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SOIL EROSION MEASUREMENT USING FALLOUT CESIUM 137 TECHNIQUE IN SIDI SALAH BASIN (EASTERN CENTRAL TUNISIA)

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Abstract

According to FAO, Tunisia is classified among the countries worst hit by different processes of soil degradation, particularly the semi-arid domain, making the example of an ecosystem with increased steppization. Climatic deterioration and inadequate reckless human intervention have led to a deterioration of edaphic factors accompanied by a progressive invasion by steppe facies at the expense of a previously dense and stable forest. This change in landscape has exposed the domain to a severe erosive manifestation and has attracted the attention of many researchers on the problem of water erosion which has been weighing heavily on rural communities for decades. Efforts aimed at estimating soil losses have been made worldwide to choose adequate ways of intervention and deal with this significant degradation. Different empirical models have been established, tested and compared to have a quantitative estimation of this degradation (Tamura, 1964; Rogowski and Tamura, 1970 a and b; Kachanoski et al., 1984, 1987 and 1993; Mabit et al., 1999, 2002, 2008 and 2013; Moukhchane, 2008; Felah 2010; Azaiez, 2016 and 2020 and Akwasi et al., 2020). In this context, it was proposed to quantify soil losses in a test watershed through the Cesium 137 method known for its preferential absorption by the soil's fine particles and its high sensitivity to mechanical erosion. To do this, a representative transect has been selected in a small basin of 2.3 km^2 in area, that of wadi Sidi Salah located on the semi-arid margins of the Eastern tell. Seven samples have been taken along the transect oriented by the soil loss map issued from the application of the USLE equation, allowing to integrate as many compartments subject to various erosive factors and processes as possible. The results of the modeling of soil loss through the Cesium 137 technique have shown a significant specific loss of 32.5 t / ha / year but one which is variable between the different compartments of the basin.

Keywords: Cesium 137, Modelling, Sheet Erosion, Soil loss, Transect Sampling

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1. Introduction

Because of its predisposition and adaptation to long-term erosion studies, Cesium 137 was used in the quantitative inventory of water erosion to establish a spatial mapping of soil losses at world scale. The Cesium 137 is an artificial radioactive isotope resulting from the fission of Uranium 235 and Uranium 238 with a half-life of 30.4 years. This by-product has been released into the stratosphere since the 1950s, then redistributed by clouds and carried to the earth's surface by precipitation.

This method has been in application since 1960s. It was used not only to obtain the net value of soil loss but also to evaluate the sediment balance (erosion and deposition) at various scales ranging from plots to catchment scales. Between suspicion and acceptance of the Cesium 137 assumption by the research community, this technique has been carried out on experimental plots and small watersheds to ensure the accuracy and the consistency in the application of the isotopic techniques on various scales. The first attempts to use Cesium 137 in erosion study were started in the mid-1960s, with Yamagata, Rogowski and Tamura among those who found a close relationship between soil loss and Cesium 137 activity decrease, but on a few months scale, because of the most recent deposition date of the Cesium 137 elements (Yamagata et al., 1963 Tamura, 1964, Tamura and Rogowski, 1965 and 1970).

The Radio-Cesium 137 displacement by runoff and mechanical process of erosion, was later confirmed and compared to the empiric modelling by other researchers, specifically relating to research results presented by Ritchie and McHenry, 1974 and 1977, Walling and Quine, 1990, Navas and Willing, 1992, Wicherek, 1993 and Felah, 2010. The same applies to specifying the emitting sectors of sediments in order to evaluate the silting up of dams and for dating deposited sediments and check dams against fast sedimentation (Sogon, 1999; Zhang et al., 2015). With regard to the Cesium 137 behavior with soil element, several studies were devoted to specifying the cation exchange capacity of clay element in soils such as illite, smectite and vermiculite which have higher affinity to Cesium 137 (Yigzaw, 2009; Grzegorz, 2006; Mabit et al., 2013 and Staunton and Roubaud, 1997).

The Cesium 137 fallout has been significantly more important in the northern hemisphere - precisely around latitude 45° north - than in the southern hemisphere due to the greatest flux of Cesium 137 since 1954 (Walling and Quine, 1990 and 1993; Moukhchane et al., 1998; Moukhchane, 2008; Zapata, 2002; Zhang et al., 2015 and Ni et al., 2017).

Its effects are still being perceived even today in central-east Tunisia. Considering research on Cesium 137, on a world scale, it can be noted that several models were developed for quantitative erosion at medium and long-term measures. The isotopic method of Cesium 137 has been applied to regions suffering mainly from severe degradation under extreme climatic conditions and which are limited and inadequate for empirical modeling. These Cesium 137 isotope tracers are a very interesting alternative capable of overcoming some of the difficulties that have accompanied previous empirical and experimental methods that required a huge amount of work and continuous monitoring on the ground.

These radioactive isotopes are of paramount importance as their introduction into the soil coincides with the major changes in the rural landscape and natural vegetation cover over the last five decades in Tunisia steppe, which have been marked by the emergence of new agricultural structures increasingly based on mechanization, mono-cropping and unsuitable tillage methods (Attia, 1977; Hamza, 1988 and Azaiez, 2016).

In particular, the use of the polydisc tractor caused the radioactive elements to be dragged deep, thus allowing their leaching with the clay fraction (Zhang, 1999 and Zhang et al., 2015). However, emphasis must be laid on the circumstances where it is appropriate to apply the isotopic method, that is not prescribed to be routinely used in such cases by rote (Rogowski et Tamura, 1970; Zhang, 1999; Grzegorz, 2006 and Fulajtar et al, 2017).

Once the requirements set out above, referring to the isotopic method, were fulfilled in central eastern Tunisia, it was possible to use this method to develop new insights on the ongoing erosion and sediment displacement in semi-arid steppe in Tunisia, in particular in the watershed of Sidi Salah, a catchment area with a pastoral function. Considering the outcomes on the studies with Cesium 137, it appears that most of the optimum adsorption of Cesium 137 occurs on the surface of the soil and its diffusion in depth becomes increasingly difficult. Its vertical displacement in soil horizons by infiltration is limited. But the samples analysed in the Eastern Central part of Tunisia have shown that fields which are deeply plowed contain a higher concentration of Cesium 137 to a depth of 20 and 25 cm. But this radioactive element was completely expunged between 25 and 35 cm of depth.

The aim of this work is to propose a quantitative estimate of soil losses and to highlight the different factors that are at the origin of the erosive effect not only by their statistical weight but also by their causality relationship (Walling and Quine, 1990 and 1993; Moukhchane et al., 1998 Zapata, 2002; Mabit et al., 2002; Felah 2010; Ben Mansour et al., 2000 and 2012; Toumi, 2013; Zhang et al., 2015 and Azaiez, 2016).

Based on this isotope technique, a preferential transect from upstream to downstream was chosen for sampling. This work does not attempt to provide a comprehensive and exhaustive quantitative study, but rather a consistent interpretation of the erosion event itself as well as its trends, depending on land use and the physical environmental characteristics responsible for sediment transport along the slopes.

2. Study Area

The watershed of wadi Sidi Salah, a tributary of wadi Saadine, extends over the semi-arid margins of the eastern Tell which has a Mediterranean climate with contrasting seasons. It drains an area of 2.3 km^2 of the eastern slopes of the Ejhaf, Diour and Fartout mountains (Figure 1).

