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An analysis of sediment production and control in Rmel river basin using InVEST Sediment Retention model

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Abstract - Water erosion is a significant menace to land and water resources. It has a significant impact on agricultural production and sustainability of surface water resources under a Mediterranean climate system, especially in Tunisia. Identification and prioritization of critical erosion areas is an important aspect for policy makers. The aim of this paper is to determine the most vulnerable areas to soil erosion in the Rmel river basin situated in the Northeast of Tunisia, and to assess the effect of a catchment-scale implementation of soil conservation measures on soil loss and sediment yield. We used the InVEST (Integrated Valuation of Environmental Services and Tradeoffs) sediment retention model to provide spatially-explicit predictions of soil loss and sediment yield.Considering soil and water conservation measures, soil loss and sediment export decreased respectively by 4 and 0.9 ton/ha/year and sediment retention by 2 ton/ha/year.Comparing this value with the reservoir capacity, it indicates that risks related to reservoir sedimentation will also decrease.

Keywords: Sediment yield, sediment retention, InVEST SDR model, soil loss.

1. Introduction

Land degradation and reservoir siltation are global environmental problems, threatening the watershed development. Sedimentation is a complex phenomenon that is widespread in the Mediterranean area, particlularly in the North African countries, where it is seriously endangering reservoir management and water quality(Billota and Brazier2008, Irie et al 2011, Walling et al 2009). As a result, reservoirs' storage capacity is decreasing (Raclot and Albergel2000; Remini et al 2009;Al Ali et al2008; Ben Mammou and Louati2007), possibly reaching 43% of their initial storage in 2030(Ben Mammou2007). This loss will impose significant impact on the Tunisian economy in terms of reducing productivity of land and consequences that manifested by the siltation of dams and hill lakes. Therefore, the assessment of sediment yield has become increasingly important for water resources management by ensuring sustainable land management and securing stable water resources.

Soil erosion and sediment yield are influenced by the interactions between climate, land cover and land exploitation(Wilkinson2005). Given this complexity, models are often used to support soil and water management such as LISEM (Limburg Soil Erosion Model) (de Roo et al.1996),the Pan-European Soil Erosion Risk Assessment (PESERA)(Kirkby et al.2008),the Soil and Water Assessment Tool (SWAT) (Arnold et al.1998), and InVEST (Sharp et al. 2016),a spatially explicit toolused to map and value the service from nature.

The InVEST SDR (Sediment Delivery Ratio)was selected in this project to understand where sediment is produced and to quantify avoided sedimentation in reservoirs, which is the sediment retention service. The InVEST model was developped as part of the the "Natural Capital Project" a partnership between Nature Conservancy and WWF(World Wildlife Fund)as well as the Stanford and Minnesota universities. While the model has been verified in different geography (Hamel et al. 2017), its application to a new basin necessitate an understanding of local sediment dynamics and observed data.

The main objective of this paper is to present the development of the InVEST model in the Rmel basin to provide spatial information for landscape management, with a focus on the landscape management scenario proposed by local stakeholders. Our analyses include calibration and verification of the model with lake sedimentation data, thereby contributing to the growing body of literature on sediment delivery modeling with simple models like InVEST.

2. Data and methods

2.1. Study area

The Rmel river basin is situated in the northeastern part of Tunisia, within a semiarid environment (Figure 1). The average rainfall is ranged between 350 and 600mm. Figure 2 shows annual rainfall variability of the Zaghouan DRE station. The main river is wadiRmel; this river flows southeastward and has nine tributaries. The Oued Rmel dischargeddirectly into the Mediterranean Sea before the construction of the Oued Rmel dam in 1996, which created an artificial reservoir with an area of 5 km^2. The area of the catchment is 640 km^2. It mainly belongs to the governorate of Zaghouan, with a small portion located in the governorates of Nabeul and Ben Arous. The study area is characterized by a central plain surrounded by mountains in the North East and in the South West. The Djebel Zaghouan is the highest point with an altitude of 1293 m(Jebari et al.2016).Human interventions in this area are numerous. Land cover changes have included deforestation, in order to increase the cultivated land for agricultural purposes (PDAI 2014). In addition, some land cover changes are caused by urban areas expansion occupying fertile soils. Most of the land cover is nowcropland. Cereals are dominant and cover a large portion of the agricultural area. Natural vegetation covers approximately 30% of the area, mainly made of scrublands and natural forest. It is mainly located on mountaintops. Figure 3a,b presents maps of LULC and different soil type of the study area.The Rmel reservoir is the main surface resource in the basin.

