

Spatial and inter-annual variability of specific sediment yield: case of hillside reservoirs in Central Tunisia

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Abstract Water erosion is the major process responsible for soil loss in Central Tunisia. It represents a main risk of sedimentation which threatens the lifetime of water and soil conservation works in the region, such as hillside reservoirs. This paper focuses on the study of spatial and inter-annual variability of specific sediment yield (SSY) estimated from sediment yield (SY) of 23 small watersheds of hill reservoirs located in the Tunisian Dorsal and the Cap Bon regions. The calculated values of mean inter-annual specific sediment yield varied from 180 to 3298 t/km²/year, over a period of 12 years (from 1994 to 2006). The selected catchments were classified into three groups according to their SSY data. The SSY map, elaborated with a geographical information system (GIS), showed an important spatial variability between watersheds of the same group. Moreover, analyses of the coefficient of variation (CV) showed that 70% of the considered sites demonstrate a tendency to moderate and high inter-annual variability of SSY. In order to identify the principal factors governing variability of erosion and sedimentation, a

multiple regression analysis was carried out using nine parameters characterizing morphology, topography, land cover, climate and protection works of the 23 considered sites. The generated model revealed that 85% of SSY variability is correlated to seven principal factors, which are drainage area (A), rainfall intensity recorded in 30 min (I_{30}), percentage of water and soil conservation works, percentage of clay and carbonate in soils, vegetation land cover, overall slope index (I_G) and rainfall amount (R_a). The obtained SSY results were compared to others cited in a large bibliographical synthesis of studies carried out at the planet scale. We deduced that the SSY values obtained in this study are among the relatively high series in the world. The high variability of specific erosion rates in Central Tunisia is believed to be related to the semi-arid climate, characterized by the irregularity and the severity of storms and the spatial and temporal variability of other multiple factors affecting erosion processes.

Keywords Water erosion · Specific sediment yield · Watersheds · GIS · Multiple regression · Central Tunisia

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Résumé L'érosion hydrique est le processus principal responsable de la dégradation des sols en Tunisie Centrale. En effet, il représente un risque majeur d'envasement qui menace la durée de vie des travaux de conservation des eaux et des sols dans la région, telle que les retenues collinaires. Cette étude s'intéresse à la variabilité spatio-temporelle de l'érosion spécifique, dans 23 bassins versants de lacs collinaires, estimée à partir de leurs taux d'envasement. En effet, ces valeurs montrent que l'érosion spécifique moyenne interannuelle varie entre 180 et 3298 t/km²/an, sur une période de 12 ans (à partir de 1994 jusqu'à 2006). Dans cette étude on propose une typologie des bassins versants sélectionnés selon leurs taux d'érosion

spécifique et leurs taux d'envasement. La carte des taux d'érosion spécifique, élaborée moyennant un système d'information géographique (SIG) a montré une importante variabilité spatiale de l'érosion spécifique entre les bassins versants d'un même groupe. L'analyse de l'écart type de l'érosion spécifique a dévoilé que 83% de la totalité des sites étudiés présentent une tendance à une variabilité inter-annuelle modérée à forte du processus d'érosion. Afin d'identifier les facteurs qui contrôlent cette variabilité on a procédé à une analyse de régression multiple sur un ensemble de 9 variables caractérisant les 23 bassins choisis. Le modèle élaboré montre que 85% de la variabilité de l'érosion spécifique en Tunisie Centrale dépend de 7 principaux facteurs qui sont la surface de drainage (A), l'intensité maximale des pluies enregistrée en 30 mn (I_{30}), la longueur de drain principal (L), le pourcentage des marnes et des argiles dans les sols (ERL), le couvert végétal (LVC), le pourcentage d'aménagement du bassin versant (WSCW) et la hauteur de la lame d'eau ruisselée (R_a). Dans la deuxième partie de cette étude nous avons fait une comparaison entre les valeurs de l'érosion spécifique obtenues dans le cadre de cette étude et d'autres valeurs citées dans une synthèse bibliographique des études effectuées à l'échelle du globe. Nous avons déduit que les taux d'érosion spécifique en Tunisie Centrale sont parmi les valeurs élevées dans le monde, mais ils ne sont pas les plus élevés. Cette importante variabilité des taux spécifiques de l'érosion en Tunisie Centrale est liée au climat semi-aride, caractérisé par l'irrégularité et la sévérité des événements pluvieux et la variabilité spatio-temporelle de plusieurs facteurs affectant le processus érosif.

Mots clés Érosion hydrique · Taux d'érosion spécifique · Bassin versant · SIG · Régression multiple · Tunisie Centrale

Introduction

Water erosion and solids transport represent major problems in the Mediterranean Basin, which is considered as a very sensitive zone to water erosion in all of its forms, for centuries (Roose et al. 2012). Indeed, reservoir siltation causes an annual loss of storage capacity, estimated to be 5 and 15 t/ha/year, for small and large dams in Tunisia (Ben Mammou and Louati 2007). To cope with this alarming situation, the Tunisian Government considered a plan for water and soil resources conservation. Since the 90s, a pilot network of hill reservoir hydrological monitoring was implemented in the Tunisian Dorsal and the Cap Bon regions. This system is monitored by the General Directorate of Planning and Land Conservation (DG/ACTA) of the Tunisian Ministry of Agriculture and the Research

Institute for Development (IRD; Camus et al. 1995). However, water erosion is related to multiple factors (climatic contrast, lithology, topography, etc.) which accentuate the aggressiveness of erosive processes and affect these hill lake reservoirs by sedimentation. Several studies on hill lakes in Central Tunisia showed that their durability is very sensitive to erosion and silting processes. In spite of the abundant bibliography on water erosion and reservoir sedimentation, it appears that most of the undertaken studies focused on sediment yield estimation in particular for small watersheds and did not deal with the spatial variability of water erosion rates at a regional level. In this context the purpose of this study is: (1) to examine the spatial and inter-annual variability of specific sediment yields (SSYs) deduced from sediment yields of small dams in Central Tunisia; (2) to compare SSYs in this particular region to those observed in the Maghreb Region and in the world.