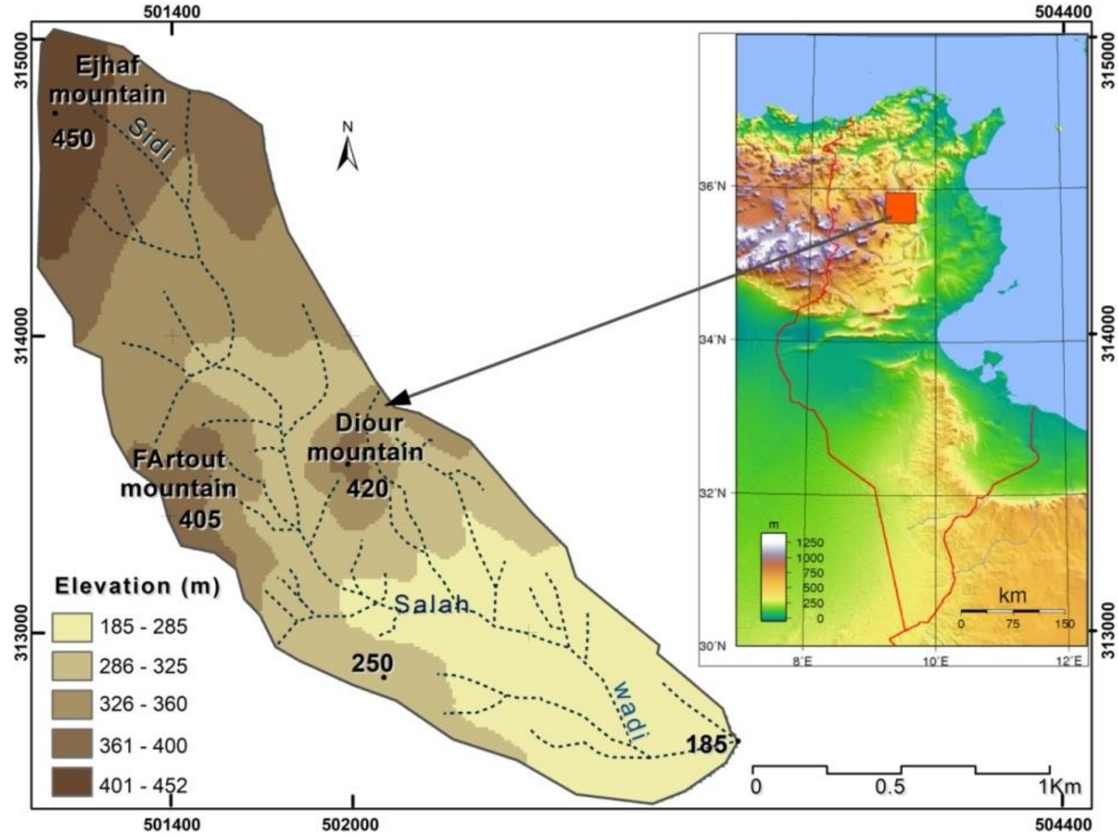

Figure 1: Location map of the study area.

With altitudes ranging from 185 m to 452 m, this watershed has an average slope of 18° and can reach 43° on the middle slopes and, to a lesser extent, on the north-western slopes.

The steepness of the slope in the middle part of the watershed, precisely on the edges of the glacis, is explained by the vicissitude of the glacis, which are partially covered by consolidated debris (Dresch, 1957). Generally speaking, it consists of an aerated and spaced landscape of low morphostructural diversity (Figure 2). Added to this is the instability of the glacis edge caused by the effects of breaking up the crust that is followed by farmers to exploit the underlying fine-textured soil layer.

Currently, these glacis on the middle stream are in the form of intensely dismantled and dissected strips overlying a clay layer that is unstable due to the predominance of clay elements of the smectite, vermiculite and illite type, susceptible to erosion process (Figure 3) (Jamoussi, 2001). Full of gypsum elements, these clays have high swelling and shrinking properties. The gypsum dissolution creates an internal cavity of different size, which disturb the slope stability, especially on the middle reaches of the water course of Sidi Salah.

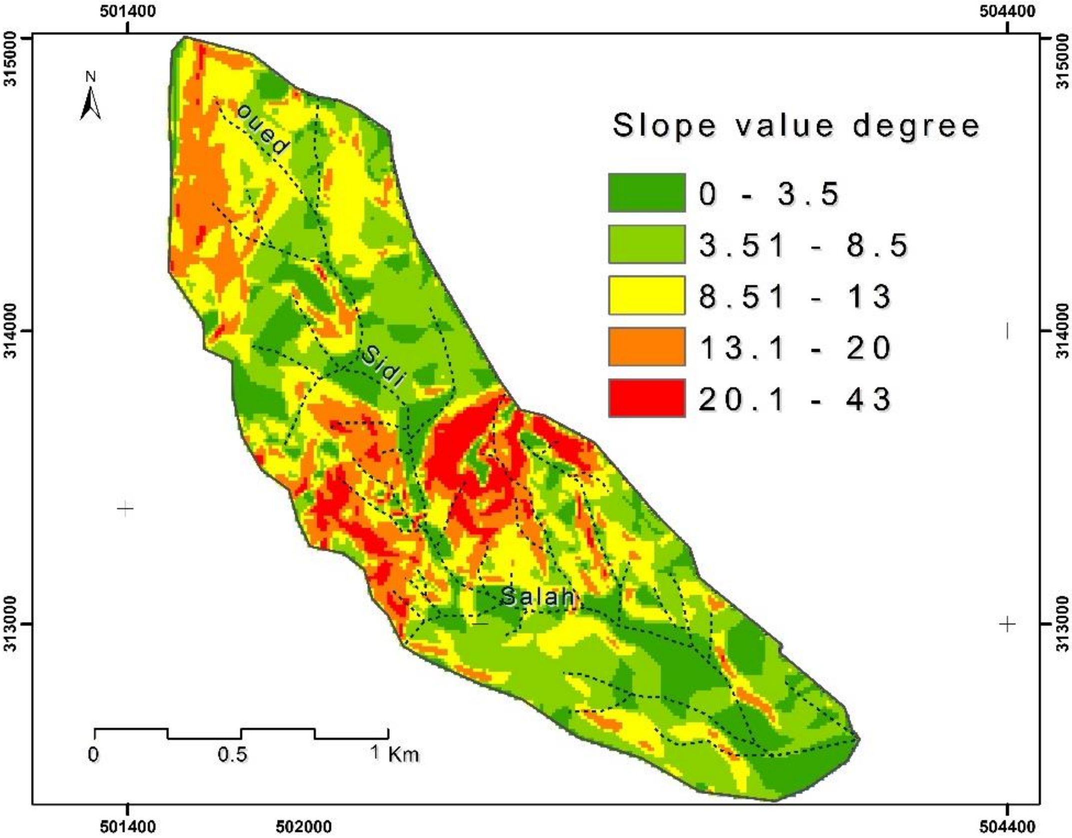

Figure 2: Slope map of wadi Sidi Salah basin. Source: Obtained from the DEM developed on the basis of the topographic map of Zaghouan at 1/25000.

All these conditions favored a rapid return of water erosion, which accelerated with the proliferation of intense and variable rainfall combined with a contrasting lithology marked by alternating marl-clayey-limestone upstream and clayey-sandstone downstream. (Hamza, 1988; Avenard, 1995; Roose, 2004; Toumi, 2013, Azaiez, 2016 and 2020 and Azaiez et al, 2020)

The surface formations are seriously affected by various forms of water erosion and prove that this watershed is widely disposed to the agents of morphogenesis, given the predominance of silty-clay and sandy-silt textured soils that are sensitive to the processes of mechanical erosion and the effects of hypodermic flow. These types of soils represent 40% of its total surface area (Figure 3). These results related to the soil texture were obtained by particle size analysis and the sand equivalent test based on the French standards already established by AFNOR (AFNOR, 1993 and 1998) and the observations of the digital Soil Map of the governorate of Zaghouan, 2003.

