

# EROSION ASSESSMENT AT SMALL HILLSIDE RIVER BASINS IN SEMIARID REGION OF TUNISIA

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The small hillside reservoirs are fundamental for the sustainability of the water resources in the semiarid region of Tunisia. The Tunisian government has initiated a policy of small dam construction since 1990. However, flash floods and severe erosion process are jeopardizing the lifetime of those small hydraulic structures. In response to such threats, there is an urgent need for the assessment of the vulnerability of semiarid watersheds to erosion. In this study, reservoir sedimentation and corresponding catchment attributes data were used to investigate the vulnerability of twenty-three watersheds to erosion in the semiarid Tunisia. Geomorphological indices were extracted from digital elevation models. Rainfall, lithological and vegetation cover data were provided by HYDROMED, an important project studying the Mediterranean semiarid periphery. We used a scoring technique to characterize the lithological and vegetation cover. The Self-Organizing Map of Kohonen was implemented to analyze the data set. The findings revealed three watershed groups on the basis of their proneness to erosion.

**Key Words:** *erosion vulnerability, geomorphological indices, scoring technique, SOM, small catchments, semiarid region of Tunisia.*

## 1. INTRODUCTION

Water shortage is a major concern in Tunisia as well as in most of the Mediterranean countries which are situated in the arid and semiarid climatic zones where the mean annual rainfall does not exceed 550 mm. Furthermore, this climate is characterized by irregular rainfall, drought, poor vegetation cover, severe soil loss and violent erosion during the flood season.

In the beginnings of the 1990s, the Tunisian government launched an ambitious program for constructing small hillside reservoirs in the northern and central region of the country<sup>1</sup>. However, with both the intensive irregular rainfall and severe soil erosion, the lifetime of these hydraulic structures is in jeopardy. Flash floods with high sediment load are threatening many of these reservoirs and some of them have already been filled up with sediment in less than 10 years (after construction). For example, the Sadine reservoir (volume of 44500 m<sup>3</sup>) in central Tunisia was entirely silted up with sediments from two floods in August 1995 and in September 1995<sup>2</sup>. In 1993, a network for studying and observing over

thirty small hillside catchments in the semiarid region of Tunisia was set up to form a hydrological database. In 1996, HYDROMED research project, led by IRD (Research Institute for development) and financed by the European Union, selected several sites for pilot schemes in countries of the Mediterranean periphery: Lebanon, Morocco, Syria and Tunisia. Several researches were carried out within this project. They aimed at building a hydrological model suitable for semiarid Mediterranean catchments, at highlighting the importance of small dams in water harvesting and at studying the sustainability of those hydraulic structures within a semiarid context<sup>3</sup>.

Therefore, a big importance was given to the erosion process and the sedimentation of the hillside reservoirs. Camus *et al.*<sup>4</sup> described the bathymetric measurement technique for the sediment that was used in eight hillside reservoirs. Albergel *et al.*<sup>5</sup> estimated the erosion using USLE (Universal Soil Loss Equation) model in twenty-four watersheds and showed that it is difficult to estimate with a simple model the siltation in the studied reservoirs because of the high variability of erosion intensity. Mahjoub *et al.*<sup>6</sup> considered twenty-three watersheds

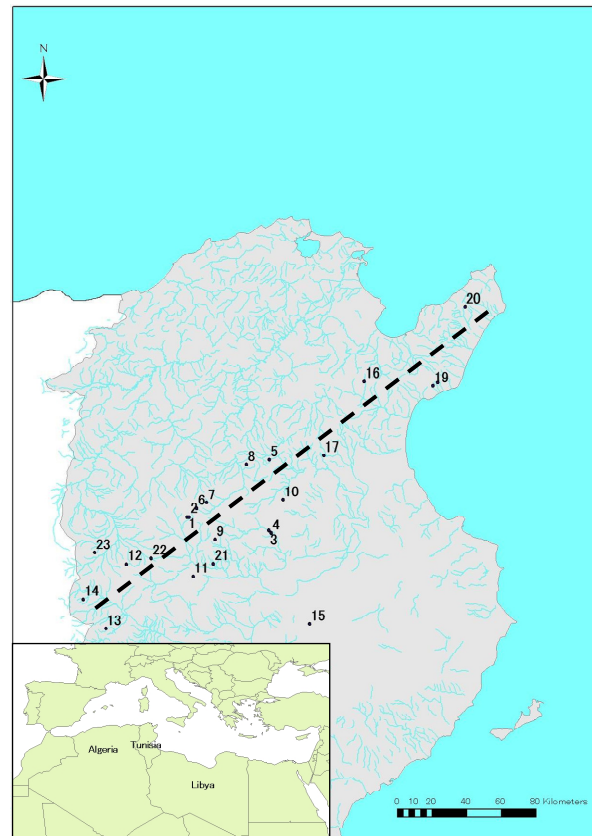
and classified them. This classification was carried out by mean of the principal components analysis (PCA). Two classes were found. The first class represents the catchments with high values of runoff coefficient and specific sediment yield and the second one includes the catchments with low runoff coefficient. Felfoul *et al.*<sup>7)</sup> determined a significant linear relationship between a watershed lithologic number and the dam efficiency for fifteen small dams, indicating that an accurate lithological survey prior to planning of new reservoirs is necessary to reduce the dam siltation. Ayadi *et al.*<sup>8)</sup> made use of hierarchical clustering and the neural network for regionalizing the erosion vulnerability. Findings revealed three groups of watersheds on the basis of their runoff coefficient, global slope index and vegetation cover.