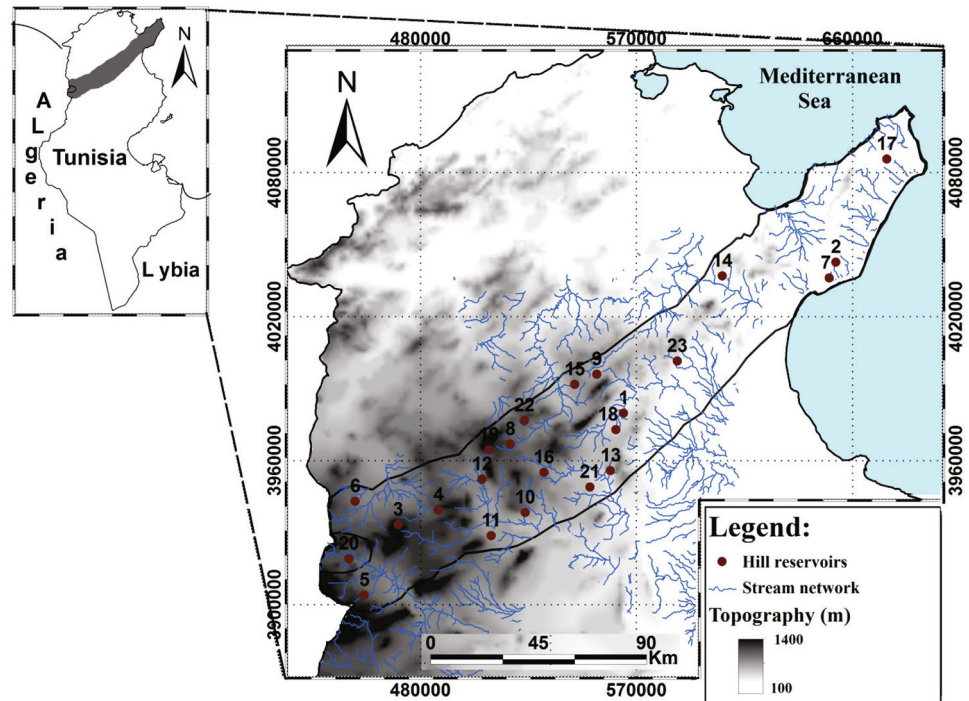
Study area and methodology

Study area

The study area consists of 23 small watersheds located in Central Tunisia, which represents the Eastern prolongation of the Saharian Atlas (Fig. 1). It is prolonged in the Southwest–Northeast direction from the Tuniso-Algerian border to the Mediterranean Sea. This zone is characterized by a semi-arid climate. Rainfall is characterized by its scarcity and its erratic distribution in both time and space. It varies between 250 and 600 mm. Temperatures are forcefully continental, with a mean annual average ranging from 18 to 20 °C. Topographically, the study area contains two large units which are the Dorsal and the Cap Bon regions. It is represented by a chain of high mountainous relief, fairly aligned and characterized by marked erosion forms and very steep slopes. Additionally, these mountains alternate with wide transverse areas, characterized by gentle slopes and crossed by many streams in alluvial plains, which are sensitive to water erosion (Sfar Felfoul et al. 2003). The altitudes of the high peaks decrease, from “Chaâmbi”, the highest mountain in Tunisia (1544 m), to “Bou Kornine” (576 m) in the Cap Bon region (Ben Slimane 2013).

Geological formations in outcrops are aged from the Trias to the Quaternary (Collinet and Zante 2005). The study region is essentially dominated by impermeable soils and sedimentary rocks. In the examined watersheds, soils are characterized by different infiltration capacities and different degrees of erodibility. However, they are essentially sensitive to erosion as the lithology is mainly marly limestone in the south and clayey gypsum in the north.

Fig. 1 Geographic location of the 23 studied small hillside reservoirs in Central Tunisia



Indeed, a mineralogical study carried out by Baccari et al. (2006) confirms that soil formations in this region are clayey and contain an important percentage of smectites. Overall, soils of the study area are especially of sandy or muddy texture and the main rock types encountered are limestone, gypsum, clay, marl, sand, sandstone and conglomerates (Al Ali et al. 2008). In the study area, soils are better characterized by the degradation of rock material rather than their organic matter content (Cerdan et al. 2004; Cudennec et al. 2007). Consequently, they are not well-developed and often shallow. The young geological relief and the rate of erosion prevent them from reaching maturity.

As for vegetation, the majority of the studied catchments are occupied by a semi-forested environment, more or less anthropized to entirely devoted to agricultural activities, in which olive trees dominate (Morschel 2006). In order to reduce soil loss, widespread water and soil conservation efforts, mainly stone terrace constructions and ches, were undertaken in many parts of the study region.

Methodology

In this study, we are interested in understanding the mode of variability of water erosion processes, on the basis of SSSY data analyses. These were later estimated from sediment yield data, measured in hill reservoirs of the 23 studied watersheds. Indeed, siltation rate in the Tunisian hill lakes was determined adopting the method developed in the Laboratory of Hydrology of the IRD-Tunis Mission, which is

based on regular bathymetry measurements of hill lakes and reservoirs and monitoring of each reservoir (Albergel et al. 2001). Sediment yield calculated between two bathymetric campaigns is obtained by adding the mass of soil exported by the discharged liquid flows to the volume of silt retained in the reservoir multiplied by its density. Next, the sediment yield is divided by the drainage area of the watershed in order to obtain the SSSY. Sediment yield values used in this study are collected from the hydrological publications of DG/ACTA and IRD over the period extending from 1994 to 2006 (DGACTA/IRD 1994–2006).

The methodology adopted in this study is as follows. First, a typology of small watersheds in Central Tunisia according to their SSSY was realized. This typology is based on a simple arrangement of the 23 considered sites into distinct groups according to quartile values (Q_{25} , Q_{50} and Q_{75}) of SSSY data. Then, a geographical information system (GIS) was used to elaborate the spatial distribution map of SSSY data and their coefficient of variation (CVs). These maps were developed in order to characterize the spatial and inter-annual variability of SSSY in Central Tunisia. Moreover, a multiple regression model was developed using the statistical analysis tool 'SPSS' to identify the most important independent factors which explain the origin of the SSSY variability in space and in time. Finally, a cartographic approach was adopted to validate effectiveness of this model and to elaborate the spatial distribution map of the simulated SSSY data.

