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Research Paper

Modeling of erosion in the Wadi Guir watershed (South-West Algeria) by the application of Geographic Information System (GIS).

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Abstract: The erosion of watersheds in Algeria is the major concern of dam managers. It depends on the nature of the soil and rainfall aggressiveness. The areas threatened by degradation due to desertification and water erosion are estimated at 50 million hectares. This area represents more than 20% of the total areas of the country, which is around 238 million hectares (MEDDI, 2015).

The main objective of this study is the mapping of erosion in Wadi Guir watershed which feeds the Djorf-Torba dam (South-West Algeria), by the combination of Geographic Information System (GIS) and the different empirical formulas used in arid regions. This contribution makes it possible, on the one hand, to determine the zones producing erosion, which feed the main Wadi, through maps of distribution of the degrees of sensitivity to erosion (SADIKI, 2004). On the other hand, the application of empirical formulas makes it possible to evaluate the forecast of solid inputs linked to citation (TOUAÏBIA et al.., 1999). This in order to control the sediment dynamics, and ensure better profitable management of the dam organs during floods and during normal operation.

Keywords: Erosion, Djorf-Torba dam, Watershed, GIS, pluviometry.

Introduction

Soil erosion is a natural phenomenon with varying degrees of complexity from one place to another (TOUMI et al.., 2013). It corresponds to the separation between the particle and its support, without including transport and sedimentation (BENSAFIA, 2016). Geomorphic conditions, hydro-climatic characteristics and socioeconomic factors are important parameters influencing the process of erosion, in arid or semi-arid zones. These different indices are particularly favorable to the initiation and acceleration of this phenomenon (KABOUR et al.., 2015). The problem of erosion is more critical in the watersheds located in the areas near the dams, it is a serious risk for the lifespan of these (TUNDU et al.., 2018).

The siltation of dams is the most dramatic consequence of erosion and solid transport. Today this problem affects many dams, several authors have shown the consequences and dramatic predictions of sedimentation in dam reservoirs, which depend mainly on the site, the size and the operating mode of the structure, we can quote: ENGEZ, 1955; MURTHY, 1970; SIMAIKA, 1970; MUKAMEDOV, 1981; KORSO, 1986 (MEKERTA, 1986). Higher values are recorded in Maghreb and more particularly in Algeria, over 30 million m³ of sediment is deposited annually at the 52 major dams in Algeria in addition to more than 2 billion m³ of sediment (National Agency for Dams and Transfer-ANBT, 2004).

The quantification of erosion, either water or wind in a watershed and the assessment of the siltation rate in dams, has been the subject of several studies in different fields based on the combination of empirical formulas and Digital Elevation Models (DEM), (NANGIA et al.., 2010; KABIR et al.., 2010). In principle, there is no reliable method representing the reality of this phenomenon. The study of erosion behavior as well as its distribution, requires the determination of the values corresponding the different parameters of the watershed, such as the morphometric conditions (the length, the slope of the slope and the area); climatic or meteorological factors (precipitation and temperature); terrain indices (vegetation and permeability) and the influence of soil condition (TECSULT, 2005; DAS, 2014; KACI et al.., 2017).

This study is part of the protection of the Wadi Guir watershed. The approach used is to combine the empirical formulas with ArcGIS software. Practically this methodology allows on the one hand showing the influence of different climatic and geomorphological parameters on the phenomenon of erosion and solid transport; and on the other hand, the application of ArcGIS software enabled the creation of thematic maps which represent the distribution of erosion.

More specifically, the results obtained in the present study should make it possible to establish a protection system to protect our structure, by determining the zones producing sediments at the level of the various sub-watersheds and classifying the degree of erosion by relative importance.

Martial mad Methods

Context and objectives of the study

We are interested in this research axis because it is a real case of a silted dam located in an arid zone in Algeria. This sediment entrainment phenomenon is characterized by a rapid rhythm from one year to another, due to the strong sedimentary dynamics of its watershed, which feeds the dam. The climate in our study area is rather aggressive, alternating between a period of floods and rains, as well as another period of winds and dry hot weather. There is reduced or sometimes non-existent of any plant cover at the watershed (AÏT HSSAINE, 2014).The present study describes a method of exploiting DTM data in SRTM form (Shuttle Radar Topography Mission), which allows the extraction of geomorphological indices (KACI et al.., 2017).

This process is going to be done by using GIS tool via developing thematic maps that contribute to the distribution of erosion across the watershed (BESKRI et al.., 2009; MARKHI et al.., 2015). This involves quantifying erosion, estimating the rate of sediments at the reservoir level and evaluating the long-term water storage capacity. We take into account the variation of the different parameters that influence the sedimentary dynamics, to ensure good management of the resource at the structure level (LUPKER, 2011; ROLLET, 2007).

