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ESTIMATION OF SOIL LOSSES AND RESERVOIR SEDIMENTATION: A CASE STUDY IN TILLOUGUITE SUB-BASIN (HIGH ATLAS - MOROCCO)

SUMMARY

Dam siltation has become a serious problem in arid and semi-arid countries under climate variability, where soil erosion and siltation represent a major challenge that face the industry of dams. In Morocco the policy of dam construction is one of the main keys in sustainable development, but unlikely, the dam siltation caused by soil erosion still present a big constraint. This study was carried out in the sub-basin of Tillouguite upstream the Bin El Ouidane dam in the High Atlas, in the region of Beni Mellal Khenifra, Morocco. The study aims to estimate the production of erosion material: soil losses, and the real soil losses rate - sediment yield, in Bin El Ouidane dam, using a combination of IntErO model - Intensity of Erosion and Outflow, GIS - Geographic information System and RS - Remote sensing. The study requires data which are collected from meteorological stations, soil data analysis, satellite images and observations during field missions. As a result, the production of erosion material in the Tillouguite sub-basin is estimated at 10,015,354 m^3yr^{-1}, the coefficient of the deposit retention is estimated at 0.283, and the real soil losses rate is around 2,838,489 m^3yr^{-1}. Given that the specific real soil losses rate is estimated at 910.02 $m^3km^2yr^{-1}$, and based on Gavrilovic classification, the sub-basin of Tellouguite is considered with a high potential of soil erosion risk, due to large bare land, and the steep land slope in the sub basin - factors that affect the storage capacity of Bin El Ouidane Dam. All the findings are a measurable indicators that are inviting policy makers to initiate appropriate measures for the protection of land degradation, all in line with the sustainable development policies in Morocco.

Keywords: Dam siltation, Soil erosion, IntErO Model, Land Use, Soil erosion, GIS, Remote Sensing.

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INTRODUCTION

Soil is a three-phase system that consists of solid particles, liquid, and gas, but also species that create a dynamic and complex ecosystem and is among the most precious resources to humans. On the other hand, soil erosion by water is acknowledged as a primary concern in the degradation of soil quality and functionality (Billi, & Spalevic, 2022; Saggau *et al*, 2022; Stefanidis *et al*., 2022; Lense *et al*, 2022; Chalise *et al*, 2019; Spalevic *et al*, 2017; Borrelli *et al*., 2016; Lal, 2014). The ever-growing availability of earth observation (EO) data and the well-established use of geographic information systems (GIS) during the last decades leads to the development of automated geospatial workflows for the estimation and mapping soil losses (Dominici *et al*., 2021; Stefanidis *et al*., 2021). It is a major global soil degradation threat to land, freshwater, and oceans; but also to the reservoirs constructed for agriculture production needs, energy, and other water supply matters (Stefanidis & Stefanidis, 2012). The sustainable reservoir management is rarther important for sustainable water resources management due to reported trends in drought conditions to mountainous and semi-mountainous areas (Stefanidis & Alexandridis, 2021; Myronidis *et al*., 2012). This process of degradation has continued to grow as a problem over time, with increasing sediment mobilization; decreasing reservoirs retention capacity (Spalevic *et al*., 2020). For over a century the scientific community has been addressing the processes governing soil erosion, the occurrence of accelerated soil erosion, and its negative associated socio-environmental impacts (Bennett and Chapline, 1928; Smith, 1914; Borrelli *et al*., 2021). Some researchers demonstrated in their studies the effect of vegetation cover and lithology on the detachment, mobilization and transport capacity of sediments (Khaledi Darvishan *et al*., 2019; Spalevic *et al*., 2019; Behzadfar *et al*., 2018; Kavian *et al*., 2018; Behzadfar *et al*., 2017; Behzadfar *et al*., 2014; Spalevic *et al*., 2013). Soil degradation and decreased water resources negatively affect agricultural production and have a negative impact on a country's economy (Ouallali *et al*., 2018). The United Nations Sustainable Development Goals (SDGs) acknowledge the significance of soil resources for sustainable development and advocate their protection in order to meet the ambitious goal of zero land degradation by 2030. This task must be integrated evaluated under the context of climate change for near and far future climate projections (Stefanidis et al., 2021). Our goal is to contribute with our research to the local demand and needs in relation to the dam siltation estimation of soil losses and reservoir sedimentation by using Global Inventions for the future Local Interventions.