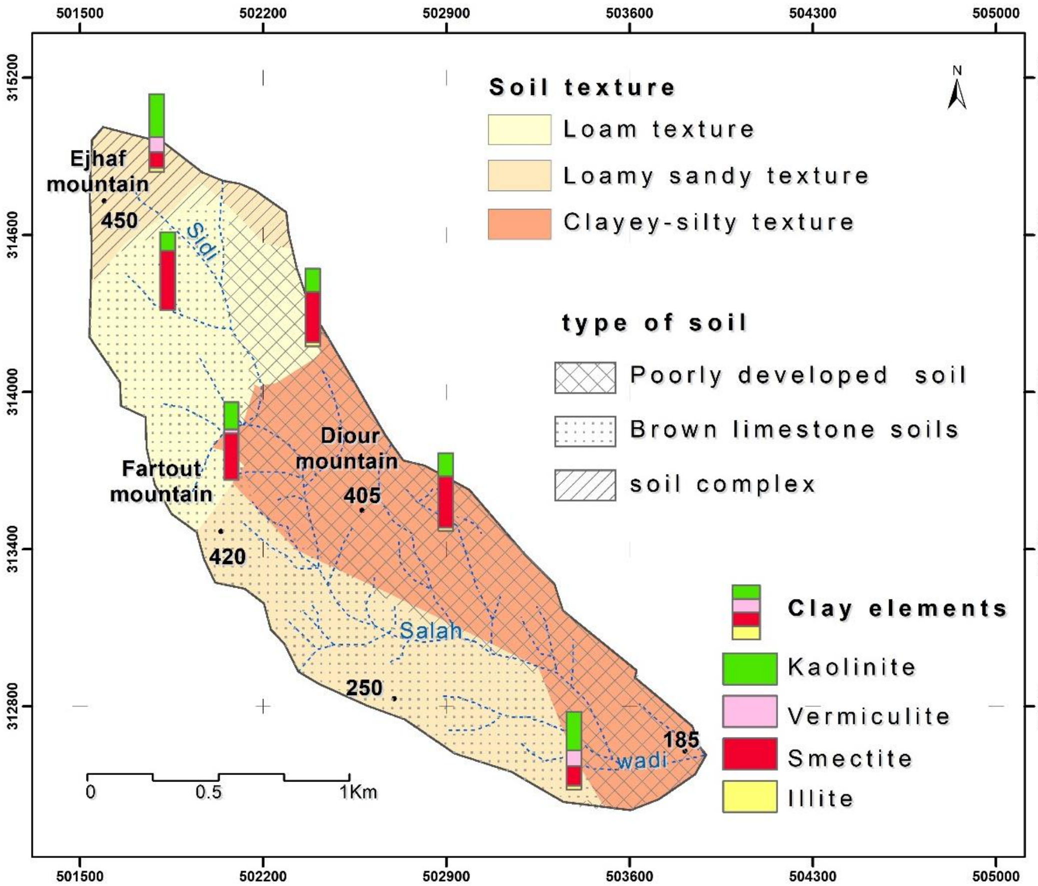

Figure 3: Type of soil, soil texture and clay elements map of the study area. Source: This map was produced on the basis of the results of particle size analysis, mineralogical analyses and the digital agricultural map of Zaghouan, 2003.

X-ray diffractograms specific to the samples taken from soils with silty-clay and silty-sandy textures as well as geotechnical tests show an enrichment in clay minerals of the illite and smectite type that are very favorable not only for swelling and shrinking but also for mechanical shear due to their low plasticity and low consistency (Yigzaw, 2009) (Figure 3).

However, these processes are subject to the unpredictability of the climate, especially the highly variable and aggressive autumn rains and the associated environmental problems (Abdelkhalek, 2009 and Azaiez, 2016**)**.

The effects of water erosion seriously affect the quantity and quality of soil and plant resources and call into question the problem of the longevity of equipment and hydraulic developments located downstream related to the enrichment of sensitive clay minerals (Figure 3). It is worth highlighting that the majority of these erodible soils are located on very steep slopes that generally correspond to the Erosion talus of the intensely dismantled glacis. Thus, the soils enriched in smectite and illite are located in the middle course of the wadi Sidi Salah, beyond two banks of the main watercourse. Anthropic pressure and climatic deterioration have given rise to a phenomenon of dematorralisation of the steppe forests marked by an inevitable expansion of the chamephyte and therophyte species on some slopes at the expense of an open garrigue because of the discontinuity of the soils on the one hand and the selective migration of the fine fraction by selective erosion on the other hand (Attia, 1977; Le Houérou, 1995 and Tassin, 2012). There has been a progressive degradation of the old plant associations that were able to fight against climatic aggressions.

Thus, an erosive manifestation began in response to the different agro-sylvo-pastoral uses that have taken over for several decades (Attia, 1977). Currently, the plant cover is essentially made up of a young secondary resinous forest, also known as anthropic, which has replaced the primitive forest (Attia, 1977; Le Houérou, 1995 and Azaiez, 2016). On the exposed slopes, a scrubland of mastic grass, Aleppo pine and rosemary, which have a great colonizing power on marly-limestone substrata, has gained ground (Le Houérou, 1995) (Photo1 and Figure 4).

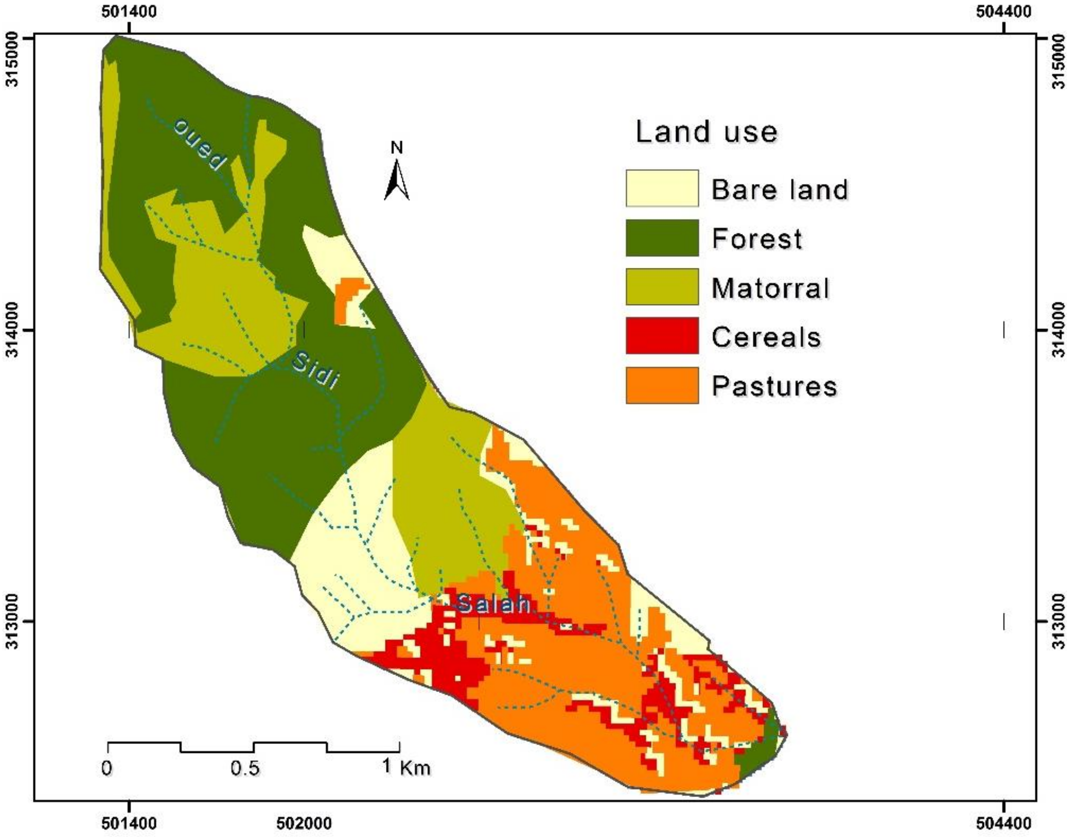

Figure 4: Land use map of Sidi Salah basin. Source: This map was produced on the basis of the digital agricultural map of Zaghouan, 2003 and Google Earth Pro Image 2019.

