikhfert	1	0	0	0	24	0	1	0	1	2	15	22	66
N-Oussane	1	0	0	0	33	0	5	4	++	++	++	++	43
Tighazrit	8	12	5	0	8	15	5	0	0	0	0	1	54
Igri Foudene	8	0	0	0	6	1	1	1	0	0	0	0	17
Asni	4	0	0	0	26	1	1	0	0	0	0	6	38
Taljarft	8	0	0	0	10	1	0	1	0	0	0	0	20
Tarzaza	0	0	0	0	34	8	8	1	40	30	33	12	166
Nombre	33	19	8	2	151	33	22	41	61	56	67	52	545
Total	62				247				236				

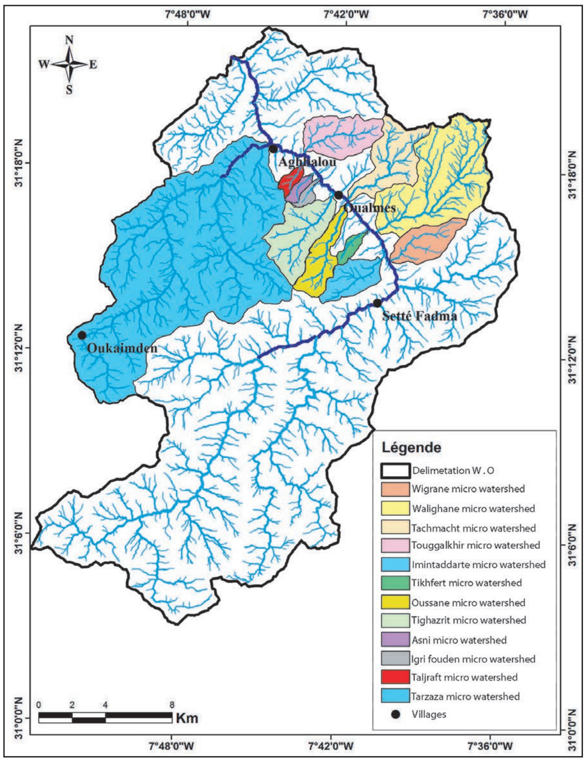

Figure 11. Map showing the distribution of micro-watershed in the Ourika sub-watershed

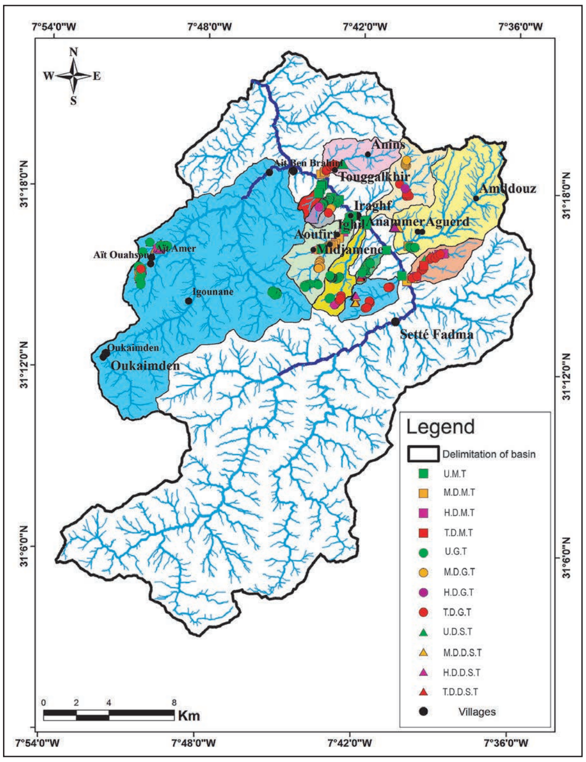

Figure 13. Map showing the condition of the inventoried thresholds in the study area

50% of the area in the sub-watershed (Fig. 13). They are concentrated on both sides of the middle section of the Ourika River, while being less prevalent in the upstream and downstream areas. The inventory of structures in the 12 studied micro-watersheds amounts to 545 thresholds (Table 4), including 62 masonry structures (Fig. 12a and 12b), 247 gabion structures (Fig. 12c and 12d), and 236 dry stone structures (Fig. 12e and 12f).