The dam siltation which results the storage capacity loss is a natural phenomenon and depends on climatic conditions, relief, soil characters and land use (Costea *et al*, 2022; Felix *et al*, 2021; Chalise & Kumar, 2020; Andjelkovic *et al*, 2018). It is accelerated and intensified with human activity such as agricultural practices, grazing and deforestation. In Morocco the dam siltation is still the biggest problem and is facing the dam construction policies, including sustainable development policy. This phenomenon requires costly investments to solve problems caused by siltation. Due to siltation, dams in Morocco lost 10% of their storage capacities, where nearly 75 Mm^3 of soil reaches reservoirs every year, and some dams such as Khattabi, Dkhila, Sidi Driss, Sidi Said Maâchou and Nakhla, have already reached their maximum storage capacities because of the soil erosion problem.

Some solutions, including forestation are implemented in order to decrease the soil losses rate and reduce the nuisance of siltation on the storage capacity of dams, but unlikely and despite more than six decades of research, sedimentation is still probably the major problem faced by the dam industry.

The Bin El Ouidane dam is the third large dam in Morocco, with 1.5 Billion m^3 of the initial storage capacity, and is considered as important key in energetic and agricultural national plans, where the dam produces almost 12% of national hydroelectric energy production and irrigates the plain of Tadla, including two irrigated perimeters of Bni Amir and Bni Moussa, with a total surface of 105,500 ha (Karaoui *et al*., 2018).

The strategic importance of Bin El Ouidane dam brings the intention and interest of researchers to siltation and soil erosion problem in the watershed of Oued El A bid upstream the Bin El Ouidane dam. The objective of the research was identification of erosion critical areas based on soil erodibility, including related geographical factors in the Tillouguite sub-basin, High Atlas, Morocco.

MATERIAL AND METHODS

Study area. Morocco, in Northern Africa, bordering the North Atlantic Ocean and the Mediterranean Sea. The Position of this area is strategic with the location along Strait of Gibraltar, and it is the only African country to have both Atlantic and Mediterranean coastlines. This study was carried out in the sub-basin of Tillouguite, with a total surface of 2954 km^2, which forms alongside the sub-basins the big watershed of Oued EL Abid with a surface of 6073 km^2 (Figure 1).

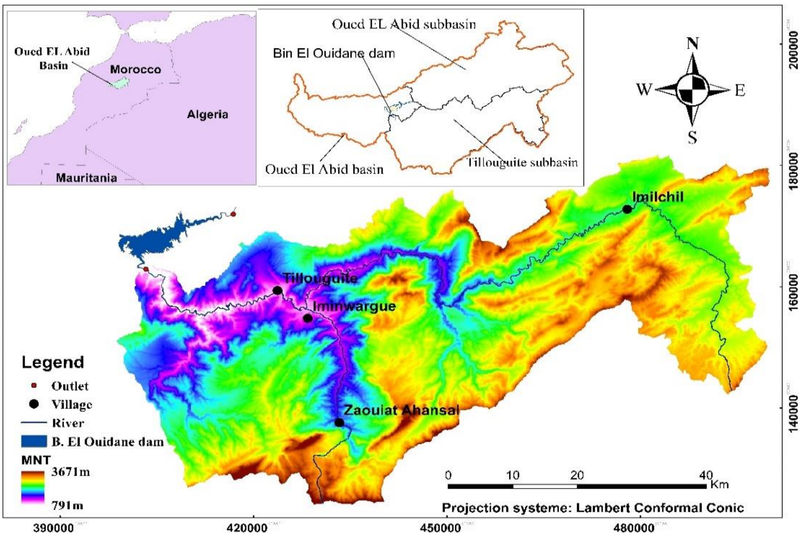

Figure 1. Study area of the sub-basin of Tillouguite, Morocco.