Photo 1: Matorral of Aleppo pine and rosemary in the upper stream of wadi Sidi Salah basin (Photograph taken in 2015).

The clearings that were established during the colonial period following land clearing for cultivation are now occupied by open bushy plant formations. These plant forms evolve rapidly into scrubland in the northern combe clearings in this watershed. On the middle slopes, however, these plant forms find it difficult to develop not only because of erosion facilitated by low density and overgrazing, but also because of their proximity to the large village community.

However, it is necessary to emphasize the interactions between the climate and the plant cover, which are exerted on a largely undeveloped soil complex. A comparison between different parts of Sidi Salah basin, shows a strong sensitivity of the western slopes of the middle and of the downstream (Photo 2 and Figure 5). This indicates that erosion is very active and severe on soils with fragile texture subjected to strong human pressure and rainfall amount whilst the low sensibility areas are dominated by forest and plant cover on a gentle slope in the upper stream (Figure 5).

Photo 2: Soil erosion in the middle course of wadi sidi Salah (Picture taken in 2015).

The water erosion sensitivity map is the product of the superposition of four layers involving several factors. They are: the permeability index obtained from the soil texture triangle, the slope map produced by the DEM on Arc GIS, the vegetation cover index obtained from the USLE equation, and the map of the hydrographic density calculated by each type of soil texture. From this combination, it seems clear that the sectors most prone to water erosion are the least permeable (clayey silty soil), the steepest, those that have the highest hydrographic density and the least dense vegetation cover. This is a very favorable situation for the formation of runoff due to infiltration relatively low (Figure 5).

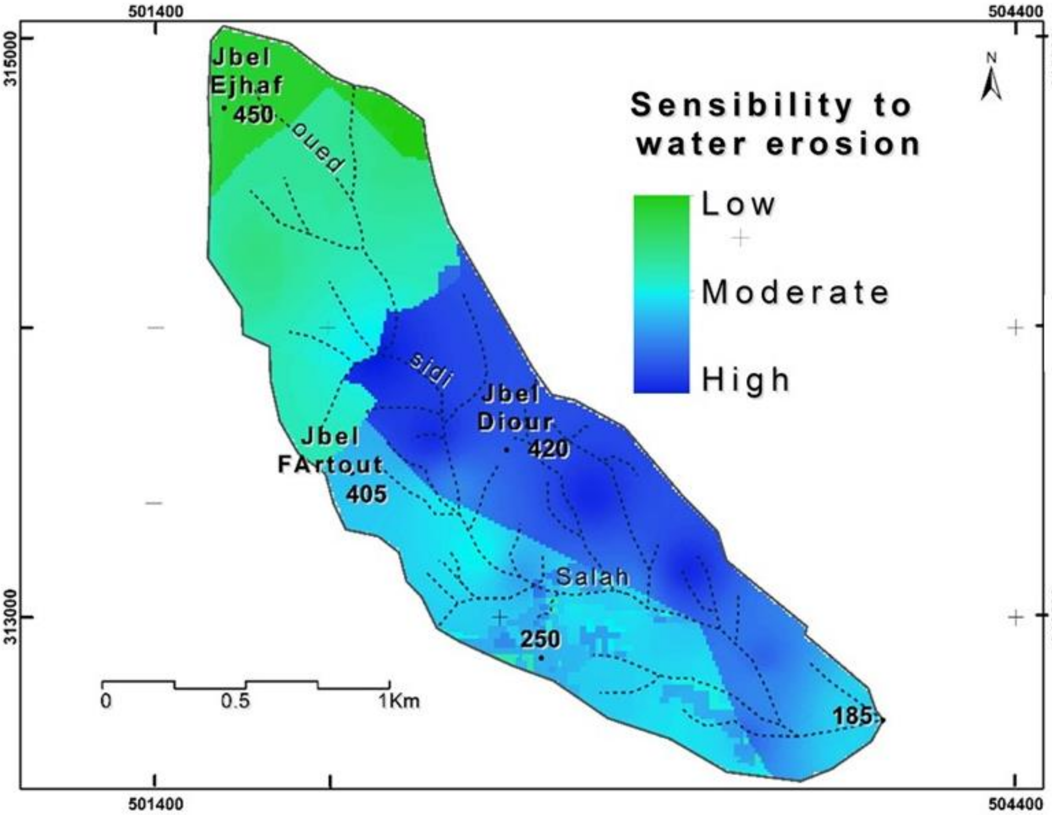

Figure 5: Erosion sensibility in the wadi Sidi Salah Basin. Source: This map was produced on the basis of the digital agricultural map of Zaghouan, 2003 and Google Earth Pro Image, 2019.

3. Method and Tools of Transect Sampling

Sampling was carried out using a 6 cm diameter PVC tube to a depth of 25 cm, which represents the average thickness of the tillage layer in this area. The quantities collected were largely sufficient for isotopic, mineralogical and granulometric analyses. These last two analyses will be of greater use in explaining the erosive manifestation from the point of view of rhythm and distribution.

The Cesium 137 technique is a universal method, applicable in different climatic, lithologic and topographic contexts (Mc Henry, 1985; Walling and Quine, 1990; Felah, 2010 and Ben Mansour et al., 2000 and 2012). Its widespread use around the world is explained by the absence of factors that would limit its application especially in the northern hemisphere. Its widespread use around the world is explained by the absence of factors that would limit its application, especially in the northern hemisphere because of the Cesium 137 abundance due to fallout from atmospheric nuclear tests conducted since 1950 in the region.

Although this approach is widely validated in the Mediterranean environment, its success, however, remains dependent on the way it is applied because some watersheds are suited to sampling by metric grid because of the high heterogeneity of the landscape, controversial topography, dissected orography and aggressive rainfall, while others are suited to division into homogeneous units, when similar landscape units are scattered over several sectors. Whereas for other elongated watersheds where the units are arranged one after the other, a representative transect had to be followed.

In the case of the watershed of the Sidi Salah wadi, the sampling was guided by two major facts.

Firstly, the results of the soil loss map resulting from the application of the USLE equation, which served as a reference, and also by the elongated shape of the watershed. The units are more homogeneous transversally and less and less homogeneous longitudinally.

The selected transect, oriented north west south east, delicately follows the arrangement of the morphostructural units and the different plant associations accompanying each surface formation. This transect passes through as many compartments as possible that have almost similar lithologic, topographic and human conditions.

Seven samples were taken from upstream to downstream on either side of the mainstream. Using a 6 cm diameter PVC tube, soil samples were taken from a depth of 25 cm because the soils are not very evolved and the regosols are not very deep. (Figure 6). This feature affected the choice of the suitable depth to carry out the sampling process as, at greater depths, steeper slopes may inhibit Cesium 137 fixation because of the clay-humic compound of the soil.

Only in the hillside reservoir the sampling was carried out over a depth of 35 cm as it constitutes the reception area for almost all the sediments coming from different compartments of the watershed, except for sediments that are trapped against obstacles within the watershed.

Sample 1 was taken in a stable reference section of a state-owned forest that is very little subject to human activity. Sample 7 was taken from the hill reservoir located downstream of the watercourse before reaching Wadi Saadine. The rest of the samples were taken in areas subject to the effects of surface water erosion to varying degrees.