Presentation of the study area

Geographic location

Our study is concerned with the Djorf-Torba dam, which is located about fifty kilometers (50 km) to the west of the city of Bechar (Figure 1). The dam occupies the fourth place in Algeria with an initial capacity of 350 hm³ (year of impoundment in 1969). The dam is intended for the amortization of water when Wadi Guir is in flood, the irrigation of the agricultural perimeters of the plain of Abadla (5400 hectares), and for supplying the region of Bechar and Kenadsa with drinking water (15hm^3/year, since 1985), (National Agency for Dams and Transfer-ANBT, 2004).

Figure 1. Overview of the dam

The Wadi Guir watershed, which feeds the dam, is located in Bechar region in the south-west of Algeria. It is bounded by the Moroccan High Atlas form one part, to the North by the Tamlal plain and the High Atlas, at the east by the Wadi Bechar watershed, to the west by the Hamada of Guir and to the south by Chebket Mennouna (Figure 2), (KABOUR et al.., 2015). It occupies an area that stretches over 23000 km² in an elongated shape, the altitudes vary from 690 m to 2700 m (Figure 3).

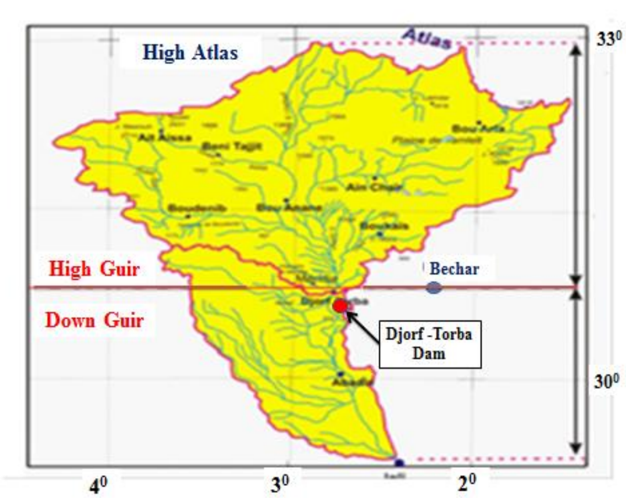


Figure 2. Situation of the Wadi Guir watershed

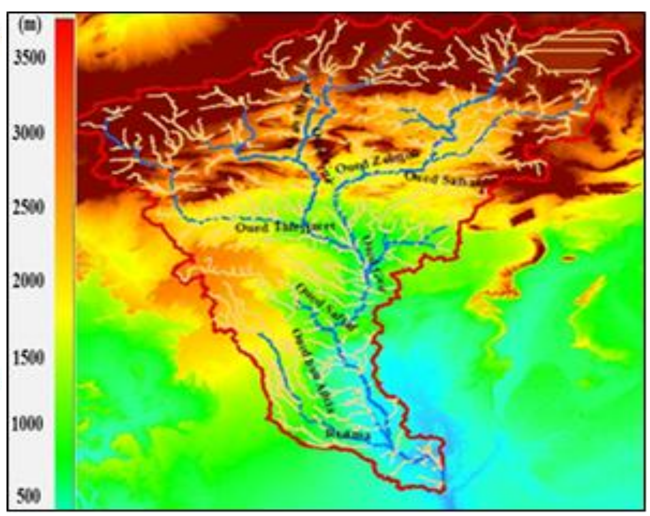


Figure 3. Wadi Guir catchment area on DEM

Climatic data

Annual rainfall is characterized by a regime of two main rainy periods, the first in winter (September to December), the second in spring (March to early May) separated by two dry periods in summer (June to August) in addition to July, January and February practically without any precipitation (source: National Agency for Hydraulic Resources, ANRH-Bechar). The climatic data collected at the Djorf-Torba station were provided by the South-West meteorology of Bechar, they are spread over a period of 15 years (1994 to 2008), (Table 1).

Table 1. Climate data (1994-2008)

Station	Pa* (mm)	Pm** (mm)	T*** (°C)
Djorf-Torba	245,55	74,18	21,85

****Pa**: Average annual rain (mm).
***Pm**: Average monthly rain for the rainiest month (mm).
***** T**: Average annual temperature (° C).

Hydrology of the site

The Djorf-Torba dam regulates the Guir-Saoura hydrological system, which is the most important river in the Algerian Sahara, with a length of more than 300 km (National Agency for Dams and Transfer-ANBT, 2004), (Figure 4). According to the hydrological study (COYNIE and BELLIER, 1985), the exceptional flood is characterized by an annual liquid contribution of the order of a billion m³. Since 1952 and over 22 years, floods of more than 300 hm^3have been recorded 1 or 2 times, 4 times more than 200 hm^3, 11 times more than 110 hm^3, with peaks of 15 to 20000 m^3/s. These values represent the sum of the sub-Wadis and the main Wadi of the hydrological system which supplies the reservoir (Figure 5).