Although catchment geomorphology is believed to be a major factor controlling the catchment erosion process<sup>9),10),11)</sup>, in all those studies more interest was given to factors like the rainfall intensity, the runoff coefficient and the lithological cover to evaluate the erosion risk in the semiarid region of Tunisia. There were no detailed studies about the geomorphological aspect or it was simply described by a single number such as the global slope index.

The hypsometric curve<sup>9)</sup> and the topographic index<sup>12)</sup> are two approaches to extract more information from readily available digital elevation model data and are better functions that describe the catchment surface characteristics than just an average or characteristic values as in the case of single numbers. In a previous work on thirty watersheds of HYDROMED project, we used the hypsometric curve and the topographic index to describe the distributions of their gomorphological characteristics<sup>13)</sup>. We visually classified them into three groups on the basis of the hypsometric integral and the peak frequency of the topographic index distribution.

Integrated analysis of specific sediment yield data with respective geomorphological indices, soil cover, vegetation and rainfall-related attributes could facilitate the understanding of the dominant factors governing the erosion process in the semiarid region of Tunisia. In this present study, twenty-three small hillside catchments were selected. Their corresponding attributes data were derived from different sources. Briefly, the raw data set used in the present study consists of 23 data samples for 6 variables.

A multivariate analysis technique is needed because it is very tough to interpret or to detect any structure in such complex raw data. There is no universally applicable data mining technique in discovering the variety of structures display in data sets. One of the most popular data mining techniques is the Self-Organizing Map (SOM)<sup>14)</sup>. It



**Fig.1** Location of Tunisia and the studied catchments.

was shown that SOM is more robust than traditional methods as PCA and the Clustering Analysis<sup>15),16),17)</sup>. Consequently, in the present study we have chosen SOM algorithm as an alternative method for optimal visualization and clustering of the data set.

This study evaluates erosion process at small hillside catchments in the semiarid region of Tunisia. Information related to the amount of sediment deposition in twenty-three reservoirs was acquired. Corresponding catchment attributes such as the integral of the hypsometric curve, the peak frequency of the topographic index distribution, the annual average occurrence of exceptional rainfall events were calculated. Two more indices were defined by a scoring technique for both the soil and vegetation covers erodibility. The data set analysis was carried out using the SOM.

## 2. STUDY AREA AND DATA PREPARATION

### (1) Selected catchments

In central Tunisia, in the semiarid Dorsal mountains (dashed line in **Fig.1**) that extend from the northeast of the country to the Algerian border in the west, we selected twenty-three catchments smaller than 10 km<sup>2</sup> for our study (see **Fig.1**). They have reliefs ranging from a minimum altitude of 70 m to a maximum altitude of 1352 m. They are

representative of rainfall gradient of the semiarid region of Tunisia, which is 250 to 550 mm of annual rainfall<sup>13)</sup>.

**(2) Data preparation: Calculation of lithological and vegetation erodible cover indices**

In a previous work, we acquired the digital elevation models of the twenty-three watersheds from the Shuttle Radar Topographic Mission (SRTM) data that is available as 3-Arc Second resolution DEMs (<http://srtm.csi.cgiar.org/>). We used GIS software to obtain the hypsometric curve and the topographic index distribution for each catchment. Self-developed tools were used to calculate the hypsometric integral (HI) and Peak Frequency (PFR) of topographic index distribution<sup>13)</sup>.

