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Insights into Soil Loss in the Jouah Basin using EPM Model and Caesium-137 as an Isotopic Tracer

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MONITORING water erosion is a difficult task, due to its complex and variable occurrence in both time and space. Climate forcing, steep slopes and anthropogenic action are the primary factors that can endanger soil resources. Located in the heart of the country's agricultural cradle, the Jīzān region is experiencing a twofold degradation of its land. It is both qualitative in the alluvial plain and quantitative in the mountainous areas. This is why it is so important to find a methodological and experimental framework that is suitable for the local conditions of the wadi Jouah watershed, which has undergone a twofold soil loss quantification. The work was started by applying an empirical model based on the Erosion Potential Model (EPM), followed by careful experimental verification using results from monitoring the Caesium- 137 Isotopic Tracer. The specific soil loss was around 35.4 t ha^{-1} yr^{-1} according to the EPM equation and around 25.5 t ha^{-1} yr^{-1} based on Caesium- 137 monitoring. This methodological validation is of crucial importance not only in determining the main sediment-emitting zones and the factors behind slope destabilization, but also in understanding and highlighting the regional context of the erosive dynamics in the intertropical, semi-arid, and mountain regions.

Keywords: Erosion rates, Kriging Interpolation, Mass balance 2 and Proportional Models, Sample Inventories, Temperature index.

1. Introduction

Water erosion is a major problem in semi-arid areas. Certain processes occur silently or even implicitly because the mechanisms of action are difficult to observe and the results will only be apparent in the long term, particularly those of diffuse run-off (Xu et al, 2019; Du et al. 2021; Aqnouy et al. 2023; Bettoni et al. 2023). A selective removal of the soil's most fertile elements (humus and fine particles) occurs progressively over time, weakening its structure. Other processes occasionally manifest themselves in dramatic form, causing disastrous damage, especially in the context of global changes characterized by an increased frequency of extreme weather patterns, which have dramatically increased soil losses. Therefore, researches that focused on the quantitative aspects of water erosion have become increasingly informative owing not only to technical advances in GIS and RS, but also to the facilities offered in terms of data collection. Most studies were focused on the global analysis of erosive events at catchment scale, based on empirical models (Azaiez, 2016, Haji et al. 2019; Azaiez, 2021a, b). It should be noted, however, that despite their involvement in collaborative environmental research projects on the scale of pilot catchments such as the El Mina and Fidh Ali wadis (Hermassi et al, 2009; Ballais et al, 2010; Mabit et al, 2013; Hajji et al. 2019; Azaiez, 2020 and 2021b), the number of specifically detailed studies was still very modest. This type of collaborative research could give the opportunity to develop sustainable projects capable of implementing a universal strategy to tackle the problem of erosion. In fact, the radioisotope method seems to meet the aims of this research, which was intended to be both preliminary and exploratory, with the purpose of gaining a better understanding of the causes of soil degradation in the Oued Jouah basin. Research launched in the early 1970s focused more closely on the qualitative aspects of water erosion, with the aim of establishing a regional classification of the various processes (with Tricart, Hamza, Joly, ballais, Auzet, Roose…). However, at the beginning of this century, technological advances and logistical improvements have provided privileged access to new high-performance work tools, in particular the different types of satellite and radar images. Since then, investigations into soil degradation have achieved a high level of precision and confidence in the results, particularly after the introduction of the isotope