Biological correction (reforestation)

Vegetation can help combat erosion by runoff through its hydrological regulation of watersheds

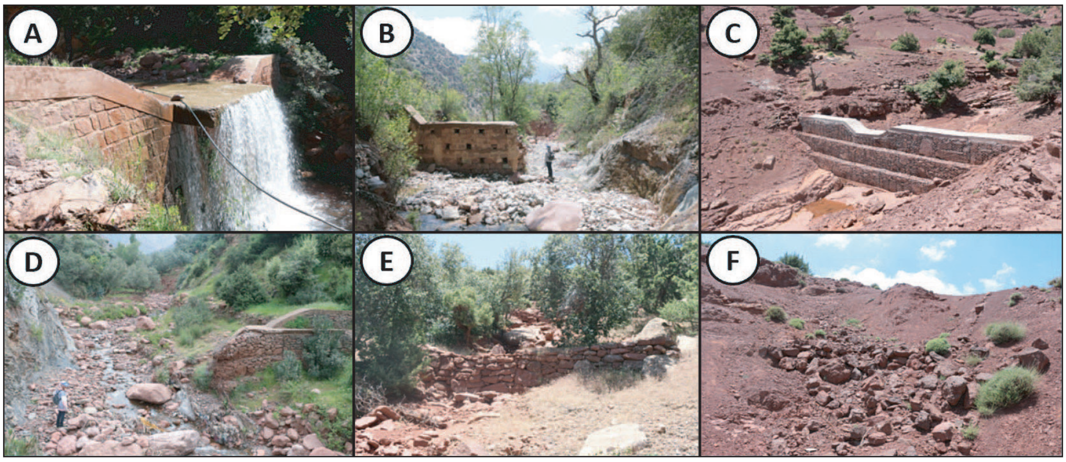

Figure 12. (a) well-functioning masonry weir in the Tachmacht micro-watershed, (b) masonry sill completely damaged at weir invert and wings at Wigrane micro-watershed, (c) newly installed normal-state gabion weir at the Tikhfert micro-watershed, (d) completely damaged gabion sill in Touggalkhir micro-watershed, (e) functional dry-stone weir at the Tikhfert micro-watershed, (f) completely damaged dry-stone weir at Tarzaza micro-watershed

(Humbert et al., 1992., Fleuriel. 1998., Fort. 1999., Lavabre and Andréassian, 2000). This hydrological regulation occurs through the interception of raindrops, increased water infiltration into the soil, extraction of water from the soil, and its release into the atmosphere through evapotranspiration. The hydrological regulation performed by vegetation results in a decrease in the quantity, intensity, and velocity of runoff. Vegetation also has the effect of attenuating and spreading the flow of runoff (Combes et al., 1995). The hydrological regulation provided by vegetation thus helps alleviate erosive forces caused by water (Moir et al., 2000).

Our study area has also benefited from biological interventions, with numerous plantations carried out, especially in micro-watersheds prone to erosion (Fig. 15). Among the tree species used in these interventions, Aleppo Pine was planted in the Walighane, Tachmacht, Touggalkhir, Tarzaza, Asni, Igrifoudden, and Taljarft micro-watersheds, while Cedar was planted in the Oussane micro-watershed, and cactus was planted in the Asni micro-watershed (Fig. 14a–14b).

Identification of ravines to be managed

Following the inventory and diagnostic analysis of erosion control measures, several thresholds in a state of total failure were detected in the following micro-watersheds (Table 5). The main factors responsible for these failures are primarily natural, related to the torrential nature of rainfall, lithology, morpho-structural conditions, and human activities. The map shows the main ravines in the micro-watersheds that need to be redeveloped (Fig. 16).

DISCUSSION

The Ourika watershed consists of around twenty micro-watersheds resulting from the dynamics of the Atlas mountain range. Following the devastating floods that occurred in the Ourika region on August 17, 1995, there is an urgent need for a better selection and method of implementing structures that can limit floods and preserve the fauna and flora. Therefore, these structures were implemented after studying the following parameters:

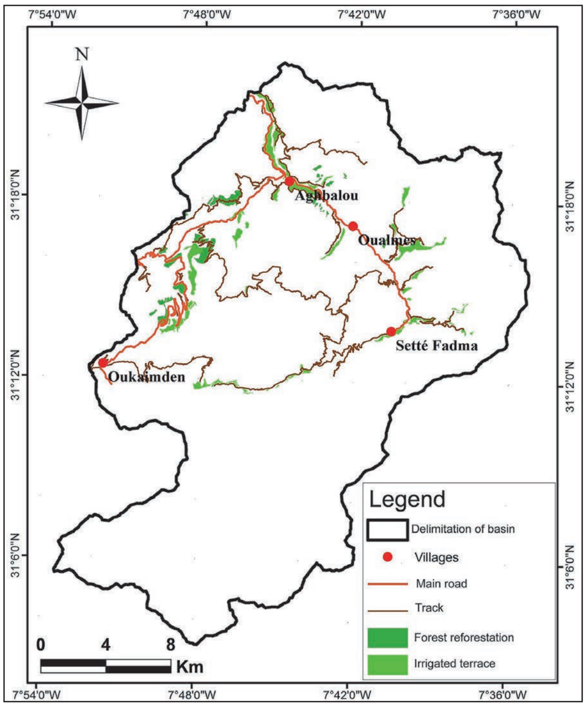

Figure 15. Forest reforestation map in the Ourika sub-watershed (extracted from Arc Gis)

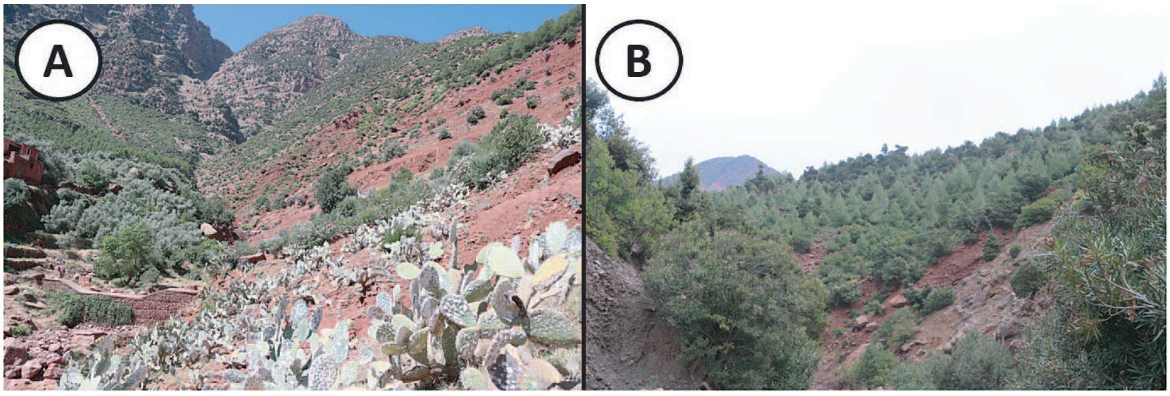

Figure 14. (a) distribution of agricultural (olive trees) and forest (Aleppo pine, holm oak, cactus, etc.) vegetation in the Igri micro- watershed Foudene, (b) photo showing reforestation with Pen d’Alep in the Touggalkhir micro- watershed

Table 5. Total failure state of the micro-basins studied

Micro-watershed	Number of thresholds destroyed
Wigrane	2 (T.D.M.T), 11 (T.D.G.T)
Tachmacht	1 (T.D.M.T), 4 (T.D.G.T)
Touggalkhir	9 (T.D.G.T)
Imintaddarte	11 (T.D.G.T) et 11 (T.D.D.S.T)
Oussane	4 (T.D.G.T)

a) geographic position of the micro-watersheds;
b) land use;
c) lithology (degree of fragility);
d) physiographic characteristics;
e) hydrological capacities;
f) the structures and means implemented to further protect the studied landscape vary from one micro-watershed to another based on their physiographic characteristics;
g) the causes of failure and degradation of the majority of the implemented measures, as analyzed through multiple field surveys conducted in almost all micro-watersheds under study, can be listed as follows:

- steep slopes amplify the stream velocity, leading to increased torrential flow;
- fragile lithology facilitates the detachment of large blocks from upstream to downstream, especially with the presence of debris cones along the tributaries, which act as reservoirs for torrential flow;
- the drainage rate, directly related to rainfall, automatically leads to the transport of a massive amount of torrential flow.

It is worth noting the critical condition of the structures chosen for flood stabilization in the Wigrane, Tachmacht, Imintaddarte, Oussane, and Touggalkhir micro-watersheds. The detailed state of the thresholds, as detected and highlighted in the table above (Tab. 4), clearly shows the total deterioration of the thresholds, especially those made of gabions. This necessitates urgent and effective intervention to reinforce and support the remaining functional structures in order to mitigate the harmful effects of floods on hydro-agricultural works, as well as another road and household infrastructure.