This reservoir has an important hydrological value since it constitutes a source of irrigation of a large perimeter of the downstream plain of Bouficha. Therefore, it contributes to economic development of the country through the development of agricultural activities and the creation of jobs. It also plays a role in flood control for the downstream urban areas.In addition to the Rmel reservoir, the study area comprises 22 hill lakes, with a watershed area ranging from ten hectares to a few hundreds of hectares. Hill lakes occupy an important place in national strategies in term of water and soil conservation. In this region, lakes represent a significant source of water for agriculture, which is the dominant economic activity in the region. Sedimentation threatens the sustainability of lakes to mobilize surface water. Storage capacity of lakes was reduced by about 50% between 1991 and 2012. Furthermore, six lakes are totally covered by silt (DGA/ACTA 2015)

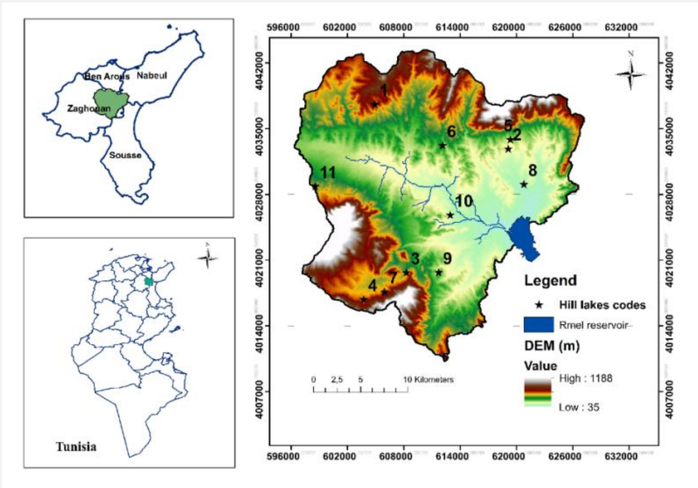


Figure1. Location of the Rmel river basin in Tunisia.

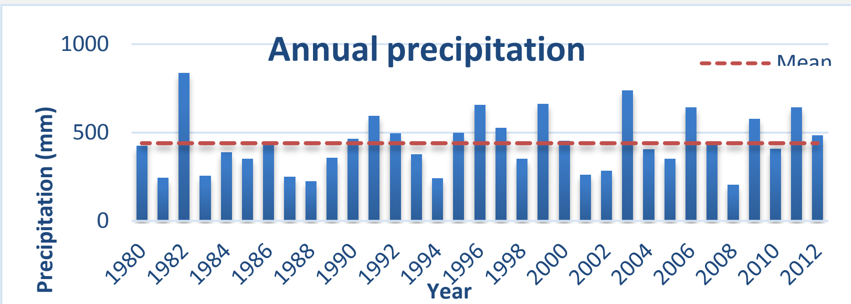


Figure 2. Annual precipitation of the station of Zaghouan DRE station (1980-1912)

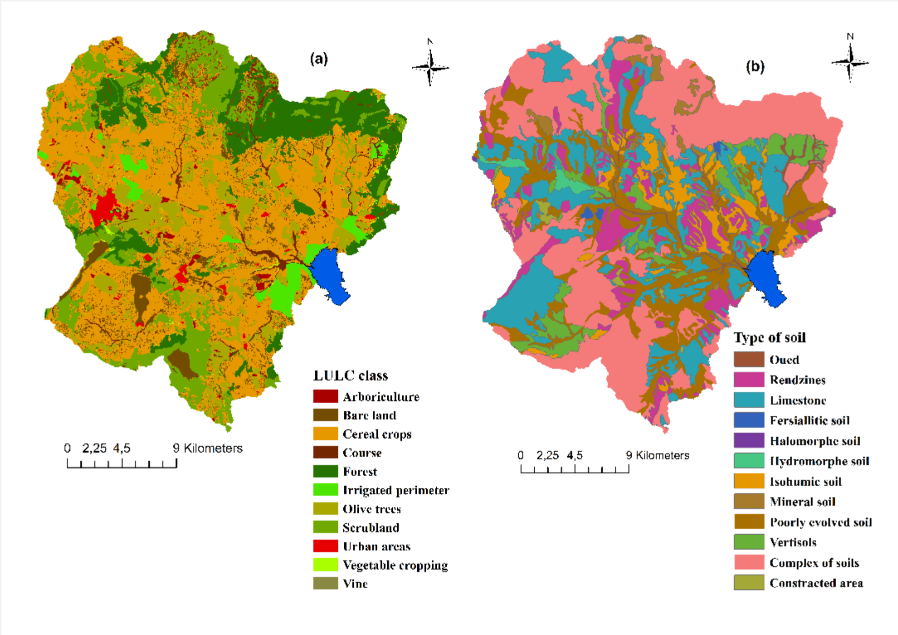


Figure 3. (a) map of the LULC class, (b) map of soil types.