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method, which has provided a better quantification of soil losses in the medium and long term (Ben Mansour et al. 2012; Porto and Walling, 2015; Mabit et al. 2018; Porto and Callegari, 2022). Numerous studies have used isotopic tracers of Caesium- 137 and radio-plomb (Pb ^{210}) to estimate long-term soil losses (between 22.26 and 30.1 years), and Beryllium-7 to estimate seasonal losses according to crop type and seasonal changes in land use (De Rosas, 2018; Zhang et al. 2018; Taylor et al. 2019; Zhang et al. 2018; Akplo et al. 2022). Most of the studies that used the nuclear approach were based on 1963 as the reference year, particularly for study areas outside the European continent. This research did not differ greatly from previous studies in terms of approach and scientific contribution. The only difference concerns the choice of reference year because this study was based on radioactive fallout from the Chernobyl accident, where 2023 was deemed to be the year of peril for Caesium- 137 fallout from the 1960s, of which only a few very insignificant traces remain. The results were verified using the empirical EPM model which is especially designed for regions that are strongly influenced by the effects of topography and temperature (Azaiez, 2021a). The choice of the extreme south-west of Saudi Arabia was largely motivated by the preliminary field investigations which showed that certain areas were undergoing a particularly severe erosive dynamic, occasionally progressing to an irreversible and alarming situation (Azaiez, 2021b). The assessment of soil loss and its trend were expressed through a series of index maps that may help to implement more effective monitoring programmes. In the same context, this study aims to propose a comprehensive assessment of water erosion problem in Jouah basin and to select the appropriate method capable to provide effective soil loss in terms of extent and rates under various conditions and land use systems by using isotopic (Caesium- 137) and empirical (EPM) methods.

Materials and Methods

- **The study area**

The watershed of wadi Jouah lies between (16° 57 min; 17° 12 min N) and (42° 56 min; 42° 60 min E).

It drains an area of 30 km^2 and is one of the main tributaries of the downstream course of the Wadi Jīzān in south-west Saudi Arabia (Figure. 1). The Jīzān region was subjected to several hydrological (Abdelkarim, 2019; Allaoua and Azaiez, 2021), rural and environmental studies that focused particularly on soil and groundwater pollution as well as salinity risk and agriculture. (Khaled et al, 2016; Al Zahrani, 2018; Al-Boghdady, 2019). However, only a few studies were sufficiently able to estimate and spatialize soil loss.

The longitudinal course of the main river clearly shows that this was a hilly catchment area, although altitudes did not exceed 546 m (Figure. 1). The mainstream channel slopes at 36.6 m/km, which is considered high enough to concentrate run-off and increase susceptibility to multiple soil erosion processes (Figure. 2).

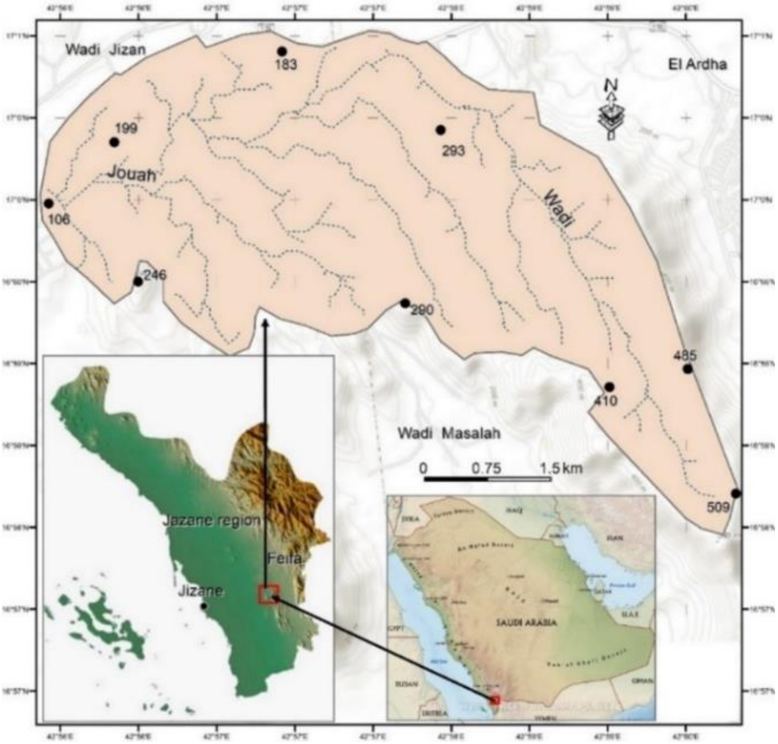

Fig. 1. Location map of wadi Joua.
Source: Open-source Map on Arc Gis Po.