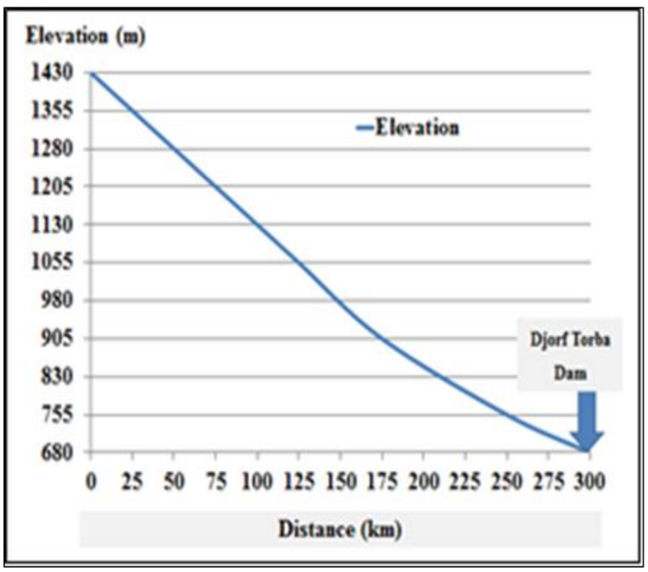


Figure 4. Longitudinal profile of the main river

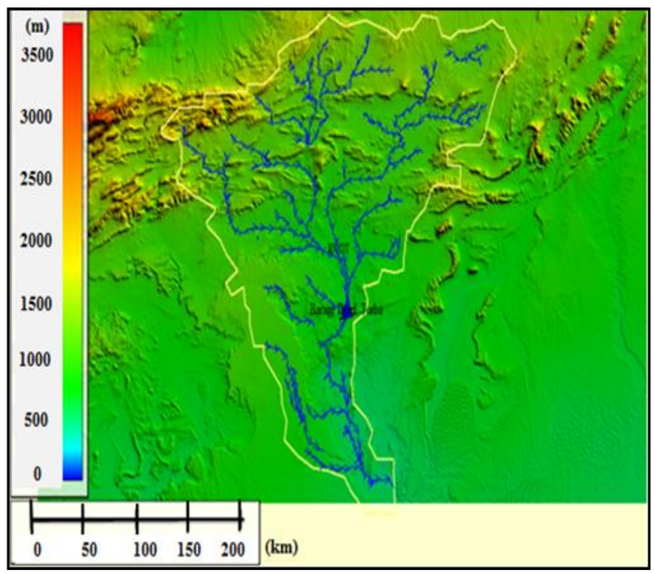


Figure5. Hydrological system of the watershed

The geomorphology of the watershed

The development of a map of erosion at the level of the watershed requires the determination of the various geomorphological parameters relating to the study area (DESHMUKH et al.., 2014).

The solid intake estimation method is based on the evaluation of various parameters related to the risk of erosion. First, we have to group all the geomorphological indices of the different sub-watersheds. Second, climate parameters have to be taken into account (TECSULT, 2005).

According to the results of the division obtained by the application of the ArcGIS software on the DEM of the study area, the Wadi Guir watershed covers a total area estimated at 23720,84 km^2. The watershed is made up of 13 elongated under-watersheds (UW) (Figure 6).

The under-watersheds have remarkably variable surfaces from 118,98 km^2 as a minimum value for the UW-12, up to 8126,6 km^2 as a maximum value for the UW-04. The watershed is practically flat, since more than 75% of the total surface contains slopes of less than 6%, the rest of the surface, approximately 25%, has slopes, which vary between 1,15 and 5,25% (Table 2).

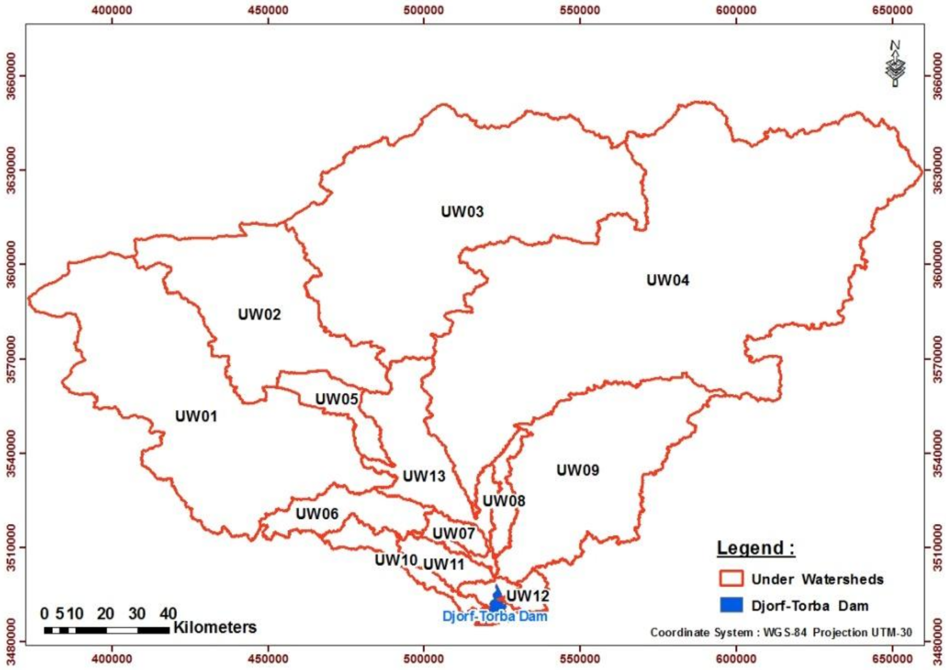


Figure 6. Installation of the Wadi Guir under-watersheds (Upstream part of the dam)