Table 1 shows the principal physical characteristics of the 23 studied watersheds. The selected sites are organized

Table 1 Principal physical characteristics of the 23 studied watersheds

No.	Catchment name	A (km ²)	I_C	I_G (m/km)	SSY ^a (t/km ² /year)
1	Gouazine	18.1	1.7	18	180
2	Es Séghir	4.3	1.1	41	190
3	Echar	9.2	1.4	35	308
4	Bouajer	4.9	1.3	32	367
5	Abdeladhim	6.4	1.3	45	432
6	Mrira	6.2	1.4	35	665
7	El Melah	0.9	1.2	36	957
8	Hdada	4.7	1.3	94	1099
9	Mrichet Anz	1.6	1.2	72	1218
10	Brahim Zaher	4.64	1.7	80	1366
11	Sénéga	3.6	1.3	87	1457
12	Sadine1	3.8	1.4	106	1469
13	Fidh Naceur	1.7	1.2	55	1652
14	Sbaihia	3.2	1.2	77	1696
15	Hnach	3.9	1.4	104	1725
16	Abdessadok	3.1	1.3	128	1951
17	Kamech	2.5	1.3	40	1966
18	Dkékira	3.1	1.2	37	2309
19	Sadine 2	6.5	1.8	59	2465
20	Arara	7.1	1.5	78	2683
21	Fidh Ali	4.1	1.2	83	2698
22	Jannet	5.2	1.5	67	2869
23	Saadine	2.7	1.4	93	3298

^a Average computed over a period of 12 years (1994–2006)

in an ascending order according to their average SSY data which they present. In fact, these studied watersheds are characterized by stretched forms ($I_C \geq 1$, I_C is Gravius compacity index: $I_C = (0.282P)/\sqrt{A}$, where A is the catchment area in km² and P is the catchment perimeter in km), which indicates well-developed stream networks. Their drainage area oscillates from 0.85 to 18.1 km², with an average drainage area of 4.8 km². The overall slope index [I_G , I_G is the overall slope index (m/km): $I_G = \text{HD}/L$, where HD is the height difference elevation (m) and L is the length of equivalent rectangle (km)] of the different catchments varies from 18 to 128 m/km. SSY values fluctuate from 180 to 3298 t/km²/year, with a mean value of 1540 t/km²/year.

Results

Spatial variability of sediment yield and specific sediment yield in Central Tunisia

Figure 2 represents a diagram of SSY data variation in the 23 selected watersheds in Central Tunisia. Values of the median (Q_{50}) and quartiles (Q_{25} , Q_{75}) of SSY data are

indicated on this diagram. This diagram makes it possible to suppose a typology of three distinct groups of catchments:

- The first group contains catchments (1, 2, 3, 4, 5 and 6) which show the lowest values of SSY ($\text{SSY} < 811$ t/km²/year). This group represents 26% of the totality of the studied sites.
- The second group comprises watersheds with moderate to high SSY data going from 811 to 2138 t/km²/year. They are mainly catchments 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16. This group represents the major part (48%) of the selected sites in this study.
- The last group covers catchments (17, 18, 19, 20, 21, 22 and 23) associated with the highest values of SSY ($\text{SSY} > 2387$ t/km²/year). It represents 26% of the studied watersheds.

Figure 3 represents the spatial distribution map of SSY data in the 23 studied sites in Central Tunisia. This map confirms a typology of three categories of watersheds according to their specific erodibility potential:

- The first category contains catchments (1, 2, 3, 4, 5 and 6) representing sites of low erodibility potential with the lowest SSY values. Sites 3, 4, 5 and 6 are located in

Fig. 2 Diagram of the specific sediment yield data in the 23 studied watersheds

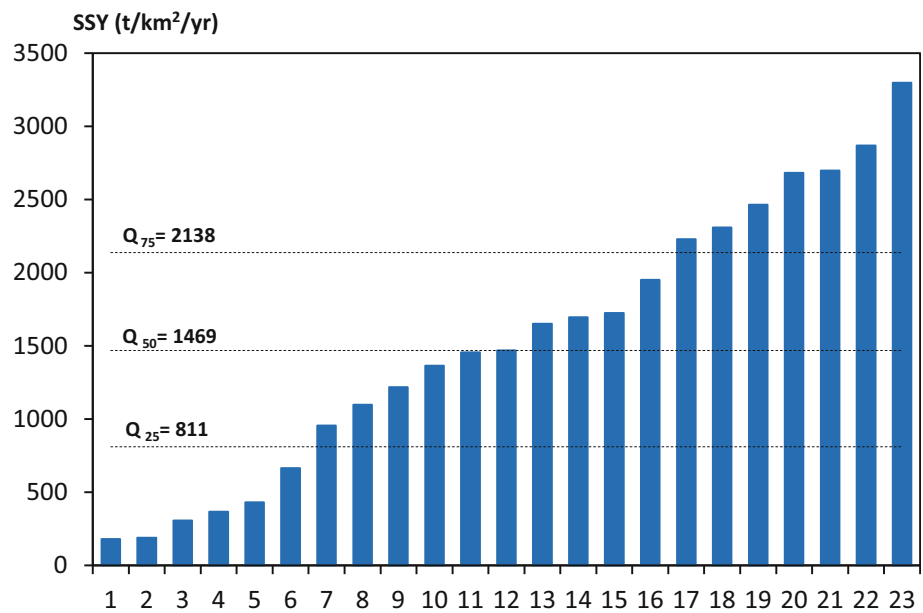
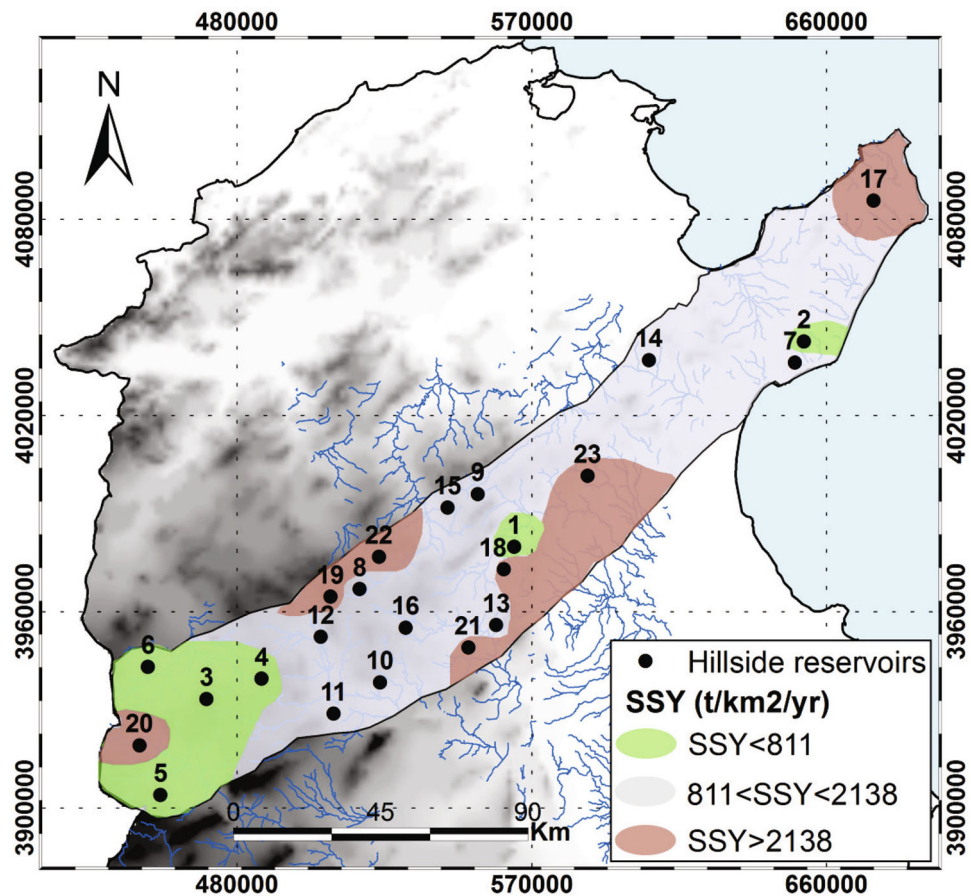