It is necessary to emphasize the need for reforestation projects, particularly in the Wigrane, Walighane, Tachmacht, Imintaddarte, and Oussane micro-watersheds, in order to stabilize the dynamics of torrential flow from the source. However, it should be mentioned and acknowledged that the structures installed in the Igri Foudene, Asni, and Taljarft micro-watersheds have been successful in capturing blocks upstream of their tributaries. It should also be noted that, despite reforestation efforts and the presence of dense forests, the gabion thresholds in the Touggalkhir micro-watershed are completely damaged, which can be attributed to the extremely steep slopes.

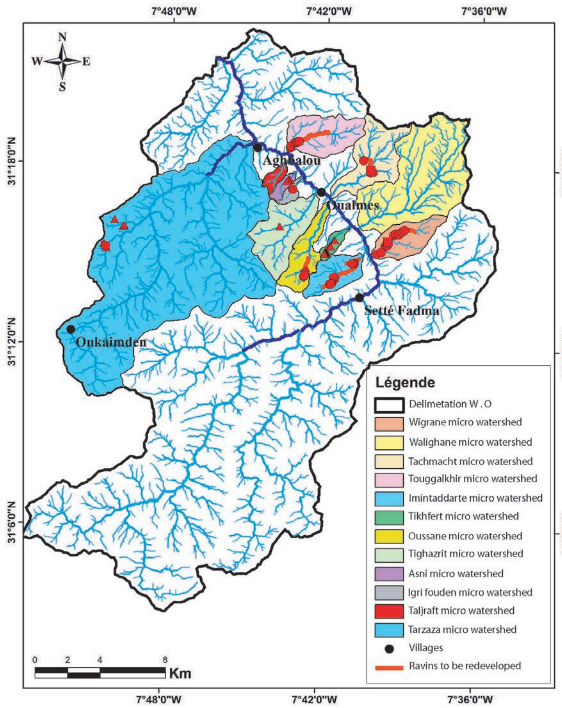

Figure 16. Map showing the ravines in the micro-watersheds with heavily damaged thresholds to be redeveloped

In summary, in order to meet the expectations of the local population and authorities, it is necessary to review the policies and strategies adopted to avoid previous failures, starting with the establishment of a roadmap as a guiding document (Fig. 16). Based on this study/diagnosis, it is evident that some micro-watersheds in the Ourika sub-watershed, such as Wigrane, Tachmacht, Touggalkhir, Imintaddarte, and Oussane, are severely degraded (Fig. 17). This situation is primarily due to the aforementioned factors. The timid and inadequate actions taken so far seem insignificant compared to the magnitude of the degrading factors. At this stage, it is important and urgent to act to restore the environment; otherwise, the trend will lead to detrimental consequences on both human (overpopulation, malnutrition, possible scarcity, social and political conflicts) and economic levels (reduced income for the population, poverty).

Based on the various field observations and calculation results, the following observations can be distinguished:

- the current condition of the torrent correction thresholds does not allow them to fulfill their anti-erosion role. The majority of them are unstable, with their spillways, streambeds, or wings destroyed;
- the instability of the thresholds is due to poor foundations, inadequate anchoring, or non-compliance with stone filling standards (shape, quality, size, and calibration), as well as the neglect of these structures after their installation (complete lack of monitoring and surveillance). This has led to the resurgence of regressive and progressive erosion between the thresholds;
- the sedimentation of transported torrents has reached 100% or even more in most cases, which indicates that the threshold has reached the end of its lifespan, especially with limited biological recovery that could replace the role of the threshold;
- weak or sometimes completely absent vegetation cover promotes the formation of new chaâbets (ravines) due to remarkable erosive activity.

Despite the implementation of anti-erosion measures since 2001, linear erosion activity remains significant, if not excessive. The degradation rate of these structures varies from one micro-watershed to another. The Wigrane, Tachmacht, Touggalkhir, Imintaddarte, and Oussane micro-watersheds, which have relatively steeper slopes and a high drainage density, are most affected by the impacts of carried blocks and intensified by violent torrential flows. Gabion thresholds struggle to withstand aggressive sediment transport in these flow networks.