Table 2. Geomorphological characteristics of sub-watersheds

N^0-UW	Perimeter (Km)	Area (Km^2)	Elevation (m)	Slope (%)
UW-01	492,52	3 477,30	804,00	7,19
UW-02	334,18	2 286,60	954,00	9,01
UW-03	499,99	4 347,70	952,00	5,18
UW-04	795,21	8 126,60	742,00	4,52
UW-05	138,50	368,00	820,00	5,25
UW-06	200,22	554,59	770,00	3,63
UW-07	88,24	165,68	720,00	1,78
UW-08	134,21	218,11	714,00	1,50
UW-09	358,22	2 211,90	704,00	3,20
UW-10	189,01	297,91	698,00	1,40
UW-11	112,59	261,57	704,00	1,15
UW-12	66,51	118,98	694,00	3,45
UW-13	599,86	1 285,90	1 236,00	5,06

Estimate of erosion in the Wadi Guir watershed.

Based on the data collected on the study area, we identified and evaluated the nature and extent of the erosion processes of the various under-watersheds, by applying several formulas and methods (Fournier 1960, Tixeront 1960, Kassoul and al 1997) (TECSULT, 2005).

The estimation of solid inputs requires knowledge of the density of solid grains. It was necessary to take samples, which are the product of the siltation of the dam inside the gallery (sample P3) and at the bottom drain (sample P4) (Figure 7). The value of the average density measured is 2,86 t/m^3.

Figure 7. Sampling points for the different samples

Fournier formula (1960)

According to Equation (1), Fournier formula is based on the nature of the precipitation and morphological characteristics of the UW studied (MEKERTA et al.., 2008).

$$Es = \left(\frac{1}{36}\right) \times \left(\frac{Pm^2}{Pa}\right)^{2.65} \times \left(\frac{H^2}{S}\right)^{0.46} \quad \ldots\ldots (1)$$

Es: Average annual specific erosion in (t/km²/year).
Pm: Monthly rain of the rainiest month (mm).
Pa: Average annual rain (mm).
H: Average elevation (m).
S: Area of the under-watershed (Km^2).

Table 3 presents the values of specific erosion (Es) and solid transport (As) for each sub-watershed. The calculation of (As) takes into account the average density of solid grains and the area of UW.

Table 3. Results of the Fournier formula according to the under-watersheds

N^0-UW	Es ($t.km^{-2}.year^{-1}$)	As ($hm^3.year^{-1}$)
UW-01	507,37	0,62
UW-02	720,12	0,58
UW-03	534,79	0,81
UW-04	394,18	1,12
UW-05	1451,65	0,19
UW-06	1 134,48	0,22
UW-07	1 859,22	0,11
UW-08	1 625,79	0,12
UW-09	552,86	0,43
UW-10	1 379,47	0,14
UW-11	1 476,18	0,14
UW-12	2 093,07	0,09
UW-13	679,67	0,31
W-Wadi Guir	**14 408,84**	**04,87**

Figure 8 shows the variation of (Es) as a function of time at the level of the various secondary rivers that feed the main Wadi. On the other hand, Figure 9 informs us about the distribution of erosion of the different UW.

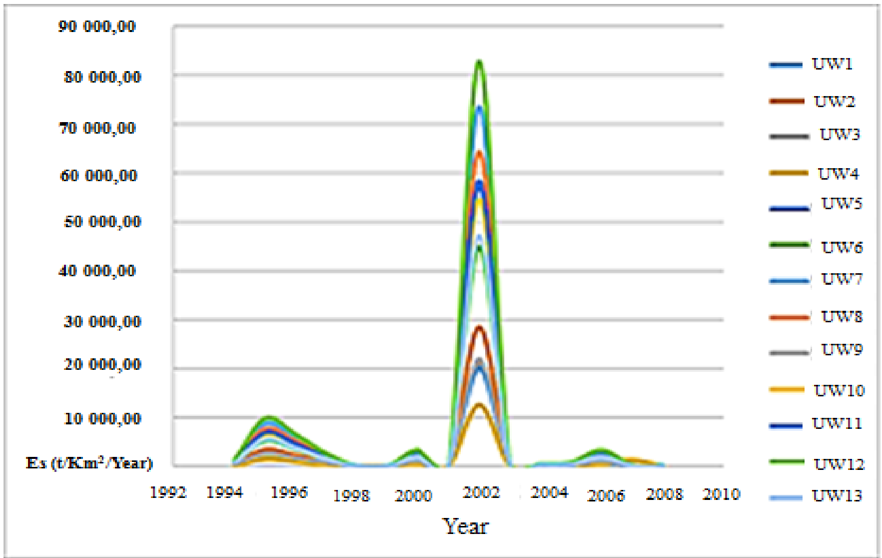


Figure 8. Evolution of specific erosion (Es) of under-watersheds as a function of time