The region of Beni Mellal-khenifra is located between the High Atlas and the plain of Tadla. The main river in Tillouguite sub-basin is Oued assif-Ahansal, which aliments with the river of Oued El Abid the Bin El Ouidane Dam.

In term of geology, the sub-basin of Tillouguite is a part of High Atlas, which is formed mainly of carbonate grounds, belonging to the Jurassic, which gives it the character of having very high mountain ranges, where the elevation varies from 791m to 3671m (Sabri *et al*., 2018; Sabri *et al*., 2019).

The average annual precipitation according to the four meteorological stations is Ait Ouchen: 419.6 mm, TiziNisly: 453.0 mm, Zaouite Ahansal: 369.8 mm and Tellouguite: 395.3 mm. A semi-arid climate is observed in the sub-basin, with 6 months of rainy season and 6 months of dry season, where over 90% of annual precipitations is during the winter and spring seasons (Figure 2).

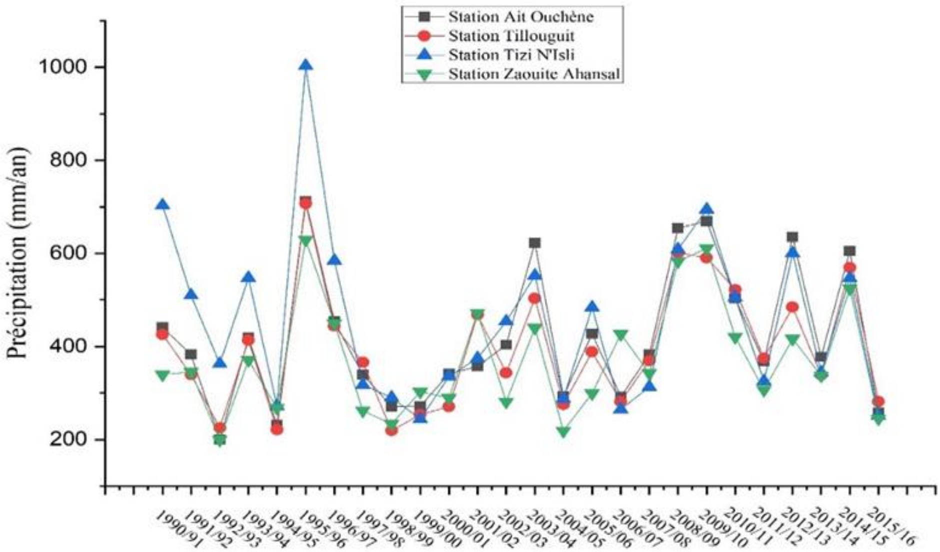

Figure 2. Precipitations in sub-basin of Tillouguite, Morocco (period: 1991-2016)

The temperature data has obtained from 4 meteorological stations measurements during 15 years, between 1991 and 2016. Where the maximum and minimum temperature ranges observed in the watershed are 26 °C to 45 °C and -9 °C to 8 °C, respectively.

The sub-basin of Tillouguite is characterized by 6 types of land use, including bare lands, which covers alongside pasture lands, the quasi totality of the sub-basin, dense forests and sparse forests, which have known a high rate of degradation in the last 20 years, and culture (Figure 3).

The soil map of Tillouguite sub-basin is generated based on the soil map of Morocco (1: 1.500.000) by Wladimir Cavalla in 1950 who was in charge of the mission on behalf the National Center for Scientific Research at the Center of agronomic research of Morocco in 1950 (Figure 4).