The rainfall data were observed during a period range of about 10 years. Investigations have shown that the 15 min duration is the most representative duration for erosive rainfall in the semiarid region of Tunisia<sup>18)</sup>. We calculated the annual average occurrence of exceptional events having peak intensity more than the following thresholds 5, 10 and 15mm. We found that the 15 min duration rainfall events with Peak Intensity (IP15) more than 15 mm are the most correlated with the specific sediment yield observations on the twenty three studied watersheds. Results of rainfall IP15 calculation are reported in **Table 1**.

Besides rainfall, previous studies on sediment yield in Mediterranean areas have revealed that lithology of the catchment also has a dominant effect. Lahlou<sup>19)</sup> showed that catchments with important areas of marls and clays have a

significantly higher Specific Sediment Yield (SSY) compared to catchments of sand, which have higher SSY than catchment in limestones or sandstones. The lithological data came from the work of Temple-Boyer<sup>20)</sup>. It describes the percentage of the catchment area which is covered by lithological type of rock. The twenty-three surveyed catchments were given scores for the lithology, vegetation cover. Score 0 represents stable rocks such as limestone and sandstone which have low erodibility degree, score 0.5 is given to the sand and 1 represents the marl and clay which are strongly erodible material. A Soil cover Erodibility Index *SEI* is calculated as follows (see **Table 1**):

$$SEI = \sum_i^{n_L} a_{L_i} sc_{L_i} \tag{1}$$

where  $a_{L_i}$  is the ratio of catchment area covered by lithology  $i$ ,  $sc_{L_i}$  is its score and  $n_L$  is the number of the different soil components.

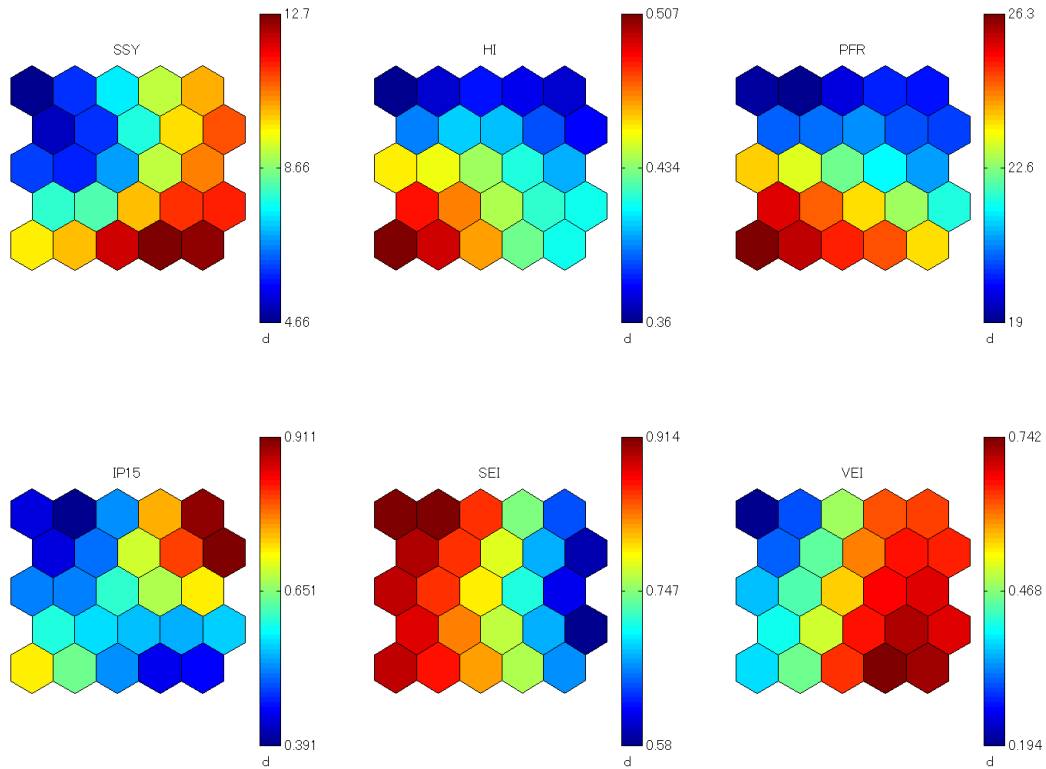
The vegetation cover of sloping land plays also a very important role in the sediment production process as well. A distinction was made between the bare lands which are highly weathered, the cultivated lands and the forests with a low erosion degree. Catchments were also classified according to the predominant vegetation cover (% of soil that was covered). The bare lands were given the score 1, the cultivated lands were scored 0.5 and the forests which are the less eroded were scored 0. A Vegetation cover Erodibility Index *VEI* is analogically defined as *SEI* (see **Table 1**):