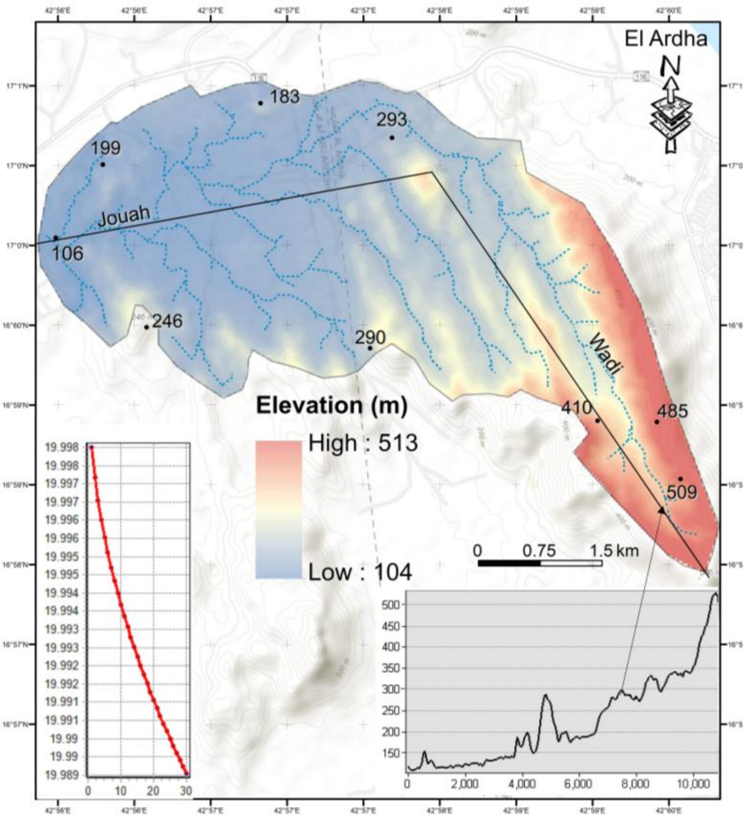

Fig. 2. Longitudinal profile of wadi Jouah.
Source: Open-source map on arc Gis and topographical map.

Surface stripping, diffuse run-off and gullying are in full expansion in the north, the west, and the south-west zones, compared with the situation in 2006 (Google Earth image, 2006). Given the great difficulty in collecting a sufficiently representative number of samples, it was deemed necessary to consider empirical modelling prior to sampling, in order to track the redistribution of the Caesium- 137 isotopic tracer. (Toumi, 2013; International Atomic Energy Agency, 2014; Moustakim et al, 2019; Azaiez, 2021 (b)). Several quantification models are available, and the choice between them requires justification according to local catchment conditions.

In the Jīzān region, the combined effect of temperature and humidity was solicited to proceed with a dual approach (experimental and empirical), which has already been shown to be effective in previous research.

- **EPM Model**

It was decided to calculate soil loss using the EPM model, which involves 3 inputs based on their statistical weight rather than their causal effect (Azaiez and Allaoua, 2021). The relationship between the different factors is expressed by the following equation:

$$WEPM = H*T*\pi*\sqrt{Z^3}$$

With:

W: average annual soil loss estimated in (m^3 */km²/year), subsequently converted into* ($t\ ha^{-1} yr^{-1}$) *to facilitate comparison with the values obtained from monitoring the isotopic tracer of Caesium- 137 and regional comparison.*
T: temperature coefficient, expressed as follows:
$T = (0.1 * t0) + 0.1$
Where: t_0*: mean annual temperature in °C*
H: mean annual precipitation in (mm).
Z: Erosion coefficient

Indeed, the final statistical formulation of this model was defined by a series of polynomial equations establishing a correspondence between the various physical properties (qualitative and quantitative) of the Wadi Jouah basin. Precipitation, temperature, and topography are the main factors in weathering, pedogenesis and morphogenesis.

***Temperature index**

Temperature fluctuations tend to have a greater effect on long-term soil conditions than precipitation. However, the effect of precipitation varies from one rainfall event to another (Deb and Kiem, 2020). to 13 hours/day, can play an important role in traumatizing the soil. This results in a very high evaporation potential (2200 mm/year to 2300 mm/year) (Allaoua and Azaiez, 2023), which can affect the stability of silty and clayey soils through the spread of desiccation cracks. The angle of incidence of the sun's rays and the duration of sunshine, which varies from 10 hours/day.