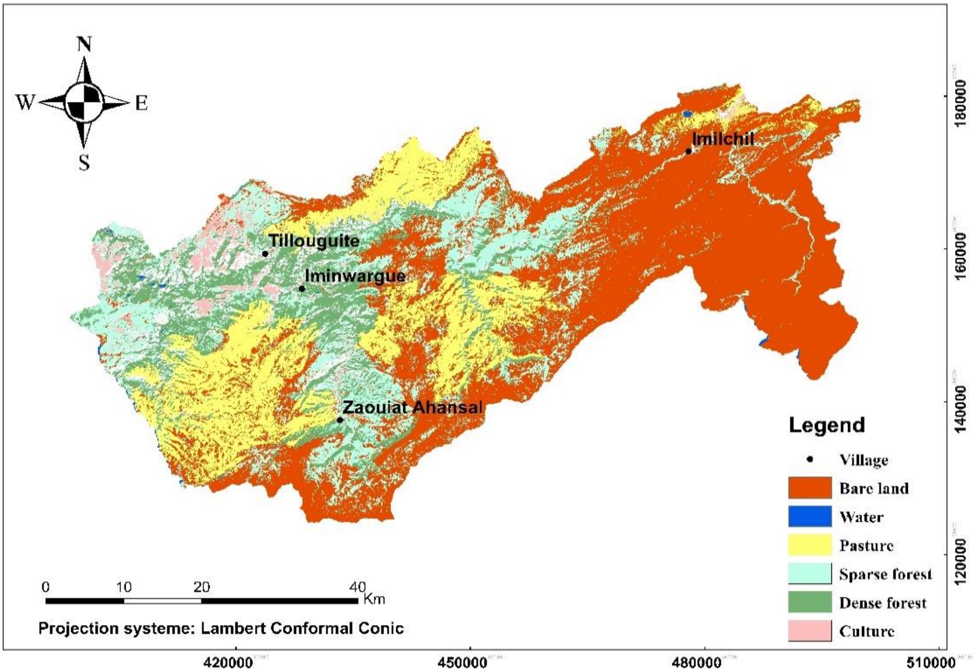

Figure 3: Land use in the sub-basin of Tillouguite, Morocco.

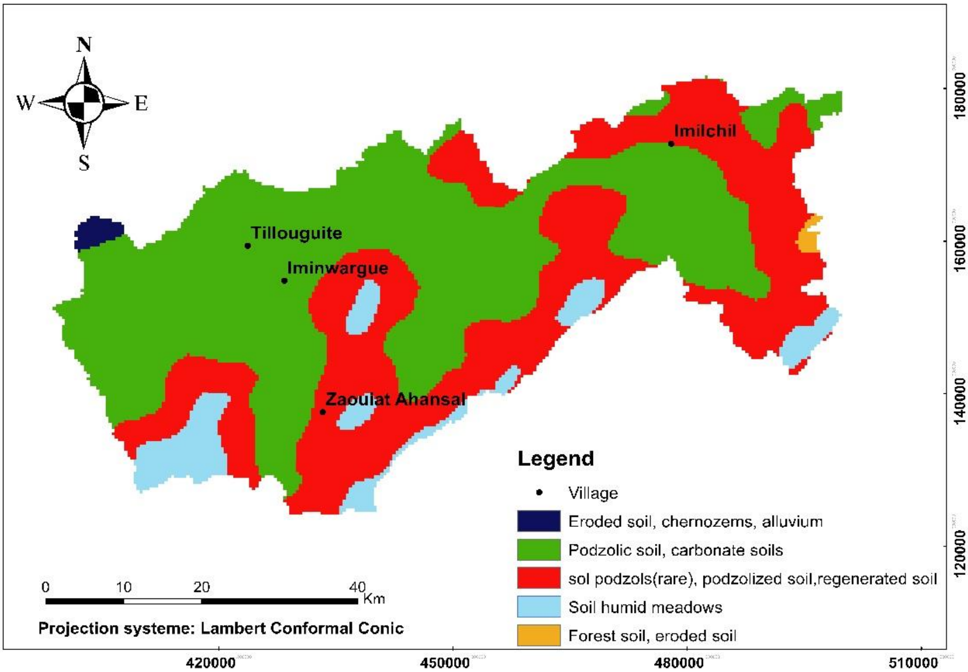

Figure 4: Types of soil in Tillouguite Sub-basin.