$$VEI = \sum_i^{n_V} a_{V_i} sc_{V_i} \tag{2}$$

**Table1** Watershed attributes for 23 studied watersheds in semiarid region of Tunisia.

No	Watersheds	Erosion		Morphology		Rainfall	Lithology					Vegetation			
		SSY (m <sup>3</sup> /ha/yr)	HI	PFR (%)	Occ. IP15	MRL (%)	CLA (%)	SND (%)	LIM (%)	SST (%)	SEI	F (%)	CL (%)	BL (%)	VEI
1	Sadine1	8.55	0.44	19.87	0.89	90	0	0	10	0	0.9	0	68	32	0.66
2	Sadine2	15.54	0.55	22.54	0.60	90	0	0	10	0	0.9	38	62	0	0.31
3	Fidh Ben naceur	9.26	0.43	21.00	0.50	80	0	0	20	0	0.8	0	57	43	0.72
4	Fidh Ali	13.95	0.41	27.24	0.25	80	0	0	20	0	0.8	0	12	88	0.94
5	Mrichet	6.51	0.50	26.46	0.63	90	0	0	10	0	0.9	0	92	8	0.54
6	Hadada	6.85	0.45	21.53	0.18	30	0	0	70	0	0.3	0	76	24	0.62
7	Jannet	16.86	0.38	24.64	0.36	70	0	0	30	0	0.7	0	62	38	0.69
8	Hanach	10.66	0.41	26.30	0.20	90	0	0	10	0	0.9	1	43	56	0.78
9	Abdessadok	9.70	0.31	21.38	0.50	80	0	0	0	20	0.8	0	57	43	0.72
10	Dekikira	12.73	0.44	21.38	0.36	60	0	0	30	10	0.6	33	25	42	0.55
11	Es Senaga	10.30	0.33	20.30	0.60	40	0	0	10	50	0.4	0	34	66	0.83
12	Echar	1.67	0.45	21.61	0.43	90	0	0	10	0	0.9	0	81	19	0.60
13	Abdeladim	1.42	0.33	17.53	0.08	100	0	0	0	0	1.0	20	76	4	0.42
14	Arara	14.89	0.40	17.23	0.11	90	0	0	10	0	0.9	59	41	0	0.21
15	Mouidhi	10.05	0.42	18.46	0.45	50	10	0	40	0	0.6	0	10	90	0.95
16	Sbaihia	8.72	0.47	28.07	0.36	90	0	0	10	0	0.9	80	20	0	0.10
17	Saadine	15.32	0.35	21.64	1.20	70	0	0	30	0	0.7	30	70	0	0.35
18	Es Segir	0.98	0.44	24.31	0.40	0	20	80	0	0	0.6	20	80	0	0.40
19	Maleh	6.60	0.50	30.00	0.67	0	90	0	0	10	0.9	40	30	30	0.45
20	Kamech	17.53	0.53	23.79	0.55	0	80	0	0	20	0.8	0	75	25	0.63
21	brahim	8.43	0.40	17.62	0.50	60	0	0	35	5	0.6	30	27	43	0.57
22	baouejer	1.73	0.34	22.15	0.50	90	0	0	10	0	0.9	80	20	0	0.10
23	Mirra	3.51	0.35	20.47	0.55	90	0	0	10	0	0.9	90	10	0	0.05

No: The number corresponds to the watershed numbers in **Fig.1** and **Fig.3**, SSY: specific sediment yield, HI: hypsometric integral, PFR: peak frequency of the topographic index distribution, IP15: annual average occurrence of 15 min rainfall events with peak intensity superior to 15 mm, MRL: marl, CLA: clay, SND: sand, LIM: limestone, SST: sandstone, SEI: soil cover erodibility index, F: forest, CL: cultivated lands, BL: bare lands, VEI: vegetation cover erodibility index.



**Fig2.** Component planes of SOM. Correlation between HI and PFR can be hunted from this SOM visualization.

where  $a_{v_i}$  is the ratio of catchment area covered by vegetation  $i$ ,  $sc_{v_i}$  is its score and  $n_v$  is the number of the different vegetation covers.