Fig. 3 Spatial distribution of the SSY data in Central Tunisia



the west of the study area. Catchments 1 and 2 are located in central and eastern region. These watersheds are characterized by their important drainage areas. This is the case, for instance, for Gouazine Basin (no.

1) characterized by the largest area ($A = 18.1 \text{ km}^2$). This group of watersheds is also characterized by well-developed and hierarchically arranged stream networks, low relief, multiple water and soil conservation works

and dense land cover, decreasing thereby the quantity of eroded sediments.

- The second category includes catchments (from 7 to 16) which show moderate to high values of SSY. They are mainly located in the center of the study area. Moderate to high values of SSY are governed by the combination of different factors, such as abrupt relief, sparse vegetation and quite marly soil lithology, causing relatively intensive hydrodynamic processes.
- The last category includes basins that show the highest SSY values. These watersheds (17, 18, 19, 21, 22 and 23) extend on both north and south sides from the Tunisian Dorsal. The exception is made for Arara catchment (no. 20), located in the west. These high erodibility potentials are explained by the association between important topography, scarcity of vegetative land cover, scarcity of water and soil conservation works, more marly soils and frequency of flash floods. All of these factors contribute to the generation of high flows, tearing off huge quantities of sediment.

It is also important to note that Fig. 3 shows a significant spatial discontinuity between watersheds of the same category, revealing a large spatial variability of the erosion process in Central Tunisia. This variability can be related to many factors (morphology, topography, lithology, flow hydrodynamic properties, etc.) which control the erosion process in Central Tunisia.

Inter-annual variability of specific sediment yield of hill reservoirs in Central Tunisia

Table 2 shows the statistical characteristics of the SSY data sets for the 23 studied watersheds, during the investigation period from 1994 to 2006. The recorded maximum value of SSY varies from 192 to 3840 t/km²/year while the minimum SSY (SSY_{min}) fluctuates between 128 and 3040 t/km²/year. The corresponding coefficients of variation (CV) oscillates between 1 and 63%, which reveals a considerable temporal variability and heterogeneity of the abrasive process in the Tunisian Dorsal and the Cap Bon regions.

Table 2 makes it possible to subdivide the 23 studied watersheds into three groups according to SSY CVs:

- The first group contains watersheds (2, 3, 12, 15, 16, 19, 22 and 23) with the lowest CV ($CV < 10\%$) indicating low inter-annual variability of SSYs in these sites. This group represents 35% of the totality of the studied sites.
- The second group represents 48% of the selected watersheds. It encloses catchments (1, 4, 7, 8, 9, 10, 13, 17, 18, 20 and 21) which show moderate CVs ($10\% < CV < 20\%$) signifying thereby a moderate to high temporal variability of the erosion process.

Table 2 Statistics of SSY data in each watershed of the 23 studied sites (1994–2006)

No.	SSY (t/km ² /year)				
	Average	Max ^a	Min ^a	SD	CV
1	180	248	128	29	16
2	190	192	187	2	1
3	308	308	304	2	1
4	367	428	304	58	16
5	432	928	240	270	63
6	665	1168	560	169	25
7	957	1137	803	158	17
8	1099	1312	736	224	20
9	1218	1392	1012	145	12
10	1366	1556	1236	156	11
11	1457	1749	1044	346	24
12	1469	1248	832	119	8
13	1652	1899	1443	197	12
14	1696	1137	803	441	26
15	1725	2080	1740	158	9
16	1951	2277	1691	115	6
17	1966	3198	1904	288	15
18	2309	2992	2125	457	20
19	2465	2611	2240	168	7
20	2683	3105	2256	351	13
21	2698	3840	2299	476	18
22	2869	3040	2765	106	4
23	3298	3632	3040	303	9