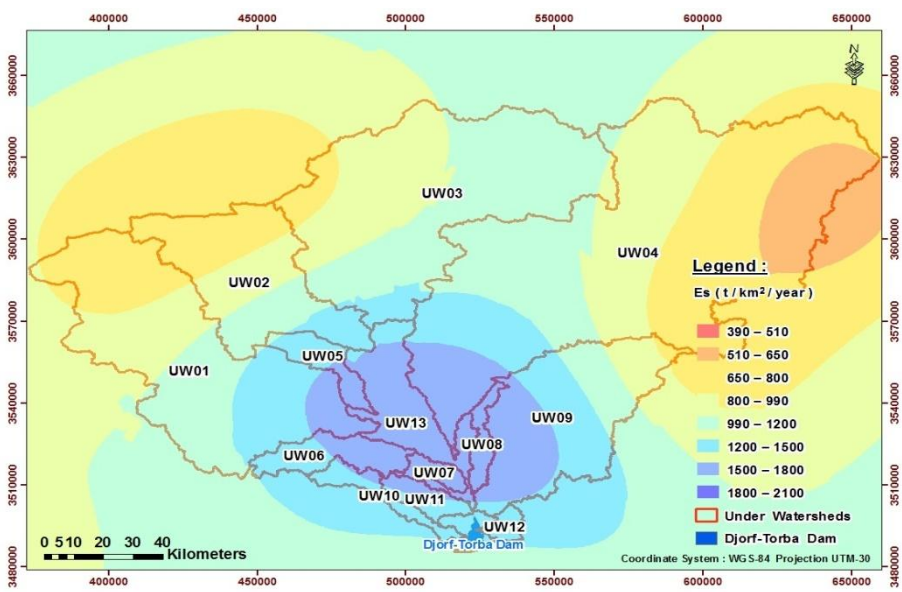


Figure 9. Distribution of specific erosion (Es) on the various UWs (Fournier Formula)

Tixeront Formula (1960)

According to Equation (2), Tixeront formula is based on the correlation between the parameter of the flow plate (Le) and the permeability (α), knowing that it is calculated based on the average annual liquid contributions. This formula is established based on the data collected from 32 Algerian basins and 9 Tunisian basins with a duration that varies between 2 to 22 years (HOUARIA, 2015).

$$qs = \alpha \times Le \quad \ldots\ldots (2)$$

qs: Average annual erosion (t / km² / year).
Le: The flow of water (mm).
α: Parameter characterizing the permeability of the watershed, which varies from 8.5 to 3200.

The dam monograph shows that there is some variation in terms of distinct geological formations, characterized by low to medium permeability and low permeability (COYNIE and BELLIER., 1985). This distribution allowed us to divide the watershed into two large parts, the high watershed is characterized by low to medium permeability, α = 350 (UW-1; UW-2; UW-3; UW-4); and the bottom where the permeability is low, α = 1400 (UW-5 ; UW-6 ; UW-7 ; UW-8 ; UW-9 ; UW-10 ; UW-11 ; UW-12 ; UW-13).
The flow of water (Le) is estimated according to two different equations:

Formula of the ANRH

According to the National Agency for Hydraulic Resources (ANRH), the runoff (Le) is calculated according to the surface of the catchment area and the average annual rain as shown in Equation (3) (KHENTOUCHE, 2005).

$$\mathrm{Le} = 0.945 \times \mathrm{P}^{2.684} \times \mathrm{S} \times 10^{6} \qquad (3)$$

P: average annual rainfall (mm).
S: the area of the watershed (km^2).

Mallet - Gauthier formula

This formula is written according to the Equation (4)(BENAICHA, 2011):

$$\mathrm{Le} = 0.6 \times \mathrm{P} \times \left(1 - 10^{-0.36 \times \mathrm{P}^2}\right) \qquad (4)$$

Table 4 shows the solid contribution (As) and the distribution of erosion (qs) from one under-watershed to another, knowing that the value of the flow of water (Le) is the result of the average calculated by the two formulas, those of the ANRH and Mallet - Gauthier.

The average values of (As) range from 0,04 hm^3/year for the UW-12 to 0,83 hm^3/year for the UW-09. The area of UW directly influences the rate of degradation. The quantity of sediment transported by the watercourse supplied by the various under-watersheds represents an annual average value estimated at 3,73 hm^3/year.