Sediment yield measurements were made on the basis of bathymetric observations of sediment volumes in each watershed reservoir. Measurements started in 1993 with up to five observations for each reservoir during about 10 years. The sediment yield is standardized by the total watershed area and thus we obtained the observed SSY.

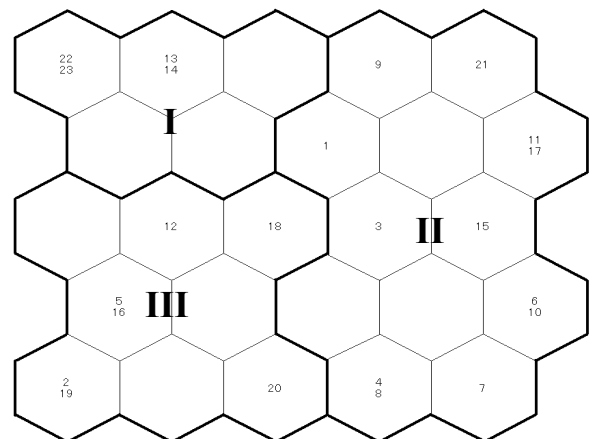
### 3. METHODOLOGY

SOM was invented by Teuvo Kohonen a professor of the academy of Finland, and provides a way of representing multidimensional data in much lower dimensional spaces usually one or two dimensions (lattice). This process of reducing the dimensionality of vectors is essentially a data compression technique known as “vector quantization”<sup>14)</sup>. In addition, the Kohonen technique creates a network that stores information in such a way that any topological relationships within the training set are maintained. A SOM is unsupervised learning algorithm. It does not need a target output to be specified unlike many other types of network. From an initial distribution of random weights, and over many iterations, the SOM eventually settles into a map of stable zones.

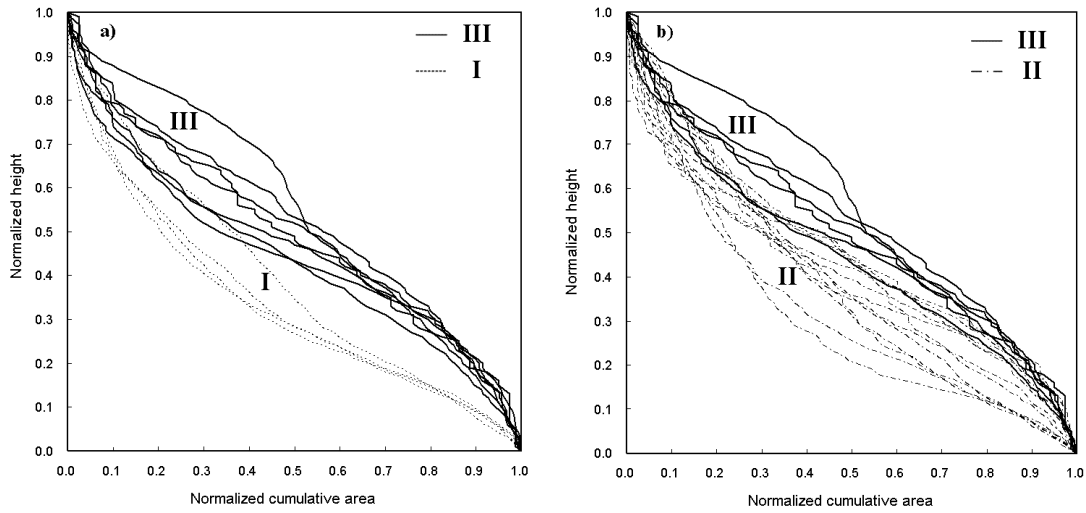
Actually, in our study the clustering procedure

is based on two-level approach, where the data set is first clustered using SOM, and then, the SOM is clustered by k-means. The k-means algorithm is one of the best-known classic statistical clustering methods. It is essentially the same as Kohonen’s learning law except that only the winner is updated, and the concept of neighborhood does not exist. The different values of  $k$  (predefined number of clusters) were tried. Finally, the best classification with the lowest Davies-Bouldwin index was chosen<sup>21)</sup>.

### 4. RESULTS AND DISCUSSION



**Fig.3** Clusters of the trained SOM units. The Latin numbers are labels of the three groups of watersheds. The numbers written inside the units indicate the watersheds label.