2.2. Methodology

SDR Model map and quantify the sediment export, the soil loss and the sediment delivery ratio. The annual soil loss is estimating using the RUSLE (Wischmeier and Smith 1978). Sediment retention is calculated as the difference between received and delivered sediment at a pixel scale and sediment export is calculated as a function of the soil loss and the sediment delivery ratio (Vigiak et al2012). The model is a GIS-based that needs raster input of climate, soil, and topography in addition to land use land cover (LULC) data.The average amount of annual soil loss is calculated by the universal soil loss equation:

$$USLE = R.K.LS.C.P$$

Where R is the rainfall erosivity (MJ. mm $(h.hr)^{-1}$, K is the soil erodibility, LS the slope length gradient factor, C is the cover management factor and P is the support practice factor.

The role of the R factor is to characterize the erosive force of precipitation on the ground. It considers the regional differences of the climate according to the type, the intensity (I_{15}) of the precipitation. This duration (I_{15}) was found representative regarding to erosion process in Tunisian semi-arid catchments (Jebari et al. 2008). The erosivity of rain is expressed according to the following equation:

$$R= E*I_{15}$$

Where R is the rainfall erosivity (MJ. mm $(h.hr)^{-1}$, E is the the kinetic energy of the rains (MJ / ha). I_{15} is the rainfall intensity in 15 min expressed in mm/h. the kinetic energy (MJ/ha.mn) of the rains is given by the following equation:

$$E=0.29\ [1-0{,}72\ exp\ (-0.05 I\max)]$$

Where Imax is the maximum intensity (mm/h)

In our study site, there is only one rainfall station with intensity data (station sbahia). We then assumed that the erosivity is uniform throughout the basin. Erosive rainfall records was analyzed during the period (1993-2001).

Table 1. K factor for each soil type

Type of soil	Area (%)	K factor (t.h/MJ.mm)
Complex of soil	34.52	0.07
Limestone	20.6	0.027
Poorly evolved soil	17.78	0.07
Rendzina	9.665	0.013
Vertisols	6.12	0.001
Isohumic soil	6.09	0.05
Mineral soil	2.33	0.036
River	1.25	0
Hydromorphe soil	0.85	0.01
Constructed area	0.44	0
Fersiallitic soil	0.34	0.01
Halomorphe soil	0.021	0.01

The outputs of the SDR model include the sediment exported to the stream, the amount of sediment eroded in the catchment, and the sediment retained by vegetation, management practices and topographic features. In the Rmel watershed, we applied the InVEST sediment Delivery Ratio to estimate the amount of soil loss, sediment export, and the reduction in sediment export that could be brought by conservation actions. The model uses an hypothetical scenario where all landcover is cleared to a bare soil. Then, the value of sediment retained by the landscape is based on the difference between the sediment export from this bare soil catchment and that of the scenario (Sharp et al. 2016). Our main objective is the identification of most sensitive areas (in terms of sediment production) inside this region to focus restoration efforts.Rainfall erosivity was calculated based on rainfall intensity data available in the Sbaihia station. The K-factor is an estimation of soil erodibility as a function of soil development and horizon texture, organic matter, and permeability. We adopted a value of K erodibility factor of soil for each unit of the watershed, from the soil map of the governorate of Zaghouan, Ben Arous, Sousse and Nabeul (Table1). Actually, the C factor values were reconsidered based on specific publications. They were mentioned in several articles among which: Bouguerra et al (2017) as well as in Meghraoui et al (2017) and Zante et collinet (2001). The values considered within our work are as follow:

Table 2. Area and C factor for different LULC class (Sources: Meghraoui et al. 2017; Zante et Collinet. 2001)

LULC class	Area (%)	C factor
Cereal crops	43.91	0.4
Scrubland	14.72	0.02
Forest	13.32	0.01
Olive trees	12.24	0.104
Bare soil	8.12	1
Irrigated perimeter	2.99	0.1
Road	1.48	0.25
constructed area	1.35	0
Arboriculture	1.21	0.098
Vegetable cropping	0.57	0.3
Vine	0.03	0.35