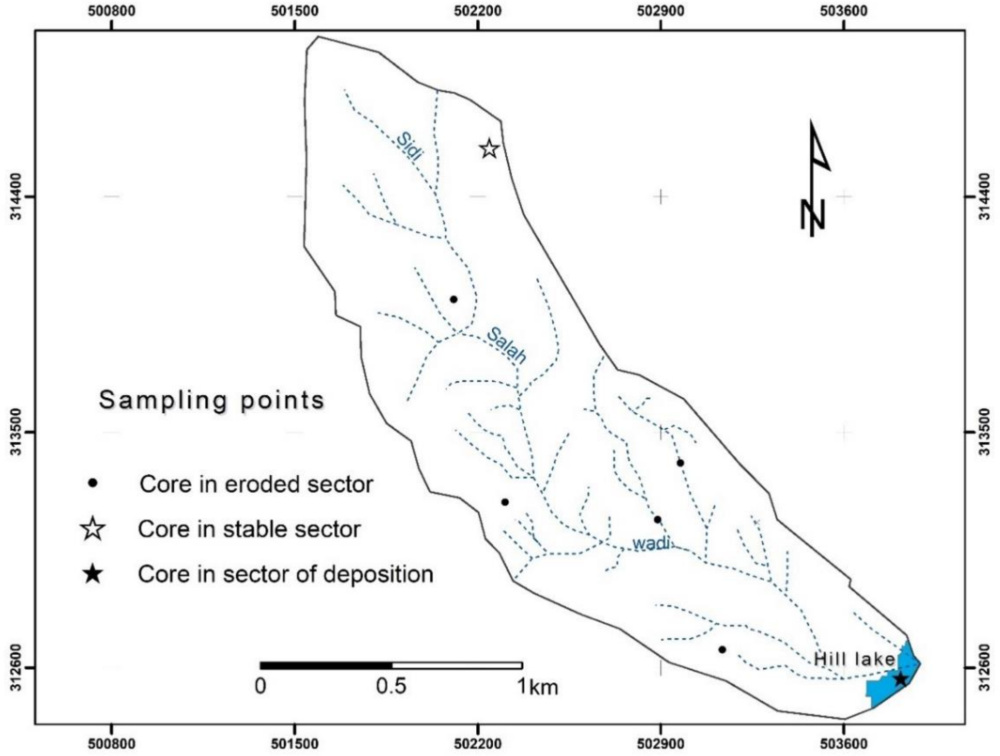

Figure 6: Map of the soil sampling locations in Sidi Salah basin.

The map of homogeneous units was then used in the generalization of the results of Cesium 137 activity in the non-sampled compartments. After applying the sediment drying protocol in the open air and then in the oven and after cleaning and removal of volatile organic matter, the fine fraction (less than 0.2 mm) was separated using a sieve.

Measurements of Cesium 137 were carried out on the whole core after its homogenisation. A sequential division of each core was not carried out due to the very high cost of isotope analysis, as this research was not undertaken as part of a funded project. The principle consists in studying the redistribution of Cesium 137 which is closely related to the movement of soil particles by physical and mechanical processes compared to a reference site whose fallout has remained stable since its adsorption by fine soil particles (Felah, 2010; Ben Mansour et al., 2012; Toumi, 2013). By contrast, at the accumulation sites the Cesium 137 content was significantly higher than the baseline value at the reference site (Ritchie et al., 1990; Zapata, 2002 and Felah, 2010).

4. Distribution of Cesium 137 activity: analysis and interpretation

The variation in Cesium 137 activity in different parts of the watershed can be interpreted either in terms of reduction or enrichment compared to a reference site. An erosive phase occurs if Cesium 137 activity is reduced in some slopes compared to the reference site. Sedimentation occurs if other areas are enriched in Cesium 137 radioactive elements, particularly in the deposition areas such as the convex banks of meanders, slope breaks, the embankments of contour benches and the hillside reservoirs (Walling and Quine 1990 and 1993; Zapata, 2002; Felah, 2010 and Azaiez, 2016).

To get the correct spatial distribution of cesium activity in the Sidi Salah basin, it was necessary to apply the Kriging method as an interpolation model from the toolbar spatial analyst tools under Arc Gis program. The Kriging interpolation was well advised to be the optimal method, in statistical terms, of interpolation and extrapolation of the Cesium 137 activity (Figure 7). It allows to make an unlimited interpolation between different values by taking into account data, their spatial position and their relative distance from the target. It also allows the definition of the spatial correlation while smoothing the real variability and making it possible to calculate the estimation error (Gratton, 2002**)**.

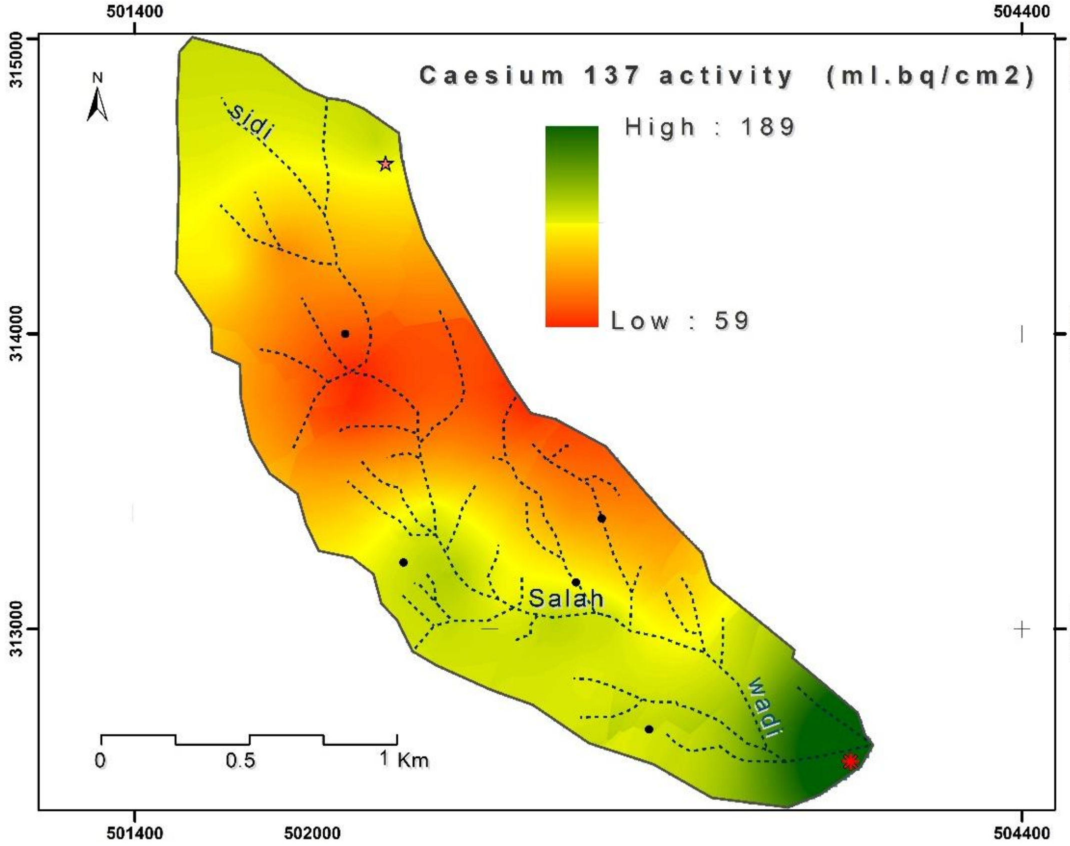

Figure 7: The Cesium 137 activity in the Sidi Salah basin. Source: This map was produced on the basis of the results of isotopic analysis, 2015, National Center for Nuclear sciences and Technologies, Tunisia.

In the Sidi Salah wadi watershed, Cesium 137 activity decreases considerably from upstream to downstream, except in the hillside reservoir in the basin outlet, where sedimentation prevails over any erosion process. This activity reaches its lowest values on the mid-slope, especially on the long and steep slopes (Figure 7). This significant reduction in radioactive elements is explained by mechanical processes related to diffuse runoff and the opening of the gullies, which caused a selective migration of the fine fraction of the soil in which the isotopes of Cesium 137 are adsorbed.

All the elements stripped and carried along the slopes are trapped in the form of deposition pockets at the convex meanders and slope breaks. Most of these isotopes that are detached by mechanical processes are decanted in the hillside reservoir of the wadi of Sidi Salah. However, it should be pointed out that the reduction of Cesium 137 activity is also linked to the specific characteristics of the Cesium 137 isotope.