SD standard deviation, CV coefficient of variation

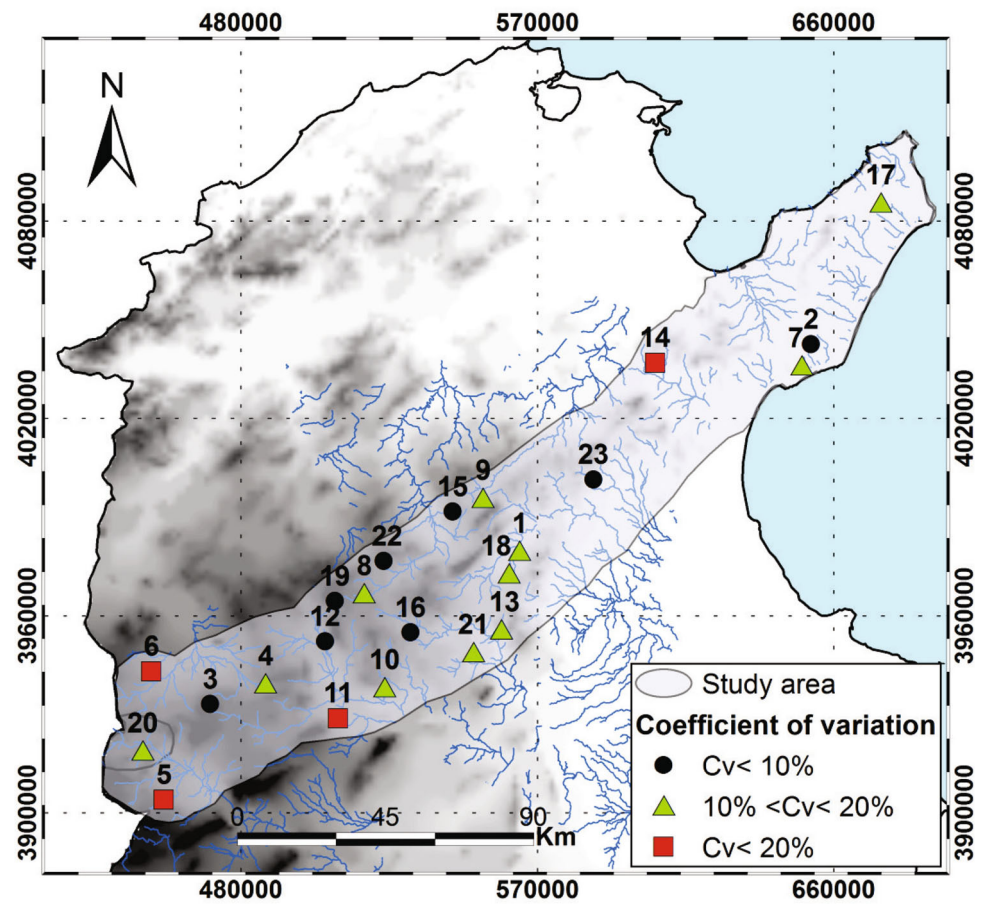
^a Maximum and minimum values of SSY computed in each site over a period of 12 years (1994–2006)

- The last group comprises 17% of considered catchments. They are sites (5, 6, 11 and 14) with high CVs ($CV > 20\%$) representative of high inter-annual variability of SSYs.

In general, 65% of the 23 studied catchments illustrate moderate to high inter-annual variability of SSY. This implies a global tendency to aggravate the erosion process, which can be related to global variability of the climatic regime in the region.

Figure 4 represents the spatial distribution of the SSY data CVs in Central Tunisia. Compared to Fig. 3, we note that in the same group of SSY, each watershed presents its own mode of variability. For example, catchments 3, 7 and 14 show moderate SSY values but different orders of inter-annual variability. Indeed, this reveals the character of locality of inter-annual variability of water erosion in Central Tunisia, which can be related to the local variation of dependent factors in each studied watershed. This may explain the spatial discontinuity between watersheds of the same CV group in Fig. 4.

Fig. 4 Spatial distribution of the CV for the SSY data in Central Tunisia



Discussion

Origin of spatial and inter-annual variability of specific sediment yield in Central Tunisia

The 23 studied catchments were classified into three categories according to their corresponding SSY values. They were also classified into three groups on the basis of topographic and geomorphologic characteristics, in many previous studies. Indeed, mature watersheds are associated with the lowest to moderate erodibility potentials. They correspond to catchments of the first and the second group, presenting low to moderate SSY values. Additionally, watersheds characterized by abrupt relief are generally more susceptible to erosion (Khébour et al. 2002). They correspond to catchments of the last group presenting the highest SSY data observed in this study. Moreover, an important spatial discontinuity between watersheds of the same group was noted. This indicates a significant spatial variability of water erosion in Central Tunisia. Previous studies showed a spatial discontinuity between basins of the same category in terms of physical, geomorphological characteristics and erosion rates (Ayadi et al. 2010). In addition, 70% of the studied sites present moderate to high

inter-annual variability of SSY data. This spatial and inter-annual variability of SSY in Central Tunisia may be related to various factors which have influence on erosion processes. We can distinguish between inter-basin factors (vegetation land cover, lithology, morphology, topography, etc.) and intra-basin factors, such as retention capacity of lakes (Ben Othman 2012). It is important to note that the Tunisian Dorsal and the Cap Bon regions, where the 23 studied sites are located, represent environments of large contrasts that are very vulnerable to water erosion (Albergel et al. 2004).

It appears that one factor cannot offer comprehensible justification of the origin of this main spatial and inter-annual variability of SSY. In this context, it would be better and necessary to combine all factors in a statistical study to clarify affinities between them and the variability of the studied processes. A multiple regression analysis was carried out using the statistical analysis tool SPSS. We used eight explanatory variables characterizing morphology, topography, hydrology, land cover and protection works in the 23 studied sites (Table 3). These variables are: drainage area in km^2 (A), length of watershed in km (L), global slope index in m/km (I_G), percentage of clay and carbonate (ERL), percentage of vegetation land cover (LVC),

percentage of soil and water protection works (WSCW), rain intensity recorded in 30 min (I_{30}) and rain amount in mm (R_a). The explained variable in this analysis is the SSY. This regression was carried out in order to explore the principal factors which explain variability of the erosion processes in Central Tunisia. The calibration phase was performed based on the observed SSY data for 10 years (from 1994 to 2004) while the validation exercise used observed SSY data for a 2-year period (from 2004 to 2006).