The practice P-factor is the water and soil conservation practices or measures that reduce the amount of runoff and control the erosion. At the Rmel river basin, measures used are only terraces. P-factor values depend on the type of management and slope. We set P-factors to a value of 0.1 for terraces with slopes ranged from 0 to 5%, 0.12 with slopes from 5 to 15%, 0.16 with slopes 15 to 25% and 0.18 with a slopes 25 to 35% (Zante and Collinet 2001). We extracted slopes of areas with conservation practices. We attribute a factor for each slope. Then these practices were combined to landuse/landcover classes. From this combinaison, we extracted a biophysical table. The variables in the table include the cover management factor C and the support practice factor P values from the USLE model. It takes into account a user defined threshold accumulation number, which is a number of upstream pixel cells that must flow into a cell before it counts as a part of the stream network. We used the default threshold flow accumulation of 1000 pixels since it resulted in a stream network that matched observations (Tallis et al. 2014). Inputs data requirement a of the model for the SDR model are given in Table 3.

2.3. Data collection

We used a 30 m resolution DEM burned and filled using Archydro toolbox for GIS. We used the National Land cover Dataset 2004 which has 14 land cover classes at 30m resolution.
The R-factor is a climatic indication that estimates the kinetic energy of rainfall at the maximum 30 min intensity. Jebari et al (2008) have demonstrated that the 15 min duration is the most representative erosive rainfall in the semi-arid region of Tunisia. From the rainfall data available in the Sbaihia station, we calculated the values of the R factor for each storm. We used rainfall intensity (I_{15max}) data over the observation period of 9 years (1994-2003)(Bouguerra et al. 2017).

Table 3. **The inputs needed in the SDR model**

Inputs	Type	Source
Erodibility	Raster (30 m)	(Zante and collinet 2001)
DEM	Raster (30 m)	SRTM
Erosivity	Raster (30 m)	15-min rainfall data (Sbaihia Station)
Usle C factor	Decimal	Wischmeier and Smith (1978)
Usle P factor	Decimal	Wischmeier and Smith (1978)
Threshold flow accumulation	integer	(Tallis et al. 2014)
K, IC, SDR max	Decimal	Default values, Hamel et al (2015), Vigiak et al (2012)

Sedimentation data of the Rmel reservoir was collected from the DGBTH (Directorate General of Dams and Large Hydraulic Works).Sedimentation data of hill lakes was collected from the (General Directorate of Water and Soil Conservation) GD/ACTA. Measurements campaigns wereachieved in 2012. The volume of sediment deposited on the bottom of hill lakes and reservoirs was converted into a mass quantityusing 1.5 t/m^3 as a density average (Ben Mammou1998). Table 4presents a summary of hill lakes and reservoir observed siltation.Considering sedimentation in hill lakes and in the reservoir, the Rmel river basin annually produces 5.57 ton/ha/yr.
We model sedimentation in lakes. Then, the model was ran and calibrated considering that sediment retained in upstream lakes do not contribute to downstream sediment export. So, the estimate for the Rmel reservoir is the quantity of sediment that really reaches the downstream. The estimates for the Rmel river basin is the average amount of sediment that reaches both lakes and reservoir.

Table 4. Rmel hill lakes and observation of siltation.

Code	Sub-catchments	Year of creation	Area (ha)	Area (%)	Sedimentation (ton/ha/year)
1	**Ressifa**	1993	290.18	0.16	35.99
2	**Reziane**	2003	107.46	0.21	55.66
3	**Roumen**	2000	135.3	0.45	32.3
4	**Jlass**	2006	452.62	0.48	88.02
5	**Lachguef**	1997	103.1	0.16	29.097
6	**Lagraguib**	2003	166.94	0.69	8.1
7	**Jou Meleh**	1993	313.01	0.21	43.66
8	**Ain Saboun**	2008	137.43	0.19	8.91
9	**Azwaz**	1998	153.66	0.43	18.72
10	**Baroun**	1996	280.36	0.27	15.03
11	**Chaabet**	1991	123.15	0.27	14.4
	Rmel reservoir	1998	58000	89.23	2.64
	Rmel river bassin sediment production			100	5.57

We calculated the difference between predicted and observed value. The calibration factor was the k_b parameter (Vigiak et al. 2012). We selected the k_b that minimizes error between predictions andobservations.

2.4. Scenario analysis

In this section, we consider the impact of soil and water conservation techniques. Actually, these interventions are based in studies conducted by the development sector. Moreover, they were identified via concertation with local population during the EU BeWater Project (RBAP, 2016). We consider water and soil conservation techniques as one of the management options. This option aims to harvest runoff water. These techniques are situated on cultivated lands. Prioritization areas were chosen based on the sensitivity to soil erosion. Table 5 summarizes the different techniques and their correspondent area.