This latter systematically loses almost half of its activity over thirty years. Another finding proved by the team of researchers at INRA Montpellier confirms that the reduction of Cesium 137 through its circulation via plants is weakened in soils with a very low organic matter content in clay minerals. In fact, a compensation can be generated by the current additional inputs from nuclear reactor emissions (Colle et al., 2005).

Another finding proved by the same research team from INRA in Montpellier confirms that only plants with a superficial root system are capable of absorbing these radioactive elements, since 90% of the Cesium 137 is concentrated in the first 10 centimeters of the tillage layer (Colle et al., 2005; Sonia Mohamed et al., 2018 and Akwasi Dwira Mensah et al., 2020**)**. Contrary to this situation, chamephytic and therophytic plants generally have a deeper root system and therefore Cesium 137 remains accessible only to the surface layer, in other words the roots close to the surface (Tassin, 2012).

All these arguments and explanations must be taken into consideration when interpreting the variation in Cesium 137 activity between the different areas of the watershed and to subsequently qualify the land losses obtained from the modeling. However, Cesium 137 activity is quite considerable in improved rangelands, dense scrub and garrigue consisting of young pine, juniper, lentisk and rosemary.

This finding is confirmed by other researchers who have emphasized the role of matorral-type vegetation cover in significantly reducing water erosion (Rogowski and Tamura, 1970 a and b; Ben Mansour et al., 2000 and 2012; Zapata, 2002; Felah, 2010 and Azaiez, 2016). In the case of this watershed, the diffuse flow presents a harmful action, solicited by a matrix texture separated by two-dimensional interfoliar spaces that favour the reopening of micro-shear planes, especially during the heavy and continuous autumn rains that occur after a long dry, hot season (Yigzaw, 2009).

5. Modeling of soil loss

To convert the Cesium 137 activity into soil losses, two models were applied to perform the calculations. The proportional model and the Mass Balance 2 model. The proportional model was applied for cultivated watersheds. (Kachanoski, 1993; Zapata, 2002 and Felah, 2010). It is expressed as follows:

$$\mathrm{Y} = 10 \times \left(\frac{\mathrm{BdX}}{100\mathrm{T}}\right) \qquad [1]$$

With

Y: the soil loss (t / ha / year),

B: the soil density of the fine fraction <0.2mm (kg/m^3),

d: the depth of the plowing layer (m),

X: the percentage enrichment or reduction of the activity of Cesium 137 and relatively expressed to the reference:

$$= \frac{[\mathrm{Aref} - \mathrm{A}]}{\mathrm{Aref}} \times 100$$

With

T: the number of years since 1963 (reference date for the start of massive Cesium 137 emissions),

Aref: specific activity in Cesium 137 (Bq / m^2) of the reference site,

A: specific activity in Cesium 137 of the sample from a degraded site.

While the Mass balance 2 model has been applied to uncultivated sectors, strongly subjected to the action of peasant society through cultivation, grazing, transformation of agricultural techniques and land use change. It is expressed as follows:

$$\mathrm{Y} = \left(\frac{10\mathrm{dB}}{\mathrm{P}}\right) \times \left[1 - \frac{\left(\frac{1 - X}{100}\right)1}{(t - 1.963)}\right] \qquad [2]$$

With
P: a corrective index linked to the selective start of the fine fraction (of the order of 0.93),
t: number of years between the departure date and the date of the sample (Zapata, 2002; Felah, 2010 and Azaiez, 2016).

A first comparison between the map of Cesium 137 activity and that of soil losses resulting from the interpolation by Kriging model in spatial analyst tools, shows a relation of proportionality between soil loss and quantity of Cesium 137 removed from the soil.

The amount of eroded soil is directly proportional to the redistribution of Cesium 137 activity. The sectors enriched in cesium are the sectors of accumulation while those which have recorded a decrease in Cesium 137 are the degraded sectors (Figure 8).

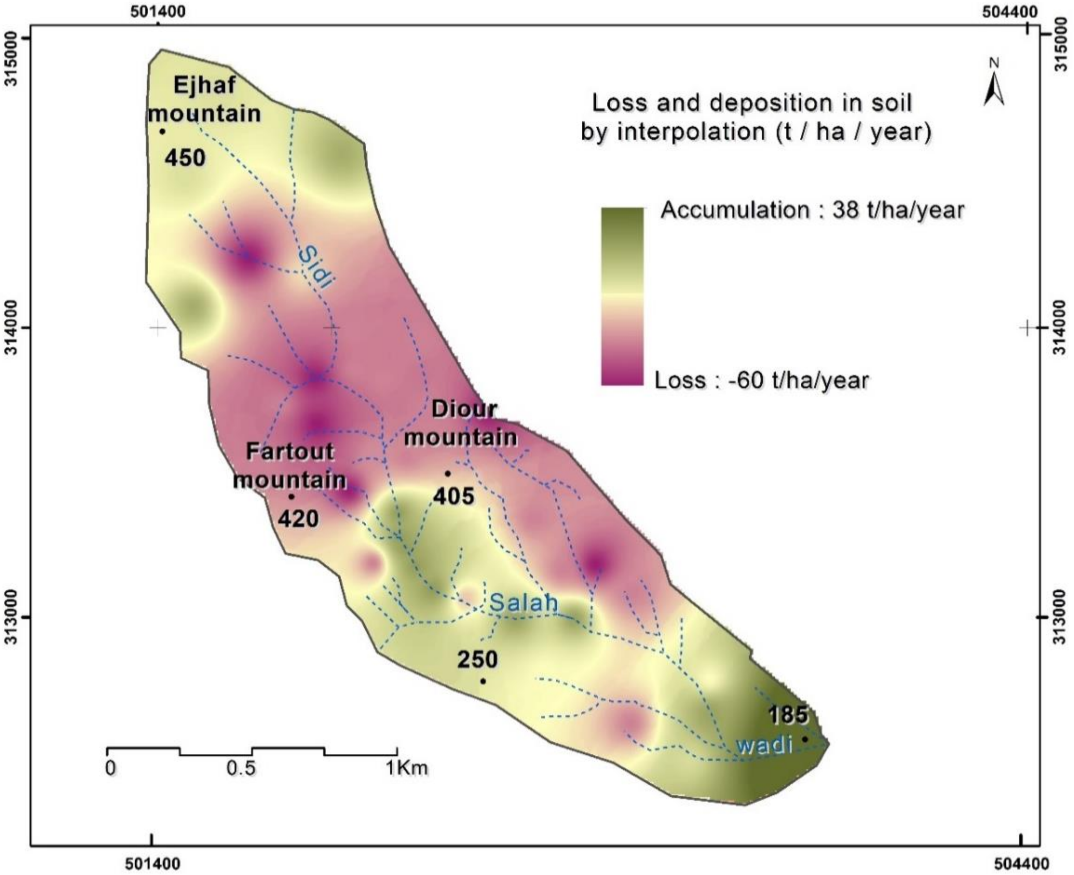

Figure 8: Soil loss in the Sidi Salah basin based on kriging interpolation method. Source: Results of isotopic analysis, 2015, National Center for Nuclear sciences and Technologies, Tunisia.

6. Discussion and recommendations

The spatialized modeling of soil losses resulting from the isotope method shows a concentration of degraded land in the center of the watershed, in other words, the areas where the greatest anthropogenic pressure has been exerted. This proves that the erosive manifestation clearly takes on both human and natural dimensions. The human dimension appears in the confirmation of the steppe character of the study area as a result of the combined effect of climate deterioration and the behaviour of the various successive farming communities. During the colonial period and in the decades that followed, they resorted to land clearing, mono-cropping and extensive grazing. These local conditions have made the watershed a very sensitive area to water erosion, as farmers do not even respect mulching in fallow land as a way of soil management because of the high pastoral load. The natural dimension is reflected in the matrix structure of the clay fraction of the soils, which is not very consistent, and the micro-aerated texture, which frequently creates a vacuum in the arable layer. This problem concerns the soils that are above the clayey-marly outcrops of the middle course of the wadi Sidi Salah and are in fact the most degraded areas. The specific loss in soils with a silty-clay texture exceeds 45.5 t/ha/year on the left bank of the wadi Sidi Salah. (Figures 8 and 9). The Ministry of Agriculture described it as an alarming situation. Based on the results of the pilot basins, the Ministry has set the value of 40 t / ha / year as a tolerance value for soil erosion in Tunisia. The rate of soil loss in sidi Salah basin is considered as one of the strongest compared with other basin localized not far from our study area (Table 1). The modelling results in the next table can be used as a guideline to identify soil erosion tolerance according to empirical and experimental models.