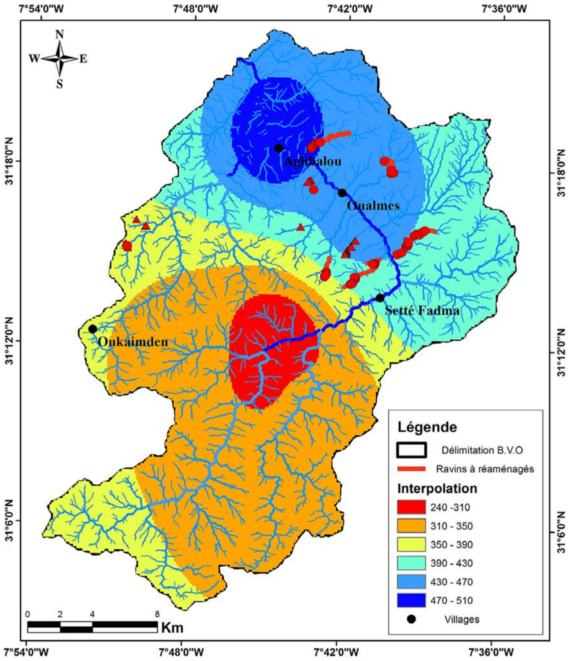

Figure 17. Map of the interpolation of the BVO with the ravines to be redeveloped

In the absence of maintenance and monitoring, the implemented techniques fail to achieve the objectives of preventing silting in these structures, thus reducing their lifespan. The techniques are often implemented and then left on their own, and the local population, unconvinced of their benefits and not involved in their implementation, does not welcome these measures imposed by the administrative authorities.

CONCLUSIONS

The climate of the Ourika watershed is characterized by its high spatial and temporal variability, with precipitation varying in amount, intensity, and geographic distribution. The average annual rainfall is around 500 mm with a coefficient of variation of 34%.

The Ourika region is known for its high and abundant relief, with two-thirds of the basin's surface located between 1600 and 3200 meters. As part of the High Atlas hydro-system of Marrakech, the Ourika river has a violent and torrential character due to its impermeable substrate, sparse vegetation cover, and steep slopes. Its north-northwest orientation exposes it to Atlantic disturbances that can generate intense rainfall.

The combination of these factors leads to sudden and violent fluctuations in river flow. The incision and erosion capacity of the Ourika river are significant, with a consistently high sediment load. Although with varying intensities, these rapid floods recur, despite the implementation of various measures to mitigate their effects, including a flood warning and announcement system (SPAC). Some of these infrastructures have proven to be effective, while others have not withstood subsequent high floods (Saidi et al., 2010).

To address this recurring danger and further improve the protection of this picturesque landscape, recognized as an essential resort for both locals and tourists, structural measures have been implemented in a participatory and partnership framework, involving all stakeholders committed to the success of this noble task.

The objective of our study was to trace the various actions carried out in this regard. Due to logistical reasons, our survey focused on twelve micro-watersheds covering an area of 203.35 km². We were able to identify and inventory all the implemented structures, including:

- 545 thresholds distributed as follows: 62 masonry thresholds (13.37%), 247 gabion thresholds (45.32%), and 236 dry stone thresholds (43.30%);
- reforestation actions using Aleppo Pine and Cedar, primarily concentrated in the micro-watersheds of Tarzaza, Touggalkhir, Walighane, Taljarft, Asni, Igri Foudene, Tighazrit, and Oussane;
- other noteworthy infrastructure includes Route 2017, connecting Ourika and Setti Fadma over a distance of 22.16 km; Route 2030 from Setti Fadma to Oukaimden covering 35.16 km, and an estimated network of rural roads spanning 171 km;
- a traditional water network composed of seguias and tafraoute (water recovery reservoirs to cope with drought periods);
- stone terraces to protect mini agricultural plots.

Despite the importance of these structural measures, they remain insufficient, especially in terms of their resistance and effectiveness. Therefore, it is necessary to undertake more integrated, improved, and appropriate projects, including a threshold policy, reforestation, combating poaching, shepherding, and cattle herding, as well as the development and enhancement of micro-plots. Additionally, there should be an expansion of the hydraulic and road network, along with projects that prioritize the well-being of the local population in harmony with ecosystem preservation and the promotion of mountain tourism.