Table 5. Areas of soil and water conservation techniques.

Techniques	Area (ha)
Contour ridges	3800
Dry stone walls	150
Shallow basins	100

3. Results

3.1. Model calibration

The correlation between predicted and observed values was high.The value of r^2 is high (r2=0.84) (Figure 5).

To evaluate the extent to which $k_b$varied spatially.The model was calibrated for individual sub-catchments. The k_b parameter varies with 0.5 increments for the 11 sub-catchments. Results show a large variability in values, ranging from 1.6 to 3.3 (Figure 6).

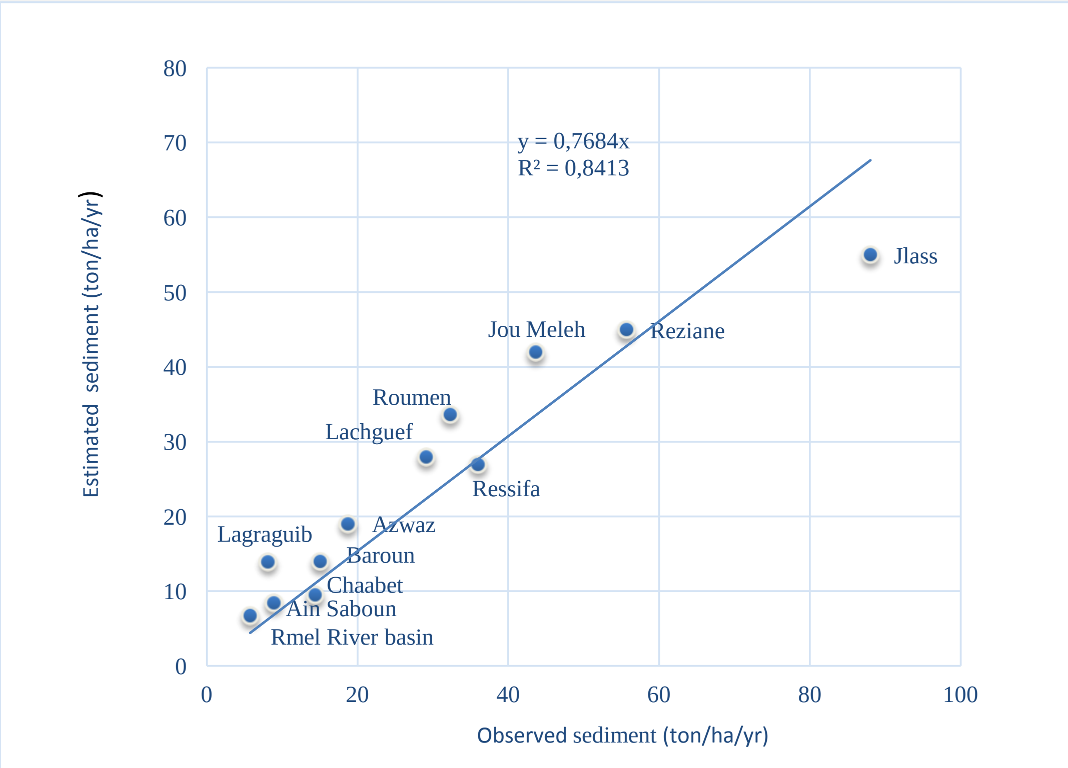


Figure 5. Correlation between observed and estimated sediment export

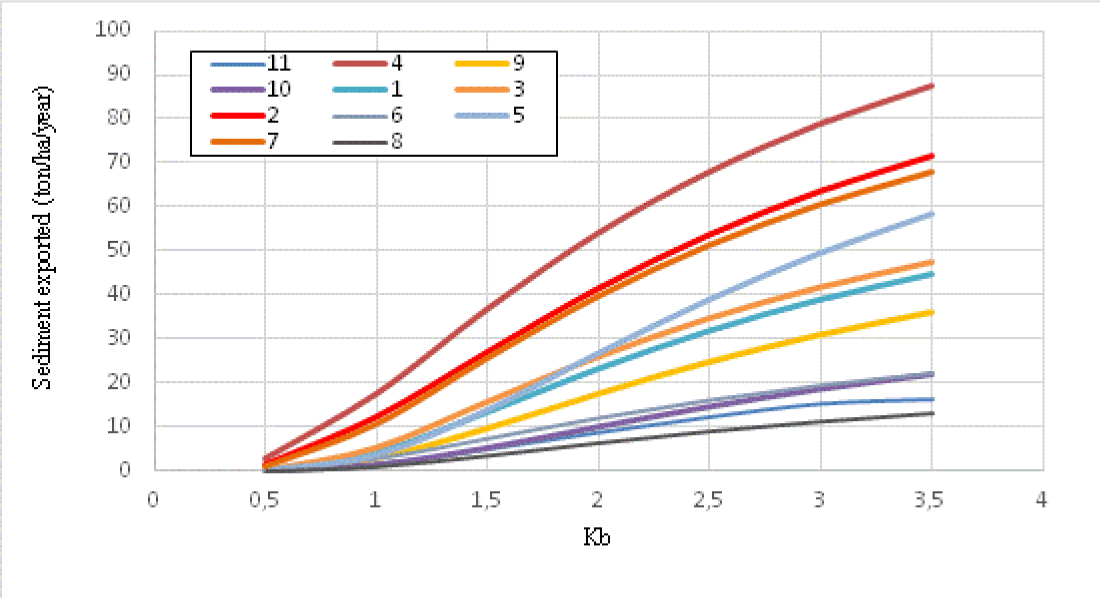


Figure 6. Sensitivity of the SDR model into the k_b parameter in the Rmel river basin case study. Each line represents a sub-catchment.

3.2. Maps of sediment export and soil loss

Studying sediment exports is important to inform land management decisions, in particular spatial prioritization for land management activities. There are six hill lakes in the Rmel river basin that werealready completely filled with silt. Their average life span is about 20 years, which is below the initial forecasts of hydraulic installation projects.