Table 4. Results of the Fournier formula according to the under-watersheds

N^0-UW	qs (t.km^{-2}.year^{-1})	As (hm^3.year^{-1})
UW-01	269,70	0,33
UW-02	269,70	0,22
UW-03	269,70	0,41
UW-04	269,70	0,77
UW-05	1078,96	0,14
UW-06	1078,96	0,21
UW-07	1078,96	0,06
UW-08	1078,96	0,08
UW-09	1078,96	0,83
UW-10	1078,96	0,11
UW-11	1078,96	0,10
UW-12	1078,96	0,04
UW-13	1078,96	0,49
W-Wadi Guir	**10 789,44**	**3,73**

The watersheds dominated by a semi-arid to arid climate are characterized by irregular seasonal and inter-annual rainfall. This irregularity has a direct impact on the erosive action and in particular on solid transport. The results obtained justify the aridity of the climate. Figure 10 represents the variation of the values of the average annual erosion (qs) in t/ km²/year according to the Tixeront equation.

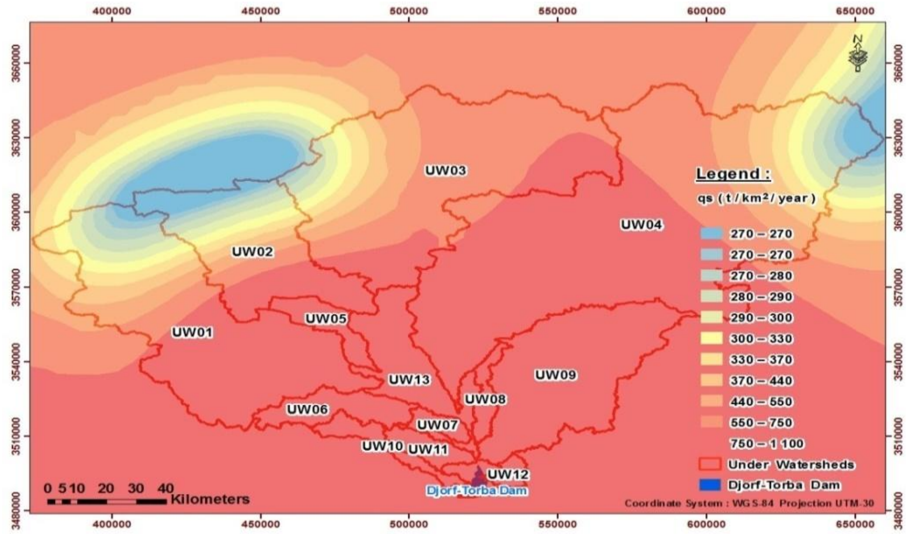


Figure 10. Distribution of the average annual erosion (qs) on the different UW (Tixeront Formula)

Kassoul et al. Formula (1997)

Kassoul et al. defined three (3) equations to estimate the erosion rate (Ta) in m^3/ km^2/year. These formulas were determined after the study of nineteen (19) Algerian dams exposed to siltation.

The choice of the equation (Ta) depends on the area of the watershed (S) and the altitude index (IA), (IA = elevation / average altitude), (Table 5).

Table 5. Criteria for choosing the formulas of Kassoul et al.

S (km^2)	**(I_A)**	**Equation**
S<1000	I_A<1	$\mathrm{Ta1} = 1433 \times S^{-0.43} - 15.24$
S>1000	1< I_A<2	$\mathrm{Ta2} = 1846 \times S^{-0.15} - 360$
S<1000	1,5< I_A< 2	$\mathrm{Ta3} = 0.463 \times S + 2026$

The altitude index is used as the second criterion for selecting the equation (Ta), in the case of under-watersheds with an area of less than 1000 km^2 (TECSULT, 2005).

According to the criteria for choosing the formulas and Table 5 above, the calculation is done as follows: The under-watersheds UW-5; UW-6; UW-7; UW-8; UW-10; UW-11; UW-12 will be calculated by the equation (Ta1), and the other under-watersheds (UW-1; UW-2; UW-3; UW-4; UW-9) by the equation (Ta2). The calculation results for the various UWs show a significant variation (Figure 11and Table 6).