The following models explain 85% of the variability in observed sediment yield:

$$\text{SSY} = 0.7I_{30} + 0.6I_G + 0.3R_a - 0.5\text{ERL} - 0.4A - 0.2\text{LVC} - 0.4\text{WSCW}. \quad (1)$$

Equation (1) shows that SSY variability depends upon seven principal explanatory variables (I_{30} , I_G , R_a , ERL, A, LVC and WSCW) among the eight used variables in the regression analysis. We note that the variability of SSY is positively correlated with variables characterizing the hydrologic regime, relief and soil lithology. These factors are: intensity of precipitations recorded in 30 min (I_{30}), rainfall amount (R_a), overall slope index (I_G) and percentage of clay and carbonate in soils (ERL). They represent acceleration factors of the erosion processes. Indeed, frequency of intensive precipitations on abrupt relief with marly soils increases the streaming aggressiveness, increasing thereby the eroded quantities of sediments.

SSY variability is inversely proportional to the evolution of factors characterizing morphology (drainage area: A), land vegetable cover (LVC) and water and soil conservation works (WSCW). Negative coefficients signify a reducing effect of these variables on the erosion processes. Indeed, the quantity of eroded sediments decreases for large drainage areas. This explains the case of Gouazine watershed (no. 1) which exhibits an important area compared to the other studied catchments. Also, multiplication

of protection works and dense vegetation land cover decrease the streaming aggressiveness and accordingly the SSY. Roose et al. (2012) indicated that the development of a vegetative cover reduced more or less strongly the risks of erosion and streaming.

The obtained relation (1) reveals that explanatory variables (I_{30} , I_G , R_a , ERL, A, LVC and WSCW) contribute at a rate of 81% to the variability of the explained variable (SSY). So, we infer the complexity of the erosion processes in the Tunisian Dorsal and the Cap Bon regions because of their dependence upon a variety of variables. Touaibia and Achite (2003) confirmed that the complexity related to erosion processes is manifested by an important regional diversity of factors that control it. Water erosion is a fundamental and complex natural process that is strongly modified by a lot of activities such as land clearance, agriculture, forestry, construction, surface mining and urbanization (Alahiane et al. 2014).

In order to validate the obtained model, we tried to measure its aptitude to reproduce observed data. In the present study, the validation exercise was performed based on observed data (SSY) for two hydrological years, from 2004 to 2006, which was not included in the training phase. The obtained model (2) confirms that variability of SSY is mainly allied to variables characterizing the hydrologic regime (I_{30}) and topography (I_G). This Eq. (2) reveals that the contribution of explanatory factors (I_{30} and I_G) in the variability of the explained variable (SSY) is about 85%, $\text{SSY} = 0.8I_{30} + 0.5I_G$. (2)

Both Eqs. (1) and (2) demonstrate that rainfall intensity is the dominating factor which controls the erosion process variability in Central Tunisia, with contribution weights of

Table 3 Statistics of the adopted parameters used in the regression analysis

Parameter	Unit	Max	Min	Mean	SD	CV
A	km ²	18.10	0.85	479	349	0.7
L	km	11.3	1.5	4.2	2.3	0.5
I_G	m/km	128	18	63	29	0.5
ERL	%	70	5	26	17	0.7
LVC	%	89	0	18	23	1.3
WSCW	%	152	1	28	37	1.3
I_{30}	mm/h	252	33	81	53	0.7
R_d	mm	153	7	48	41	0.9
SSY	t/km ² /year	3298	180	1558	942	0.6

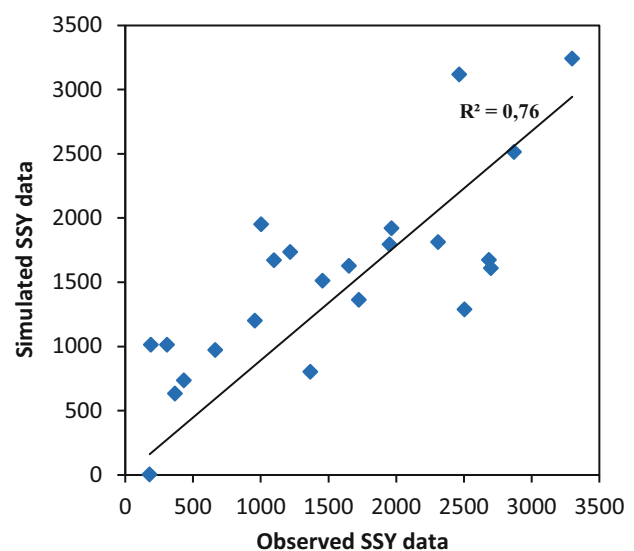


Fig. 5 Scattergram of observed and simulated SSY data (t/km²/year)

0.7 and 0.8, respectively. In fact, in semi-arid Central Tunisia, rainfall intensities recorded at 30 min were often alleged as being the essential cause of erosion (Zahar and Laborde 1998). These torrential intensities occur mostly during autumn and spring seasons on the highest and the central regions of Tunisia, where rainfall is fairly strong and doubles under the continental effect (Albergel et al. 2001). According to Imumorin and Azam (2011), precipitations have as a consequence a reduction in the size of the particles, which, with the indices of consistency, explains the sensitivity of the grounds to water.

The model presented by Eq. (1) may be considered more appropriate and more robust. This model implies a number of explanatory variables which control the erosion

process variability in reality. So, it can provide more reasonable estimations of SSY data. Figure 5 represents the scattergram between observed and simulated SSY data obtained by Eq. (1). This figure shows a reasonably good agreement between observed and simulated values, with a correlation coefficient of 0.76.

Cartographic performances of the GIS ArcMap 10.2 were used in order to validate the efficiency of the obtained model (Eq. 1) representing spatial variability of SSY in Central Tunisia. Firstly, the spatial distribution maps of the seven explanatory factors (I_{30} , I_G , R_a , A , ERL, LVC, WSCW) were elaborated on the basis of a simple interpolation (Fig. 6). Then, each map was multiplied by its corresponding coefficient of regression in Eq. (1) using the