Table 6 reveals that the mean annual sediment yield for all sub-catchments was 26.87 ton/ha/year. Results demonstrate that the sub-catchment Jlass is the largest contributor to sediment yield with a value of 55 ton/ha/year. However, the Rmel river reservoir presents a low sedimentation with an average of 2.64 ton/ha/year. This can be explained by two facts. The first is that the large parts of sediments are caught by the lakes situated on the upstream reservoir. The second is that the main river Rmel in the basin of about 46 km length has remarkable steady slopes of 3% all along its course, presuming an equilibrium situation.

Table 6. Sediment exported and sediment retention service for Rmel sub-catchmentssoil loss.

Lakes	Sediment exprted (ton/ha/year)	Sediment retention (ton/ha/year)
Roumen	32.3	35.9212
Ressifa	35.99	20.12668
Reziane	55.66	85.7696
Lagraguib	8.1	13.6108
Lachguef	29.097	46.9448
Chaabet	14.4	9.5592
Jlass	88.02	35.19628
Jou Meleh	43.66	47.8492
Baroun	15.03	2.632
Azwaz	18.72	7.6916
Ain Saboun	8.91	1.26

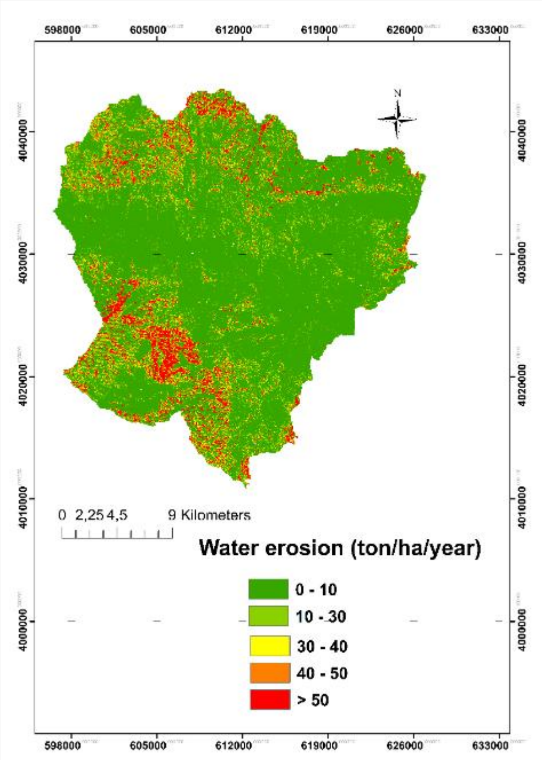


Figure 7. Spatial representation of soil loss in the Rmel river basin.