**Fig.4.** The Hypsometric integral of group III is bigger than the group I and II.

Input variables for SOM are: specific sediment yield ( $\text{m}^3/\text{ha}/\text{year}$ ), hypsometric integral, peak frequency of the topographic index distribution (%), the annual average occurrence of exceptional events having peak intensity more than 15 mm (events/year), soil erodibility index and vegetation erodibility index. In this work, the SOM map has been chosen as a rectangular grid with number of nodes  $nb$  determined using the following formula of Vesanto *et al.*<sup>22)</sup>:

$$nb = 5 \times \sqrt{n} \quad (3)$$

where  $n$  is the number of samples. The hexagonal lattice was used to display the network nodes on the SOM, because it preserves better the neighborhood relations than rectangular one.

After selecting a map size of  $5 \times 5$  the map is trained with the input variables. In **Fig.2**, six Component Planes (CP) and their color bars on the right were used to visualize the distribution of the twenty-three input vectors for six different variables via the  $5 \times 5$  nodes map. The red color corresponds to high values of the variable, the green color represents moderate values and the blue color matches with low values of the studied variable. The CP can be used for correlation hunting. For example, as it can be observed in **Fig.2**, the color shades of SOM nodes in SSY and VEI exhibit a decrease of the sediment yields and the vegetation cover erodibility from the right to the left. The more the soil is protected by vegetation the less it is eroded. We can also notice in **Fig.2** that HI and PFR of the topographic index distribution are positively correlated as it was mentioned in a previous study<sup>13)</sup>.

To accurately determine the catchment groups, the clustering is carried out using a two-level approach, where the data set is first clustered using SOM, and then, the SOM is clustered by k-means. Thus the watersheds were classified into 3 groups labeled in Latin numbers (I, II and III) where each

group represents a union of SOM neurons (see **Fig.3**). Group I includes the watersheds 13, 14, 22 and 23. The maximum number of watersheds is in the group II and they are 1, 3, 4, 6, 7, 8, 9, 10, 11, 15, 17 and 21. Finally, the group III contains the watersheds 2, 5, 12, 16, 18, 19 and 20.

In **Fig.3**, we can clearly observe that borders between clusters I and III and between II and III are due to the discrimination effect of the Hypsometric Integral (HI). In fact overall watersheds, the HI in group III is the highest. **Fig.4a** and **Fig.4b** show that the shape of the hypsometric curves of the group III is convex whereas it is concave for the groups I and II. The HI is an indication of the watershed proneness to erosion<sup>9)</sup>. Concave shaped hypsometric curves indicate that the watershed is stabilized and the convex hypsometric curves indicate more proneness to the erosion process. The watersheds of the group III have an HI between 0.44 and 0.55, so they are highly susceptible to erosion. For group I, the HI values were ranged between 0.33 and 0.40. They are less prone to the erosion than group III. The watersheds of the group II have intermediate values of HI between the group I and III.

The **Fig.2** shows that *VEI* is also a good discriminator factor for the studied watersheds. *VEI* decreases from the right to the left of the CP. Therefore, we can see in **Fig.3** a border separating a sparsely vegetated group II and densely vegetated groups I and III.

We can notice from the **Fig.2** that the erosive rainfall events (IP15) affect more the watersheds belonging to cluster II. There is less erosive events occurrence in the group I and III.

Finally, the soil cover erodibility index lithology (SEI) shows a very poor correlation with specific sediment yield in the study area, although their strong correlation has often been reported<sup>19)</sup>. This observation suggests that the role of lithology is masked due to its association with other factors.

## 5. CONCLUSION

The studied watersheds are split in three groups along the Dorsal area. In the central part of the Dorsal mountains, the watersheds belonging to the group II are the most vulnerable to the erosion since they are exposed to frequent erosive rainfall events, the vegetation cover is sparse and the HI values are relatively big. In the western part of the Dorsal axis near the Algerian border, the watersheds of the group I are less prone to erosive rainfall events, the vegetation cover is dense, the HI values are relatively the lowest and hence those watersheds are the less prone to erosion. The group III in the extreme north of the Dorsal axis, are submitted to a moderate erosion intensity. The watersheds 12, 2 and 5 geographically belongs to group I and II respectively. However they are clustered within the group III because they have big HI values.

The watersheds of the group II needs construction of both vegetative and mechanical soil and water conservation structures to reduce the sediment load and conserve water for integrated watersheds management. However, both the group I and III need minimum mechanical and vegetative measures to reduce sediment loss but may require more water harvesting type structures to conserve water at appropriate locations in the watershed for conjunctive water use.

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