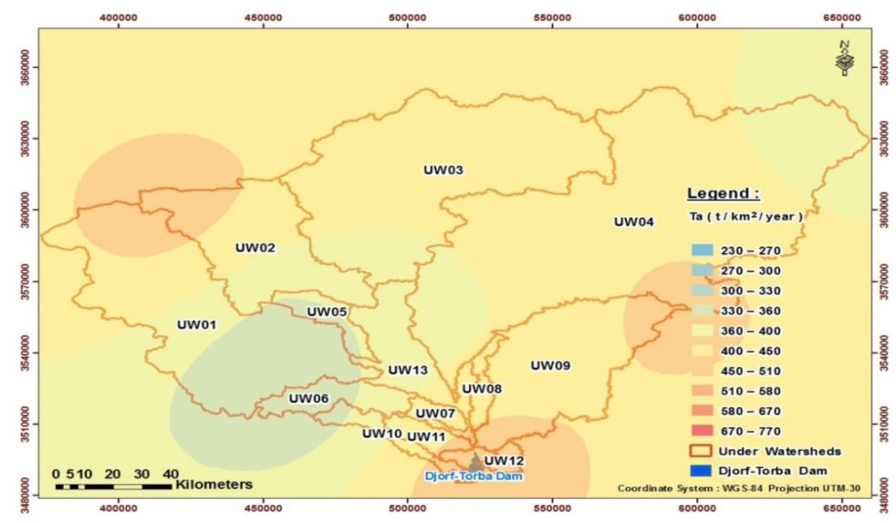


Figure 11. Distribution of the erosion rate (Ta) on the various UWs (Kassoul and al formula)

Table6. Results of Kassoul et al. formula as a function of the under-watersheds

N^0-UW	Ta ($m^3.km^{-2}.year^{-1}$)	As ($hm^3.year^{-1}$)
UW-01	183,31	0,64
UW-02	218,57	0,50
UW-03	165,40	0,72
UW-04	118,35	0,96
UW-05	97,72	0,04
UW-06	79,46	0,04
UW-07	143,97	0,02
UW-08	126,21	0,03
UW-09	221.46	0,49
UW-10	108,47	0,03
UW-11	115,58	0,03
UW-12	168,33	0,02
UW-13	270,74	0,35
W-Wadi Guir	**2 017,57**	**03,87**

The estimation of erosion and solid transport through the three (3) methods showed representative values. This can be justified by the influence of the different parameters to be taken into account for each formula. The average annual contribution, which represents water erosion, is estimated at 4,18 hm^3/year (Table 7).

Table7. Water erosion of W according to the different methods applied

Formula	Es ($t.km^{-2}.year^{-1}$)	As ($hm^3.year^{-1}$)
- Fournier	14 408,84	4,87
- Tixeront	10 789,44	3,73
- Kassoul et al.	5 770,25	3,87
- Annual average contribution	-	4,18

Rate of wind erosion

Arid and semi-arid areas are characterized by low rainfall, heavy flooding and low plant cover. The soils are almost of sandy texture with flat topography, they are easily erodible by the wind. Wind erosion degrades the soil; it affects more than 500 million hectares worldwide (ZOBECK and SCOTT VAN PELT, 2014). In Algeria especially in arid and semi-arid zones, the eroded area is estimated at 32 million hectares (Ministry of Agriculture, Rural Development and Fisheries, 2015).

Many parameters are involved in the quantification of wind erosion, such as wind speed and direction, the average size of sand particles as well as the geomorphological characteristics of the site (AMROUNI et al.., 2015). Several recent works concerning wind erosion due to the transport of sands were presented by ANDREAS, 2004; VISSER et al.., 2004; CORNELIS, 2006; BENLI et al.., 2018.

Our zone of study is one of the most exposed areas to winds in the West of the Algerian Sahara. These winds are particularly violent; that is, heats and dry. The monthly average values and the speed of the wind recorded during the period 2000 to 2016, vary between 10 to 18 km/h (BEN CHEROUDA and DJABALLAH, 2018). The land is particularly flat (National Agency for Dams and Transfer-ANBT, 2004), with a stripped ground of sandy texture. This characteristic is justified by the nature of the samples taken in November 2017 (P1 and P2, Figure 7).

According to the studies previously undertaken in the arid and semi-arid areas, the percentage of wind erosion represents an average rate estimated at 10% compared to hydrous erosion (ZAOUI, 2019). Table 8 shows the values of total erosion to take into account.

Table8. Values of total erosion

Formula	Es (t.km^{-2}.year^{-1})	As (hm^3.year^{-1})
- Fournier	15 849,72	5,87
- Tixeront	11 868,38	4,10
- Kassoul et al.	6 347,28	4,26

Evolution of the silting in the reserve of the dam

The forecast of annual siltation rates at dam reservoirs directs us to take into account Equation (5) (REMINI and HALLOUCHE, 2005). This formula is suitable for the Maghreb regions (case of our dam).

$$\text{Tenv}\ (\%) = 1.6228 \times t^{0.8707} \quad (5)$$

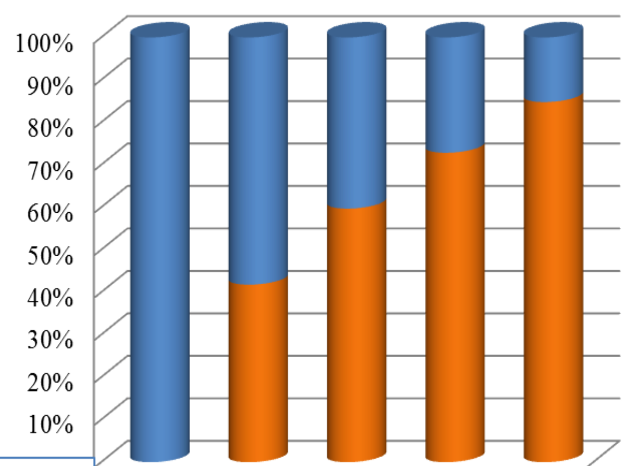
Tenv: Rate of siltation.
t: Number of years in operation.