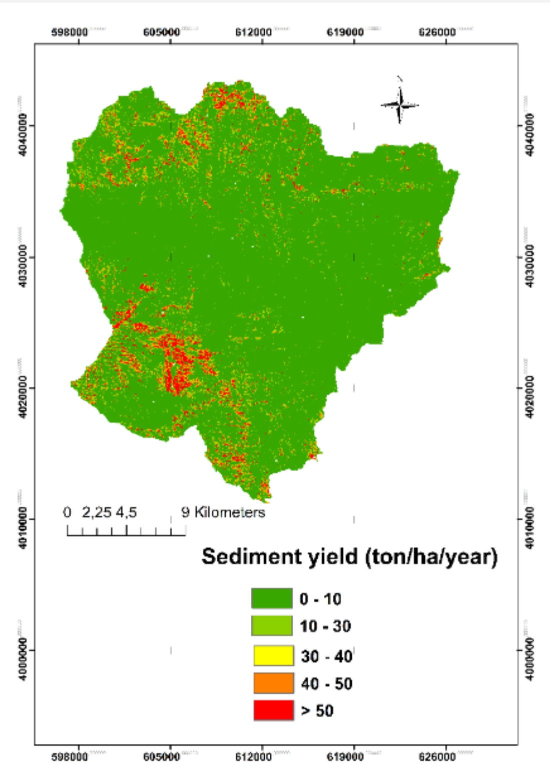


Figure 8. spatially distribution of sediment export

Mapping sediment yield and soil erosiongives the ability to identify land areas with high sediment export potential (Figure 8) and land areas with high erosion (Figure 7).

High sediment export areas are observed in the southeast and the northwest of the basin. Most of these fragile areaspresent high slopes and are occupied by agricultural activities and bare soil that increases the risk of erosion.The central part presents very low sediment export despite the presence of cultivated land. This can be explained by the presence of low slopes.

Soil erosion touches a large part of the basin. The plain presents low erosion risk; however, the northern and southern parts present a high erosion risk.

Shi (2012) and Zhu(2014) demonstrate that soil conservation measures taken in field decrease on site soil erosion and sediment production. However, sources areas that deliver sediments at the catchment scale are not necessary areas with high local soil erosion rates. This meansthat conservation activities according to soil loss amounts are efficient for on-site soil erosion problems. Therefore, considering the sediment export map is very important to develop management plans to preserve water storage capacity.

Sub-catchment Reziane provides the highest sediment retention with a value of 306.32 ton/ha/yr followed by sub-catchment Jou Meleh with a value of 170.8 ton/ha/yr sediment retention. The lowest contributor to sediment retention is Ain saboun with a value of 1.8 ton/ha/yr (Table 6). Table 7 summerize sediment export, soil loss and sediment retention of the Rmel

Table 7. Sediment export, soil loss, and sediment retention of the Rmel reservoir

	Sediment export (ton/ha/year)	Soil loss (ton/ha/year)	Sediment retention (ton/ha/yr)
The Rmel river basin	5.2	36.5	29

Hill lakes in the basin can be classified into two groups (Figure 9). The first group contains lakes that belong to the plain (Azwaz, Baroun, Chabeet, Ain Saboun, Lagraguib). This group presents low sediment exports because of the low slopes, and low sediments retention caused by the absence of natural vegetation cover. The second group contains lakes located in mountainous areas (Ressifa, Jou Meleh, Reziane, Jlass, Roumen, Lachguef). This group presents high sediment exports because of high slopes that coincide with cultivated land and fragile soils. Sediment retention in this area varies with or without the presence of natural vegetation.