REFERENCES

1. Affo Biao Kokou A. 2015. Contribution à l’étude phytoécologique et à l’évaluation de la qualité des écosystèmes ripisylves du bassin versant de l’Ourika (haut-atlas) (Mémoire de 3ème cycle). Ecole Nationale Forestière d’Ingénieurs, Salé. 99.
2. Bochet E., Poesen J., Rubio L. 2000. Mound development as an interaction of individual plants with soil, water erosion and sedimentation processes on slopes. Earth Surface Processes and Landforms, 25, 847–867.
3. Beuselinck L., Steegen A., Govers G., Nachtergaele J., Takken I., Poesen J. 2000. Characteristics of sediment deposits formed by intense rainfall events in small catchments in the Belgian Loam Belt. Geomorphology, 32, 69–82.
4. Combes F., Hurand A., Meunier M. 1995. The mountain forest: a flood remedy, in: Research report no. 3, BVRE by Draix, Cemagref Éditions, Grenoble,113–121.
5. Doukkali O. 2003. Evaluation of the longevity and performance of water and soil conservation techniques in the Ourika- DREF watershed of the High Atlas Morocco. 3rd cycle thesis ENFI, Salé, Morocco, 113.
6. El Alaoui el Fels A., Saidi M., Errachidi S. 2003. Flood frequency analysis and generation of flood hazard indicator maps in a semi-arid environment, case of Ourika watershed (western High Atlas, Morocco).
7. GTZ. 1998. Causes of soil degradation and approaches for promoting a sustainable land use, edit, Markgraf Verlag, Germany, 98.
8. Ilmen R. 2004. Contribution to the study of recreational use of the Ourika Valley with a view to its development. (Thesis of the 3° cycle of the National Forestry School of Engineers of Salé). ENFI, Salé (Morocco), 133.
9. Moir W.H., Ludwig J.A., Scholes R.T. 2000. Soil erosion and vegetation in grasslands of the Peloncillo Mountains, New Mexico. Soil Science Society of America Journal, 64.
10. Moret L. 1931. Geological research in the Atlas of Marrakech. Note and Mr. Serv. Mines and geol map. Morocco, 18, 262.
11. Namous M. 2012. Quaternary Evolution And Current Dynamics Of A Geomorphological System Of Active Chain Front: The Example Of The Ourika Watershed (Morocco). Thesis. Faculty of Sciences Semlalia Marrakech, Morocco.
12. O’Loughlin C., Xinbao Z. 1986. The influence of fast-growing conifer plantations on shallow landsliding and earthflow movement in New Zealand steeplands. 18th IUFRO World Congress, Ljubljana (Yugoslavia), IUFRO.
13. Sabir M., Roose E., Merzouk A., Nouri A. 1999. Traditional management techniques water and anticorrosive control in two terroirs of the western Rif, Morocco, ORSTO Bulletin, Rome, Italy, 139–147.
14. Saidi M., Daoudi L., Aresmouk M.E., Fniguire F., Foukrim S. 2010. The floods of the oued Ourika (High Atlas, Morocco): Extreme events in a semiarid mountain context. Comunicações Geológicas, t. 97, Lisbon, 113–128.
15. Saidi M.E. 1994. Genesis and spread of floods in a sub-arid environment: Example of the oued Souss (Morocco). Bulletin of the Association of French Geographers, 1, 94–111, Paris.

16. Ouhammou A. 1991. Overview on the staging of the vegetation of the Ourika basin (High Atlas of Marrakech, Morocco). Monthly bulletin of the Linnean Society of Lyon 60, 401–405. https://doi.org/10.3406/linly.1991-14131
17. Proust F. 1961. Stratigraphic, petrographic and structural study of the Block Oriental of the Ancient Massif of the High Atlas (Morocco).thesis, Montpellier, France, 272.
18. Proust F. 1973. Stratigraphic, petrographic and structural study of the Eastern Block of the Ancient High Atlas Massif. Morocco. Memo Note. Serv. Geol. Morocco, 254, 15–53.
19. Proust F., Petit J.P., Tapponnier P. 1977. The Tizi n’test accident and the role of stalling in the tectonics of the Western High Atlas (Morocco). Bulletin of the Geological Society of France 7, 541–551.
20. Van-Dijk P.M., Kwaad F.J.P.M., Klapwijk M. 1996. Retention of water and sediment by grass strips. Hydrological Processes, 10, 1069–1080.
21. Villard N., Schmitt M., Tacnet J.M. 2014. Torrential correction: design & feedback on an innovative cable dam. National Days of Geotechnics and Geology of the Engineer JNGG 2014 Ŕ Beauvais July 8–10.
22. Viles H.A. 1990. The agency of organic beings: a selective review of recent work in biogeomorphology. In Vegetation and erosion: processes and environments. Ed. J.B. Thornes. Chichester, John Wiley & Sons Ltd, 5–24.
23. Rey F. 2001. influence of the spatial distribution of vegetation on the sedimentary production of marl gullies in the Southern Alps. Doctoral thesis. Joseph Fournier University, Grenoble I. France, 183.
24. Mathys N. 2003. Erosion quantification in the small marly experimental catchments of Draix (Alpes de Haute Provence, France). Calibration of the ETC rainfall–runoff–erosion model, 01. https://doi.org/10.1016/S03418162(02)00122-4