***Erosion index (Z)**

This index incorporates additional qualitative information to determine the degree of vulnerability of the watershed's various sections to water erosion. It considers soil erodibility, average slope, and the most frequently observed forms of erosion, such as stripping, gullying and landslides.

- **Caesium- 137 method**

Nine samples were selected at different points in the topo-sequence along Wadi Jouah. In each unit, the soil was sampled to a depth of 20cm, then dried, mixed, and sieved with a 250µ sieve to separate the fine clay fraction because Caesium- 137 particles are preferentially adsorbed on the surfaces of clay elements. (Mesrar et al, 2017; Azaiez, 2021).

After conditioning in geometry for several days, the soil samples were analyzed by gamma spectrometry to obtain the mass activity (Am) of Caesium- 137 in (Bq/kg). The mass activity (Am) of Caesium- 137 is expressed by the following equation:

$$Am = N\,net/Tc * L_{\gamma}*$$

Where:

N net = The number of net hits below the peak,

Tc = Counting time (seconds);

$I\gamma$ = The intensity of the γ radiation (85.5%);

M = The mass of the sample (kg).

Ɛ = Detection efficiency

(Damnati et al, 2012, Azaiez, 2016).

Caesium- 137 activity was obtained in ml Bq/gr, then converted to Bq/kg and finally to bq/m$^{2-1}$ once the weight, sampling cylinder volume, fine fraction density and surface area were all known.

Two conversion models were used to estimate soil loss. The first is a proportional model applied to cultivated areas. It is expressed according to the following equation (Zapata et al, 2009; Zhang et al, 2018, Azaiez, 2021 (b)):

$$Y = 10 * \frac{B.d.x}{100\,.T}$$

Where:

Y= Soil loss (t ha^{-1}yr^{-1})

d= Plough layer thickness (m);

B= Soil density of the fraction < 0.2 mm kg m-3);

*X= Percentage enrichment or reduction in Caesium- 137 activity expressed (Aref-A)/Aref *100);*

T= number of years since the maximum fallout of Caesium- 137 (year 1986) and date of sampling

Aref= The specific activity of the Caesium- 137 activity in the reference site by Bq/m^{2})

A = specific Caesium- 137 activity of the soil sample taken by (Bq/ m^{-2}).

This distinctive approach, based on the type of land use and land cover (LULC), made it possible to follow the correct procedure, guaranteeing a reliable quantification of soil losses. As regards the application of Mass Balance Model 2, an adjustment parameter needs to take account of the selective outflow of fine soil components carried away by run-off as well as the exponential reduction in Caesium-137 activity with depth, because Caesium- 137 particles can be carried deep into the soil by both leaching and deep ploughing.

This adjustment parameter was inspired by a modeling study carried out on the middle course of Wadi Abha in 2021. This was done because it was decided not to carry out a sequential analysis of one of the 9 samples taken in the present watershed. This calls into question the high cost of isotopic analysis. The mass balance 2 model is expressed according to the following equation (Zapata and Nguyen, 2009; Navas et al, 2011 Porto et al, 2015; Xu et al, 2019; Azaiez, 2016 and 2021 (c)):

$$Y = \frac{10.\ d.B.}{P}\left[1 - \left(1 - \frac{X}{100}\right)^{1/(t-1986)}\right]$$

Where:

Y= Soil loss (t ha^{-1}yr^{-1}) ;

d= Plough layer thickness (m);

B= Soil density of the fraction < 0.2 mm kg m-^{3});

*X = percentage reduction in Caesium- 137 activity (Aref-A)/Aref * 100);*

P = corrective index for the fine fraction.

1986 = Reference year for Caesium- 137 fallout

It is however important to note that both equations are derived from the equation of the Kachanoski model applicable for mixed landscapes having an interference between cultivated sectors and others under natural vegetation (Azaiez, 2016 and 2021).