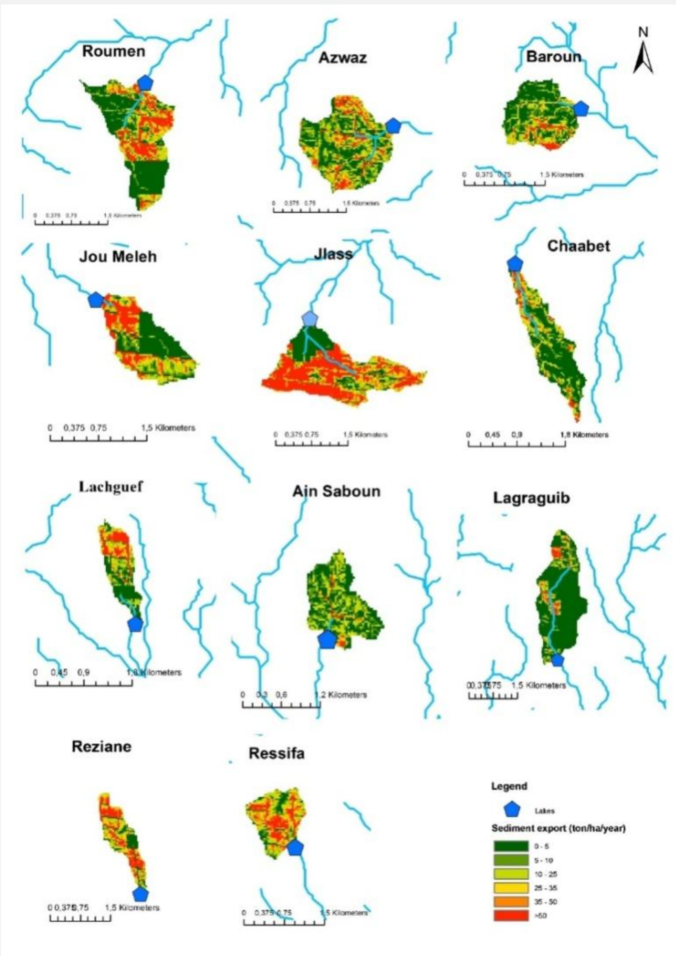
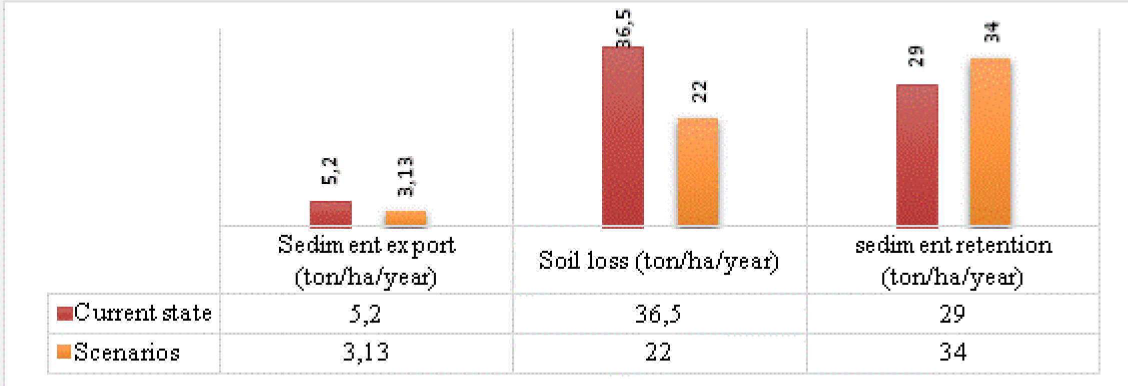


Figure 9. Sediment export maps for each sub-catchment.

3.3. Sediment export of the management scenario

Results show that sediment retention increase by 2.01 ton/ha/year after the application of the conservation scenario and a decrease in soil loss and sediment export by respectively 4 ton/ha/year and 0.9 ton/ha/year (Figure 10). The higher rates of sediment exportedalso meana greater amount of sediment to be retained by the natural vegetation and anti-erosive activities.
Comparing these results to the capacity of the reservoir, which is 22 million m^3 of water reveals a significant value in terms of decreasing costs related to reservoir sedimentation and securing water resources availability.



	Sediment export (ton/ha/year)	Soil loss (ton/ha/year)	sediment retention (ton/ha/year)
Current state	5,2	36,5	29
Scenarios	3,13	22	34

Figure 10. Sediment export, soil loss and sediment retention variation for current landscape and the scenario of development**.**

Water and soil conservation techniques would directly reduce water erosion. These practices improve water management in the basin by reducing sediment export and other risks related to drought and flooding. These measures have many benefits like using water runoff on the upstream parcels, maintaining the fertility and productivity of agricultural lands and the reduction of sediment export to the Rmel reservoir. However, these techniques may includes some risks like the decrease of cultivated lands and constraint on direct grazing of animals during the execution of work (RBAP2016).
Wind erosion process is not considered within the current work. In fact, in the Tunisian semi-arid areas only water erosion is having a major impact (toy et al ,2002). In Tunisia water erosion is the dominant process that causes reservoir siltation (Jebari et al. 2009).
The global soil assessment map shows that majority of water erosion in Tunisia is ranges between 0 and 100 ton/ha/an which is in coherence with results founds in our study. Moreover, publication in Tunisia showed that soil loss are high around 100 ton/ha/year (Jebari et al. 2009). Our results are in coherence with national and international publications.

4. Conclusion

Water erosion dynamics in the Rmel river basin were evaluated using InVEST SDR model. This model differed in that it spatially examined and consider the three water erosion dynamics , which are soil loss, sediment exported and sediment retention service. InVEST SDR model examined also the impact of management and conservation techniques on water erosion dynamics.Results show that water erosion rates are coherent with the Global Soil Erosion assessment and local publication. Moreover, Results indicatepositive affects under interventions of water and soil conservation techniques. These interventions could play a important role on reducing soil erosion in the upstream areas of watersheds, and reservoir siltation.

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