Method. With an increased abundance of observed data and the aim of mapping spatially distributed soil erosion rates with a better understanding of their mechanics (Cook, 1937), scientists are developing quantitative soil-erosion prediction equations based on physical factors such as climate, soil characteristics, vegetation type, and topography (Zingg, 1940) for a century. Several mathematical models classified as empirical, conceptual, or process-oriented have been developed to predict soil erosion processes at different spatial and temporal scales (Merritt *et al.*, 2003; Morgan and Nearing, 2011; Nearing, 2013). Batista *et al.* (2019) reported that today “there is no shortage of soil erosion models, model applications, and model users' but there is still acknowledge gap on the validity, quality, and reliability of the modelling application results”.

Despite the significant progress made in model development and input parameterization, output uncertainties persist due to the non-linear relationships and thresholds at play between driving factors and the subsequent erosion processes, as well as the difficulties of upscaling model findings from the local scale to larger ones (Borrelli *et al*., 2021.; DeVente and Poesen, 2005).

Today, with the well-established use of geospatial technologies like Geographic Information Systems (GIS), spatial interpolation techniques, and the ever-growing range of environmental data; soil-erosion models play an increasingly important role in the design and implementation of soil management and conservation strategies (Panagos *et al*., 2015). The applications of soil erosion models are growing (Auerswald *et al*., 2014), alongside the scale of their application (Borrelli *et al*., 2017, Naipal *et al*., 2018). These models play an important role as tools to support decision-makers in policy evaluations (Borrelli *et al*., 2021; Olsson and Barbosa, 2019).

Accurate information on the existing land-use pattern and its spatial distribution is a prerequisite for soil conservation planning and assessment of the soil erosion rate. It is essential for the development of adequate erosion prevention measures for sustainable management of land and water resources (Thakur et al, 2018).

In this study we used the IntErO model, which is based on EPM- Erosion Potential Model (Gavrilovic S., 1972). The EPM was created to estimate the annual sediment yield and the transport of sediments based on physical, climate, geological and hydrological characteristics of the river basin such as the temperature, the mean annual rainfall, the soil use, the soil properties and some other factors in the watershed scale, with arid and semi-arid climate, where it has been used in Europe, Middle-Est, North-Africa, America, under arid and semi-arid climate. In recent times the EPM is repeatedly applied in several watersheds in the Mediterranean area, especially in the South East Europe - Balkan region (Kostadinov *et al*., 2006; Tazioli, 2009; Dragicevic *et al*., 2017; Tavares *et al*., 2019; Tosic *et al*, 2019.; Spalevic *et al*., 2020; Dragicevic *et al*., 2022), and also in arid and semi-arid areas of the south-western USA (Gavrilovic Z., 1988).

The method was based on the factors affecting erosion in a watershed, which are dependent on the temperature, the mean annual rainfall, the soil use, the geological properties, and some other factors in the watershed scale (Gholami *et al*, 2013; Khaledi Darvishan *et al*., 2017).

The Intensity of Erosion and Outflow - IntErO program package was developed to predict the runoff peak discharge, the intensity of soil erosion, and the sediment yield in a variety of watershed forms. The model was tested in different countries such as Bosnia & Herzegovina, Bulgaria, Croatia, Czech Republic, Italy, Iran, Montenegro, Macedonia, Serbia, Slovenia, Morocco, Brazil and Nepal, in arid and semi-arid climate (Mohammadi *et al*., 2021; Ouallali *et al*, 2018).