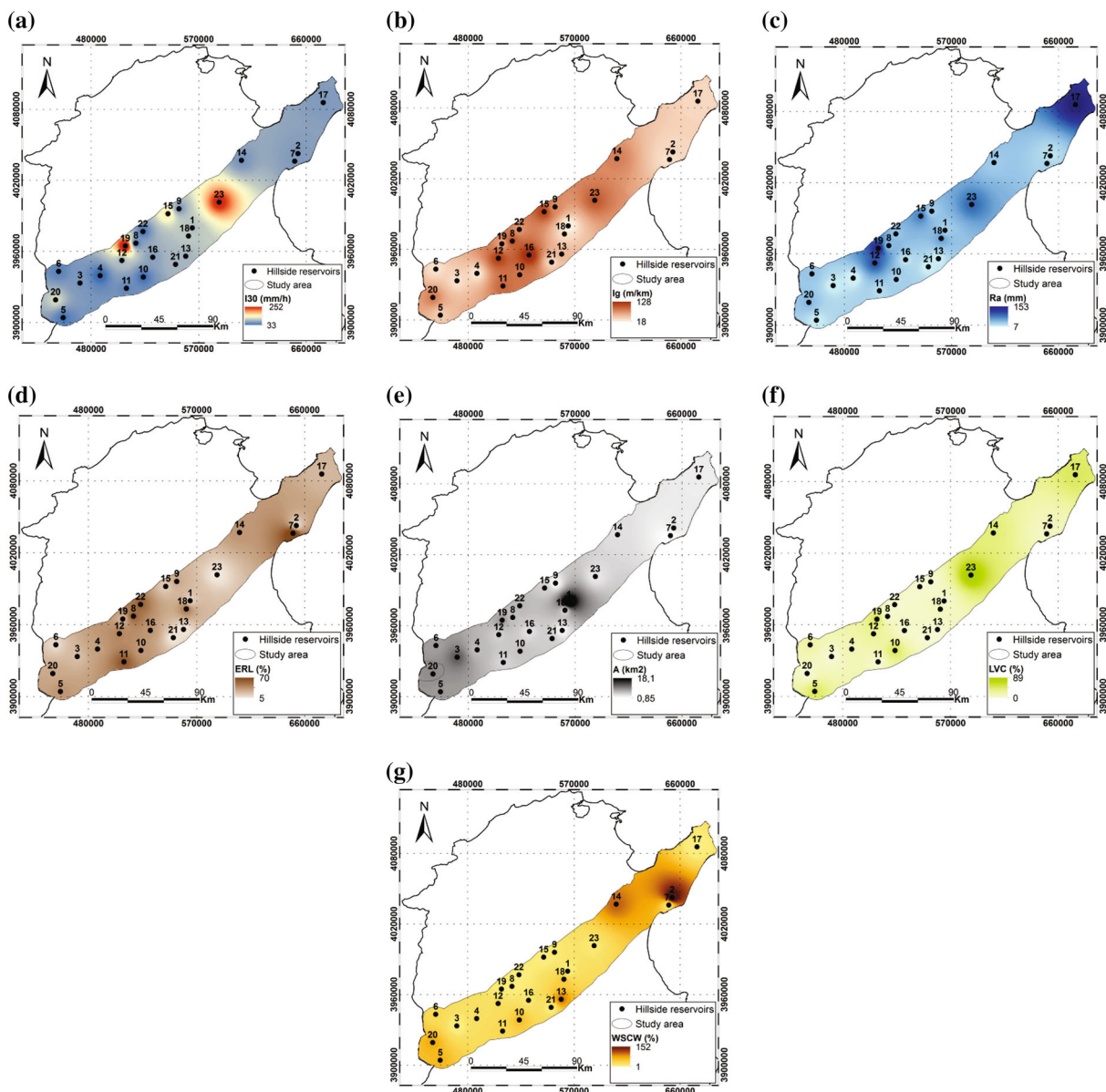
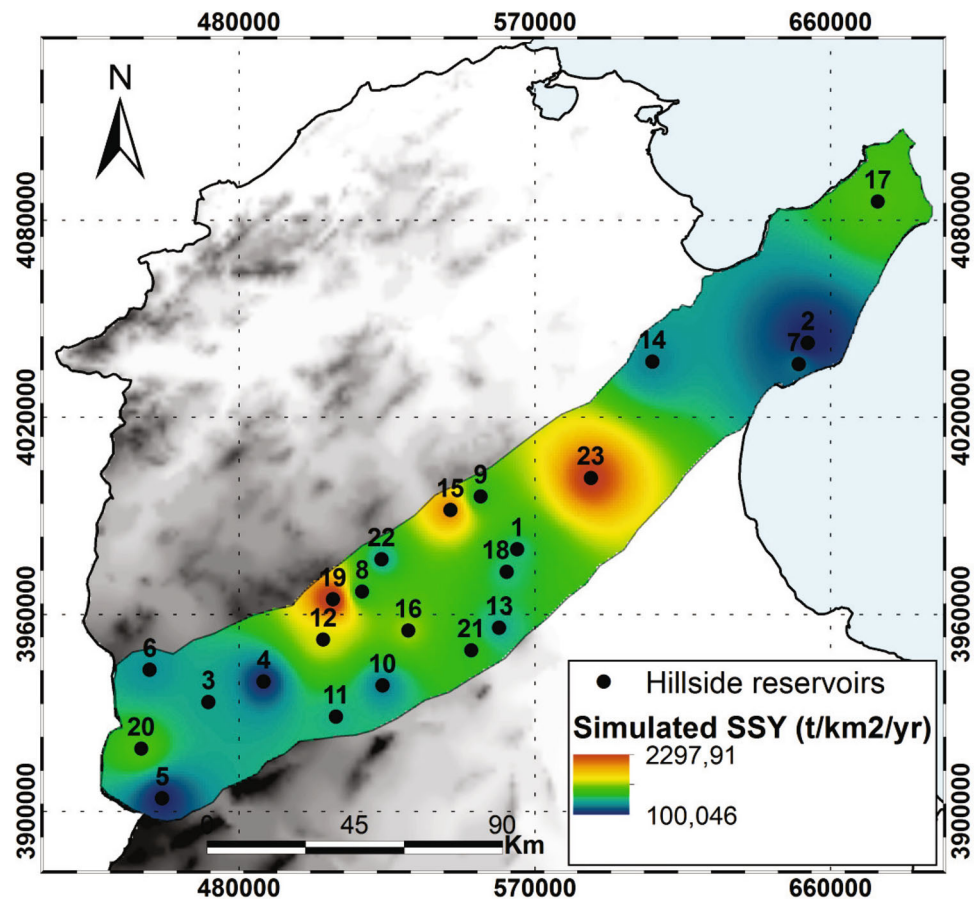


Fig. 6 Spatial distribution of the explanatory factors of water erosion in Central Tunisia

Fig. 7 Spatial distribution of the simulated SSY data ($t/km^2/year$)



'Raster Calculator' functionality in the ArcMap GIS. Finally, the superposition of the seven obtained maps yielded the estimated SSY map.