Watershed names	**Specific soil loss (t/ha/year)**	**Model**
El Mssine	34	USLE
Jannet	26	KINEROS model and USLE
Chaddad	39	USLE (adjusted)
El Ogla	30	USLE, RUSLE, MUSLE and FAO
Sidi Salah	32.5	Cesium 137
	39.8	USLE

Table 1: The average rates of soil loss in a few basins in order to define tolerable soil erosion values in central eastern Tunisia.

The erosion speeded up considerably under increasing pressure from deforestation in the upper stream and the compaction of the soil resulting from inappropriate agricultural practices going against the equitable use of soil and water in semi-arid region. These facts are at the origin of the appearance of suffosion holes in agricultural plots, degraded pastures and grazed fallow land. On the calcareous back slopes and the open combe in marly-limestone outcrops, the soil loss nevertheless remains much lower than the specific loss of the watershed (32.5 t/ha/year). The establishment of a sediment budget must be taken with caution. Because only a part of the detached elements is carried downstream while a good part of these sediments remains trapped within the watershed in the form of small benches in the convex meanders or in the form of pockets fixed by riparian vegetation that develops in tufts.

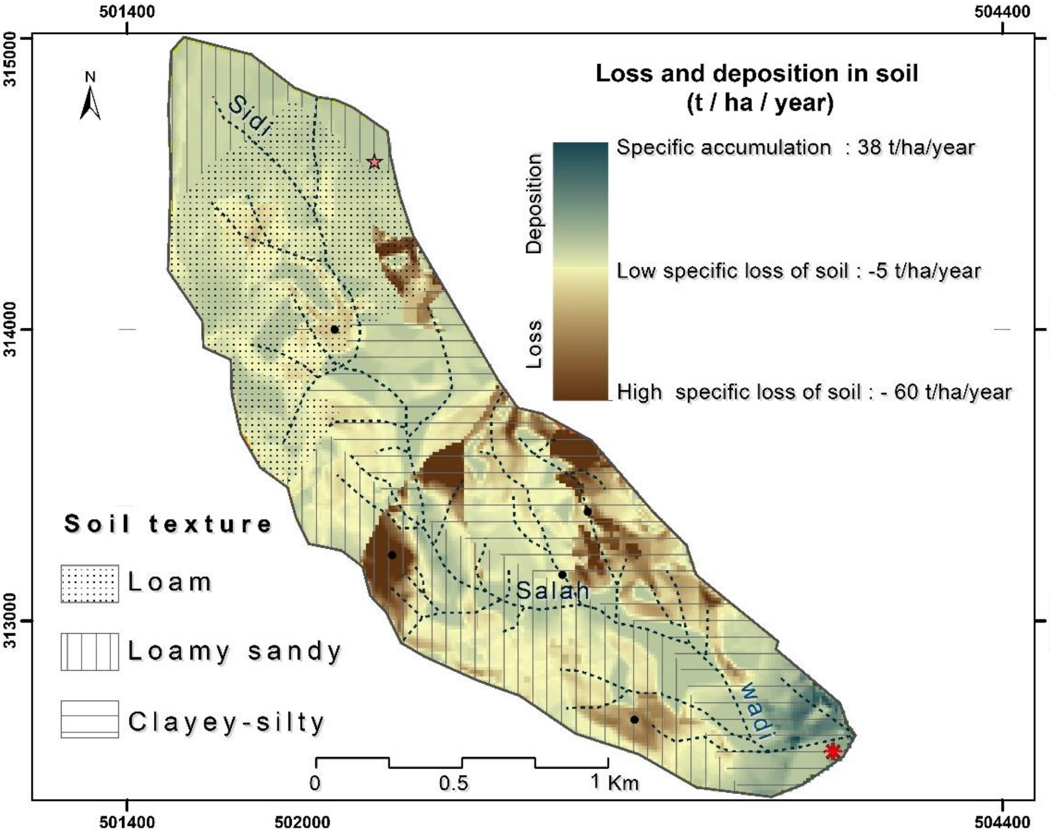

Figure 9: Map of relationship between soil loss and soil texture in the Sidi Salah basin. Source: Results of isotopic analysis, 2015, National Center for Nuclear sciences and Technologies, Tunisia, particle size analysis and the agricultural map of Zaghouan, 2003.

The advantage of this technique compared to those previously developed is that it has helped to obtain an overall budget for the movement of soil particles. Several reproaches can be made about the modeling via the isotope method of Cesium 137 applied in the watershed of the Sidi Salah wadi.

Firstly, it only provides an estimate of long-term (40 years) soil losses, but on a seasonal scale, it does have a number of deficiencies. The erosive manifestation differs from one season to another and even from one rainfall to another. Also, the limited number of samples taken (Felah, 2010 and Azaiez, 2016, Ni et al., 2017). Indeed, with exhaustive sampling the results could have been better and more accurate, but not radically different from the results obtained. These results would probably have shown caution if a sequential analysis of each sample had been chosen instead of simply calculating a simple average of the Cesium 137 activity over the entire core. The highest accuracy of erosion rate was obtained at scale of different cores collected on representative sites selected between the upper and the outlet basin. However, the results remain the lowest at the catchment scale because of its spatial variability and heterogeneity between all basin units. The Cesium 137 method requires a careful modelling because it cannot be used automatically everywhere under all forms of erosion. It is not the appropriate method for sectors prone to gully erosion with varying degrees of rigor.

Only sheet and rill erosions are involved because of the runoff removing the soil in sparse sheets of topsoil and can be extending to 25 cm of depth. All other types of water erosion are not taken into consideration in the modelling process. It seems advisable consider various forms of erosion in Sidi Salah basin, particularly gully erosion and badlands constitute the main type of soil erosion that occurs in the clayey-silty soil sector. Thanks to this revolutionary technique of cesium 137, it was possible to quantify soil loss in the inter-gully sector.

However, this was not the case for the badlands sectors strongly affected by ravines and gullies in the middle courses of wadi Sidi Salah. That is why it is important to take a few simple steps to ensure a good result before choosing the isotopic technique at the catchment scale (Ni et al., 2017). Despite these limitations, the Cesium 137 is still an appropriate method for erosion study.

Due to its wide use in the analysis of environmental changes, Cesium 137 is regarded as being the most promising application to measure quantitative erosion of soil, providing new, continuously updated, information about the erosion process. A detailed study into soil loss needs more than one illustrative and standard approach. The phenomenon is a far more complex issue than commonly believed.

There is no single method that has been proven to be, alone, effective for quantifying soil erosion. In fact, various complementary methods and techniques should be used to do real field research and to achieve the objectives of the study. In fact, it was possible to compare the modelling results with the empirical ones through the USLE equation, that involves, among others, 6 factors: LS factor describing the slope, R factor which measures the rainstorm, K factor taking into consideration the soil erodibility index, C factor related to land use index and finally the P factor which includes all anti-erosion works in the basin (Figure 10).