In this study we used IntErO model specifically, to estimate the soil losses in the sub-basin of Tillouguite and sediment yield in the Bin El Ouidane dam, based on the following equations:

$$W_{yr} = T_i \cdot H_{yr} \cdot \pi \cdot \sqrt[2]{Z^3} \cdot F \qquad \text{Equation 1}$$

$$T_i = \sqrt[2]{\frac{t_0}{10}} + 0.1 \qquad \text{Equation 2}$$

$$Z = Y \cdot X_a \cdot (\varphi + \sqrt[2]{I_{sr}}) \qquad \text{Equation 3}$$

$$G_{yr} = W_{yr} \cdot R_u \qquad \text{Equation 4}$$

$$R_u = \frac{(O \cdot D)^{0.5}}{0.25 \cdot (Lv \cdot 10)} \qquad \text{Equation 5}$$

where: W_{yr} = Annual erosion (m^3 km-^{2} yr-^{1}); T_i = Coefficient of temperature (dimensionless); H_{yr} = Mean annual rainfall (mm yr^{-1}); Z = Coefficient of erosion (dimensionless); F = Basin area (km^2); t_0 = Mean air temperature (°C yr^{-1}); Y = Soil resistance to erosion (dimensionless); x_a = Coefficient of soil use and management (dimensionless); φ = Coefficient of visible erosion features (dimensionless); I_{sr} = Mean slope (%); G_{yr} = Sediment production (m^3 km^{-2} yr^{-1}); Ru = Coefficient of retention (dimensionless); O = Basin length (km); D = Difference in basin elevation (m) and; Lv = Length of main stream (km).

Based on the data mentioned we obtained the data needed to run the IntErO program package. The input data needed for modelling of soil erosion processes and runoff are presented in the table below (Table 1).

Table 1: Modelling inputs data for Tillouguite sub-basin, Morocco.

Inputs	**Symbol**	**Value**	**Unit**
River basin area	F	2954	km²
The length of the watershed	O	457.84	km
Natural length of the main watercourse	Lv	154.12	km
The shortest distance between the fountainhead and mouth	Lm	99.23	km
The length of the main watercourse with tributaries	ΣL	55594	km
River basin length measured by a series of parallel lines	Lb	120	km
The area of the bigger river basin part	Fv	1603.45	km²
The area of the smaller river basin part	Fm	1350.55	km²
Altitude of the first contour line	h0	700	m
Equidistance	Δh	110	m
The lowest river basin elevation	Hmin	650	m
The highest river basin elevation	Hmax	3226	m
A part of the basin with very permeable product from rocks	fp	0.46	
A part of the basin area consisted of medium permeable rocks	fpp	0.22	
A part of the basin consisted of poor water permeability rocks	fo	0.32	
A part of the river basin under forests	fs	0.09	
A part of the basin under grass, pastures and orchards	ft	0.07	
A part under bare land, plough-land and ground without grass	fg	0.84	
The volume of the torrent rain	hb	165.5	mm
Average annual air temperature	t0	16.8	°C
Average annual precipitation	Hyr	450	mm
Types of soil products and related types	Y	1.3	
coefficient of the river basin planning	Xa	0.84	
Numeral equivalents of visible erosion process	φ	0.61	

RESULTS AND DISCUSSION

After preparing the inputs required for IntErO model, the model was run and came out with outputs data which is shown in Table 2.

Based on the results, we concluded that there is a possibility of the appearance of large flood waves. The value of the coefficient G of 18.91 indicates a very high density of the hydrographic network in the sub-basin. The value of 73.48% indicates the existence of steep slopes in the sub-basin. The value of the Z coefficient of 1.695 indicates that the watershed belongs to category I of destruction. The results indicate also that the force of the erosion process is excessive in the sub-basin.

Table 2: Modelling results for Tillouguite sub-basin, Morocco.