Figure 7 represents the spatial distribution map of the SSY data estimated by Eq. 1. This map proves that the estimated SSY data are more reasonable. They vary from 100 to 2300 $t/km^2/year$. Indeed, they are close to reality and the observed data which range from 180 to 3300 $t/km^2/year$. Moreover, Fig. 7 shows almost the same subdivision of the 23 studied sites into three groups on the basis of their estimated SSY values. In general, sites located in the western region show weak specific erodibility potential. The central part is characterized by sites with moderate estimated SSY. Watersheds located in the northern and the southern sides of the study area display the highest estimated SSY values.

Central Tunisia SSY values with respect to the bibliography

SSY data for the 23 considered watersheds in this study show an important spatio-temporal variability. They fluctuate between 180 and 3298 $t/km^2/year$ for drainage areas varying from 0.85 to 18.10 km^2 . Also, it appears that this is mainly related to the inconsistency of a range of factors

controlling water erosion processes in Central Tunisia. In order to identify their importance, our SSY data were compared to those cited in the bibliography.

At a regional scale, the Tunisian soil generation rate, which represents the tolerable soil loss, is fixed between 200 and 700 $t/km^2/year$ (Renard et al. 1997). Indeed, we note that 91% of the studied watersheds present SSY values higher than the extreme value of this interval. This confirms the aggressiveness of water erosion processes in Central Tunisia and their corresponding siltation rates, which decrease the storage capacity and lifetime of hillside reservoirs. Indeed, some reservoirs were already filled with sediments in less than 10 years after their construction (Hentati et al. 2010; Hermassi et al. 2013). Additionally, at an African scale, the average SSY is estimated at about 1000 $t/km^2/year$ (Tamene et al. 2006). The mean value of our SSY data (1540 $t/km^2/year$) exceeds by more than 50% this average, indicating much higher erosion rates in small watersheds of Central Tunisia.

A bibliographical synthesis of SSY at a small watersheds scale ($A < 1000 km^2$) shows large variability in erosion rates, which are from 7.3 to 17000 $t/km^2/year$ (Laignel et al. 2006). In addition, the most often used and cited in the bibliography is the synthesis of Milliman and Syvitsky (1992). It is based on 280 rivers representing a

variety of catchment sizes, climates and geomorphologies that may be encountered at the globe scale. This synthesis indicates that erosion rates range from 0.3 to 36000 t/km²/year (Laignel et al. 2008). It was also shown that the large heterogeneity of SSY, as it is the case in this study, is an international global problem. Indeed, this conclusion results from the complex interaction of many factors such as climate, geology, topography, land uses and human activities (Meybeck et al. 2003; Benkadja et al. 2015).

The obtained SSY values are among the relatively high recorded values at the planet scale, but they are not the highest. Their fairly high variability is explained by the semi-arid climate in the Mediterranean region, high vulnerability of clayey soils, sparse vegetations and marked relief in the Tunisian Dorsal and Cap Bon regions.

Conclusion

The SSY in the Tunisian Dorsal and Cap Bon regions varies between 180 and 3298 t/km²/year, with a mean value of 1540 t/km²/year. SSY values showed an important heterogeneity of the erosion processes. Indeed, the 23 studied catchments are subdivided into three distinct groups according to their SSY values. The first group contains watersheds with low SSY values located in the west of the study area. Association between large drainage area, gentle topography, dense vegetative cover and multiplication of water and soil conservation works resulted in the attenuation of streaming aggressiveness, giving thereby relatively small quantities of eroded sediments. The second group contains watersheds located in the centre of the study area characterized by moderate relief, fairly marly soils and sparse vegetation, and, therefore, moderate values of SSY. Watersheds of the last group represent the highest values of SSY. Frequent flash floods on abrupt slopes and uncovered and marly soils aggravate the erosion situation, yielding huge quantities of eroded sediments.

A spatial discontinuity was noted between watersheds of the same group of SSY. This discontinuity reveals an important spatial variability of erosion and silting processes, which is related to local and global variability of factors controlling these phenomena. Indeed, we infer that water erosion and reservoir sedimentation are two multi-factors, complex and non-linear phenomena, which made it fairly delicate to consider a certain typology of small catchments in Central Tunisia, according to their SSY.

The spatial distribution of the CV of the mean inter-annual SSY showed that 65 of the 23 studied watersheds demonstrate a global tendency to moderate and high inter-annual variability, that may be related to the variability of the factors controlling water erosion and sedimentation in the study area. Indeed, the regression model elaborated in

this study shows that 85% of the erosion process variability depends upon seven principal factors, which are: precipitation intensity, rainfall amount, drainage area, relief, soil lithology, vegetative land cover and water and soil protection works. The cartographic application in a GIS allowed the validation of the obtained regression model. Indeed, the elaborated map proved that the estimated SSY values (from 100 to 2300 t/km²/year) are close to the observed data (from 180 to 3300 t/km²/year). This map confirmed also that the study area is divided into three groups reflecting various climatic, hydrologic and geomorphologic characteristics. This map represents a powerful tool for the knowledge of the spatial variability of water erosion and hillside reservoir siltation in Central Tunisia. The obtained map is considered an essential tool for future developments of water and soil conservation works. It allows the identification of the zones threatened by water erosion, requiring priority interventions with respect to the implantation of anti-erosive practices.

SSY values obtained in this study were compared to others cited in a large bibliographical synthesis, in order to appreciate the importance of our SSY series at the world scale. We concluded that SSY values obtained in this study are among the high values, but they are not the highest at the world scale. Their high variability is related to the semi-arid climate, characterized by the irregularity and the severity of storms and the spatial and temporal variability of other multiple factors affecting erosion processes (morphology, topography, soil type, vegetative cover, etc.).

Finally, and as a further research activity, multivariate statistical approaches may be used in order to identify the major factors controlling water erosion variability in each of the identified group regions in Central Tunisia.

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