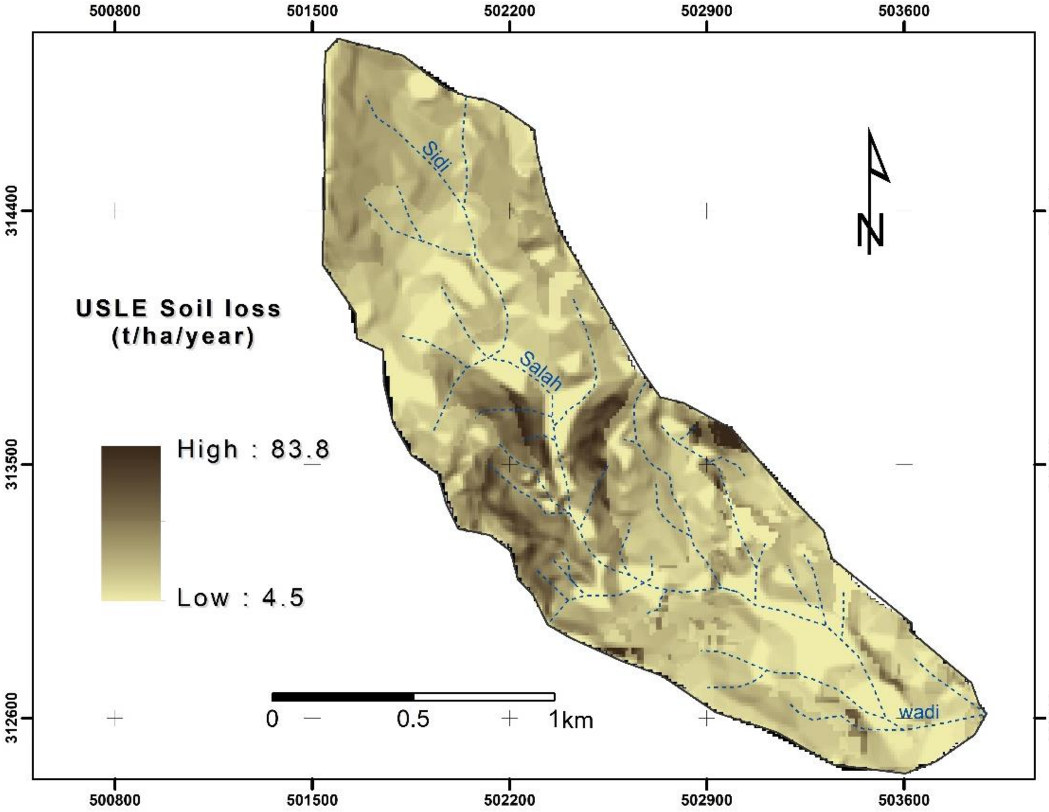

Figure 10: Soil loss in the Sidi Salah basin obtained by application to the USLE equation. Source: Results of modelling process under Arc Gis program.

This present research opens the way for the monitoring of the various actions taken against erosion, able to provide a sufficient environmental protection in Sidi Salah basin.

Until 2019, this watershed remained without any development, in particular, the absence of soft slope techniques and especially mechanical benches as the most widespread method of erosion control in the semi-arid area. It is the technique that is booming in the Maghreb countries, to the point that it has become the unique solution to tackle all forms of water erosion (Avenard, 1995; Nasri, 2002 and Roose, 2004).

However, this is not the case for this watershed in the central east of Tunisia. No total or partial retention benches were installed, only stream treatments with stepped gabions and gully head treatments with sills or dry-stone piles. This absence of benches on the mid-slope in the middle course wadi is reasonably justified by the predominance of clay and marl and the concentration of gypsum element in the soil. Under these conditions, the benches and heavy developments only worsen erosion rather than counteract it. Moreover, the most degraded slopes are south-facing, in other words, the hottest and driest. They are therefore the most suitable areas for the formation of crust which hinders infiltration and favours the concentration of runoff water and its overflow over benches.

Very quickly the latter will be subject to the opening of rills, breaches, gullies and then ravines if this process is combined with the opening of suffosion tunnels. All these areas will be transformed into Badlands territory as a phase of deterioration that cannot be reversed. Indeed, the strategy of the fight against erosion is not only the simple technical operation of setting up certain soil conservation structures, but first of all it is necessary to build a good knowledge of the laws of nature before embarking on the application and falling into the choice of a badly designed and badly conceived development (Hamza, 1988; Nasri, 2002 and Azaiez, 2016 and 2020). The effort of local stakeholders must act directly on the factors responsible for the erosion dynamics. Benches are very expensive, in terms of both installation and maintenance, and yet they are not the miracle solution for all types of soil (Avenard, 1995). Sometimes simple structures, lighter and cheaper than benches, can ensure the stabilization of ravines either by biological treatment or treatment of watercourses by sills or dry stone piles.

Sometimes all three techniques can be used together, depending on the physical entity being studied. It is these last structures that have been adopted in the watershed of wadi Sidi Salah from the year 2013 (Figure 11), some of which have shown promising results in 2019 as shown in the Google Earth Pro images. A retention of sediment and water occurred behind the sills implanted on the course of some gullies, which favored the appearance of a dense riparian vegetation cover. Depending on the objectives of the anti-erosion strategy undertaken, local stakeholders can choose the plant species suitable for protecting the slopes. If the objective is to stop the concentration of runoff water and to minimize silting of downstream dams, it is recommended to choose repellent plant species that are less grazed by livestock to avoid the problem of overgrazing. In contrast, if the main objective is to stabilize slopes and improve degraded rangelands, in this case it would be necessary to plant species that are suitable for livestock grazing.

Figure 11: Treatment of watercourses by stepped gabion sills. Source: Google Earth Pro Image 2012 and 2015.

However, the success of the erosion control strategy remains dependent on the participation of the key partner, the farming community (Mabit et al., 1999, 2002 and 2008; Roose, 2004 and Fulajtar et al., 2017). However, it is also important to select the suitable methods of tillage under semi-arid climate in order to preserve water and soil. The appropriate tillage practices and the making stubble decomposition in situ may increase the soil resistivity. Inversely, treating the soil to the minimum necessary should reduce water loss by evaporation, increase soil organic matter and its water retention power.

7. Conclusions

As a conclusion on the subject of water erosion, it turned out that the problem of soil degradation remains a topical issue that is difficult to study through a single method or a universal model that could be effective at different spatio-temporal levels. A first observation on the problem of erosion has been established through the present study, which has allowed the application of a modeling of sheet and rill erosion, also the sector appear to be slightly less affected by gully erosion over the last four decades through the Cesium 137 technique. It was found that land use, soil texture characteristics, rainfall intensity and topographic slope, especially the clear break in slope in the middle course, are the main indicators of erosion dynamics. The rate of loss varies considerably according to these factors, particularly the rate of vegetation cover. The results obtained constitute a first step in understanding the manifestation of erosion. Several comparative studies between isotopic and empiric methods (especially USLE and RUSLE models) have already been developed in Morocco to ensure the accuracy of the Cesium 137 outcome, especially those by Moukhchane, Bouhlassa and Bouaddi 1998, Sadiki 2005, Moukhchane 2008, Felah 2010 and Ben Mansour et al. 2012. Subsequently, some attempts and tentatives in the same direction have been made in Tunisia and Algeria by Toumi in 2013 and Azaiez in 2016. These efforts lead towards an easier future collaboration to adopt a regional approach to identify common quantitative and qualitative aspects of water erosion in Maghreb countries in the Mediterranean context. A second step is to make all experiences and results available to allow a promising collaboration with most Mediterranean countries in order to develop and implement an integrated regional strategy for addressing the erosion problem at Mediterranean scale. So, we have structures in place, but they require expansion and consolidation. In terms of validation of the modelling process in the present research, it was possible to compare the specific soil loss with that obtained by the empirical model of the universal equation USLE applied in the neighboring watershed of the Chaddad wadi, not far from Sidi Salah basin, where a maximum loss of 63 t/ha/year was recorded, calculated using the adjusted Universal Equation USLE (Azaiez, 2020). This comparison proves once again that regional erosion was controlled by the same factors (slope, soil texture, land use and a climate affected by extreme heat and dry periods).

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