Results	**Symbol**	**Value**	**Unit**
Coefficient of the river basin form	A	0.54	-
Coefficient of the watershed development	m	0.89	-
Average river basin width	B	23.99	km
(A)symmetry of the river basin	a	0.91	-
Density of the river network of the basin	G	18.91	-
Coefficient of the river basin tortuousness	K	1.88	-
Average river basin altitude	Hsr	2223.58	m
Average elevation difference of the river basin	D	1432.58	m
Average river basin decline	Isr	73.48	%
The height of the local erosion base of the river basin	Hleb	2908	m
Coefficient of the erosion energy of the basin's relief	Er	123.86	-
Coefficient of the region's permeability	S1	0.78	-
Coefficient of the vegetation cover	S2	0.95	-
Water retention in inflow	W	9363.25	m
Energetic potential of water flow during torrent rains	2gDF^½	3600.58	m km s
Temperature coefficient of the region	T	1.33	
Coefficient of the river basin erosion	Z	1.695	
Production of erosion material in the river basin	Wyr	1001535	$m^3\ yr^{-1}$
Coefficient of the deposit retention	Ru	0.283	
Real soil losses	Gyr	2838489	$m^3\ yr^{-1}$
Real soil losses per km^2	Gyr (km^2)	910.02	$m^3 km^2 yr^{-1}$

Bathymetric measurements at the Bin El Ouidane dam have reported that the sediment yield rate is 5 million m^3 per year. Where previous studies, in the watershed of Oued El Abid using the USLE/RUSLE model (Wischmeier and Smith, 1978; Williams, 1975; Renard, 1991), estimated the soil losses at 8.000.000 $m^3\ yr^{-1}$ and the sediment yield at 5.200.000 $m^3\ yr^{-1}$ (Sabri *et al*., 2016).

Being a spatially explicit model is the biggest advantage of the RUSLE whereas the IntErO calculates sediment yield collectively for the whole basin. Where the RUSLE model is more focused with the calculation of soil loss only, the IntErO also computes maximum outflow from the river basin, asymmetry of the river basin and coefficients of river basin form, watershed development, river basin tortuousness, region’s permeability, and vegetation cover; these parameters are also of paramount importance in determining the soil loss of a landscape. A major advantage of IntErO over RUSLE is it calculates both the sediment delivery ratio and sediment yield but RUSLE does not. RUSLE only calculates gross soil erosion rates which may or may not include soil that is lost from the river basin as not all the erosion materials generated get lost from the basin but sediment yield measured by the IntErO is the actual volume of soil leaving the river basin (Chalise *et al*., 2019).

Other study using the IntErO model in the sub-basin of Oued El Abid estimated the soil losses at 3.960.115 m^3 yr^{-1}, and the sediment yield in the dam of Bin El Ouidane at 1.200.000 m^3 yr^{-1} (Sabri *el al*., 2019). The results of this study came out with the sediment yield in the watershed of Oued El Abid, upstream of the dam of Bin El Ouidane, which gathers both sub-basins of Oued El Abid and Tillouguite, and is estimated at 4.100.000 m^3 yr^{-1}, which is about 10% less than the bathymetric measurement in the Bin El Ouidane dam.

CONCLUSION

This study shows the effectiveness of the combination of RS, GIS and IntErO model to estimate the soil losses and sediment yield, based on data, which have obtained from satellite images analyses and meteorological stations measurements, but also on data from soil analysis and field observations.

The sediment production in the region of the Bin El Ouidane dam, that counts the results from the two sub-basins of the El Abid and Tillouguite, is estimated at 4.1 Mm^3 $year^{-1}$, and shown close match of the results obtained by modelling and the bathymetry studies.

This study also confirms the effectiveness of the IntErO model in assessing the soil loss in a North African country that is outside of the Balkan Peninsula where the IntErO model is frequently used. The research approved the technical capability of IntErO model in soil erosion modelling and sedimentation estimation, under semi-arid climate in large spatial scale. Also, this study could provide important support to decision makers and planners to simulate scenarios to reduce soil erosion in the watershed of Oued El Abid and plan interventions against storage capacity loss in the dam of Bin El Ouidane, but also to the other river basins with similar physical-geographic conditions all over the World.

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