The results of the solid contribution (As) of the above-mentioned formulas (Table 8) enable the estimation of the silting up of the Djorf-Torba dam as a function of time. Table 9 shows the prediction of siltation in percentage by the application of different methods, as well as the bathymetric survey carried out at the Djorf-Torba dam in 2004 (ANBT, 2004).

Table 9. Estimation of siltation according to the different methods

Year	2004	2019	2030	2040
- Fournier (%)	58,70	83,86	100	-
- Tixeront (%)	41,00	58,57	71,46	83,17
- Kassoul et al (%)	42,60	60,86	74,25	86,42
- Remini & Hallouche (%)	35,87	48,93	58,18	66,40
- Lifting bathymetric (%)	25,00	-	-	-

We note in Table 9, that the formulas of Tixeront, Kassoul et al, show results close to the evaluation of siltation as a function of time. However, the other methods of Fournier, Remini and Hallouche overestimate or underestimate these same values. Figure 12 represents the average values.



Year	1969	2004	2019	2030	2040
Storage Capacity (hm^3)	350,00	203,70	141,00	95,01	53,22
Silting (hm^3)	-	146,30	209,00	254,99	296,78

Figure 12. Assessment of the siltation at the Djorf-Torba dam

Results

We have shown in Figures 9 to 11 the distribution of erosion estimated by the application of the three formulas (Equations of Fournier, Tixeront, Kassoul et al), for the different under-watersheds areas of Wadi Guir. According to the results of the solid contribution, it is noted that the area of the catchment area, which feeds the reservoir of the Djorf-Torba dam, is exposed to dense erosion, which varies from one place to another. The difference in the values of specific erosion (Es) and solid transport (As) are justified by the variation of the geomorphological parameters, which characterize each UW. We see that the solid transport regime of Wadi Guir is important.

The silting up of the Djorf-Torba dam is the sum of the solid inputs from all the under-watersheds (Table 8). The solid average annual intake varies between 4,10 and 5,87 hm^3/year with an average difference of more than 1 hm^3/year. The siltation rate calculated in 2019 is estimated at 60% of its storage capacity.

We compared the results obtained through the four methods applied, by a comparative study with the results of the bathymetric survey carried out at the Djorf -Torba dam in 2004.

According to the bathymetric survey, annual silting is around 2,5 hm^3/year with a silting rate equal to 25%. The equation of REMINI & HALLOUCHE is the closest estimate for a siltation rate of 35,87% with a solid annual contribution appreciated at 3,59 hm^3/year. However, this value is low compared to the values of other formulas (Fournier; Tixeront; Kassoul and al). Note that this comparison is only for the year 2004, as this is due to the absence of data related to bathymetric surveys of other years.

It is important to emphasize that the formulas for estimating solid contributions have shown an acceptable range with respect to the hypotheses of each formula (deviations of 6%, 1% and 16%; respectively for the equations of Tixeront, Kassoul et al. and Fournier).

Conclusion

This study is part of better protection of the watershed of Wadi Guir by determining areas, which are sensitive to mass movements of solid transport. It also helps take the necessary measures to ensure better exploitation of the Djorf-Torba dam.

The results of our research have shown the influence of the different climatic and geomorphological parameters on erosion. On the other hand, the application of the different formulas used in this work (Tixeront, Fournier, Kassoul et al.), allowed to establish a relationship between this phenomenon and the characteristics of sub-watersheds.

These results also allowed estimating the percentage of siltation of the reservoir. According to the results obtained, in case where no preventive measures are taken the siltation percentage will exceed 80% by 2040. This level of siltation will induce a serious malfunction of the dam.

The use of the ArcGIS software enables us to obtain accurate results, by drawing up thematic maps, which represent the distribution of erosion (Figures 9 to 11). The importance of this approach lies in the fact that it helps distinguish the most affected areas that are in the lower part near the dam reservoir. This area represents more than 23% of the area of the watershed. The rest of the under-watersheds (UW1, UW2, UW3 and UW4) located in the upper Guir part represents approximately 77%, the erosion of this part ranges between low to medium. The multi-criteria analysis of the various parameters helped assess and map the degree of erosion in the area of influence of the UW.

The dam of Djorf-Torba allows greater control of water and certain development in the areas of southern Algeria. The role of this dam is to supply Bechar city with drinking water and irrigate the lands of the Abadla plain (an area of 5400 hectares). In view of the strategic importance of the dam on the economic and social level, it is essential to remedy the problem of siltation that is increasing steadily; and ensure better management of the environmental fallout linked to discharges from dredged vessels and dropped downstream.

Considering wind erosion, we notice that the siltation of the dam increases from one year to another depending on climate change.

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