3. Results

The multiplication of three parameters related to the equation (EPM) allowed new answers regarding the multiple facets of water erosion in semi-arid highlands, which remain unknown in terms of their contribution to land degradation. To accomplish this, the thermal index was treated in two stages: first as an annual spatial average varying between 31.6 °C downstream and 27.5°C upstream depending on altitude and exposure (Figures. 3 and 4), then as an index deduced through the period 1978/2022. In fact, when precipitations are accompanied by a rise in temperature, soil dissolution and dispersion increases (Figures. 5 and 6). This was confirmed by the significant turbidity of run-off water. The temperature effect contrasts substantially between east and west. The index reaches its maximum in the western part downstream and decreases in the east with altitude, as a function of the topographical thermal gradient (Figures 3, 4, 5 and 6). It should be pointed out, however, that seasonal variations were very slight. The temperature factor is therefore omnipresent all year round, but it has become more pronounced with the peak of the monsoon rains in summer. This combined effect of rainfall and temperature increases the erosive potential of the region.

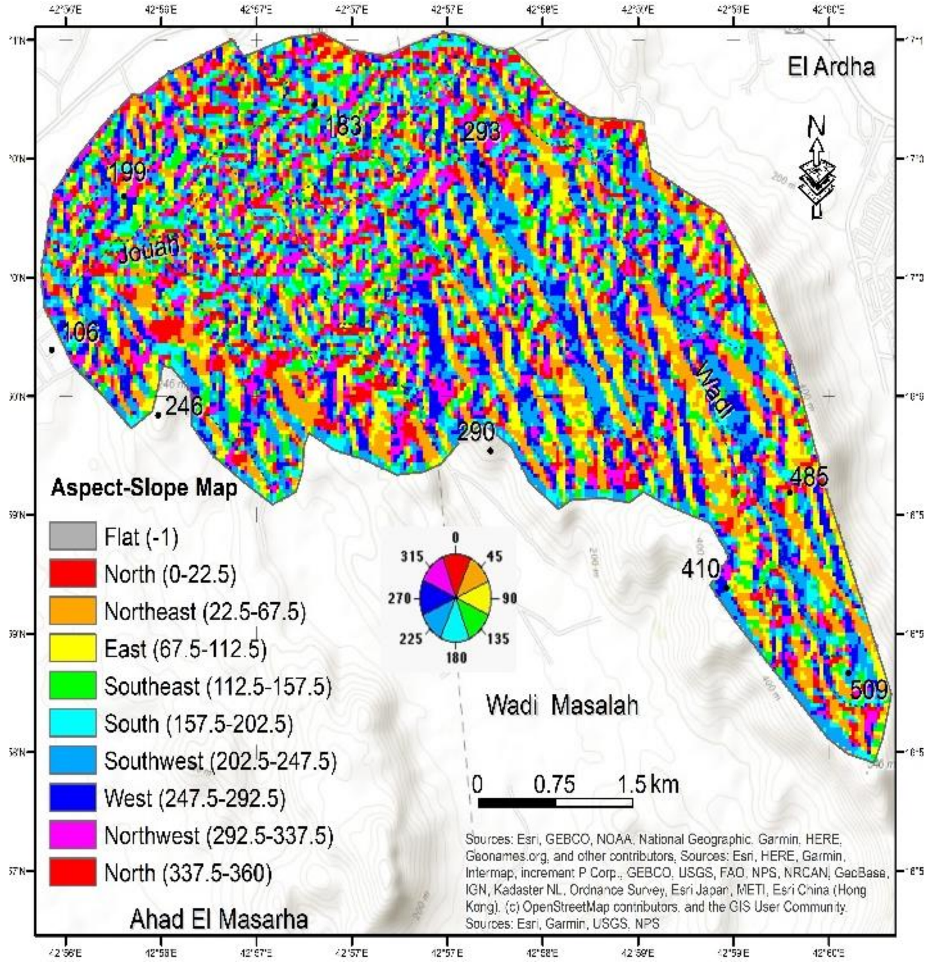

Fig. 3. Temperature estimation in wadi Jouah based on slope exposure.
Source: Geoprocessing of SRTM image (30 m).

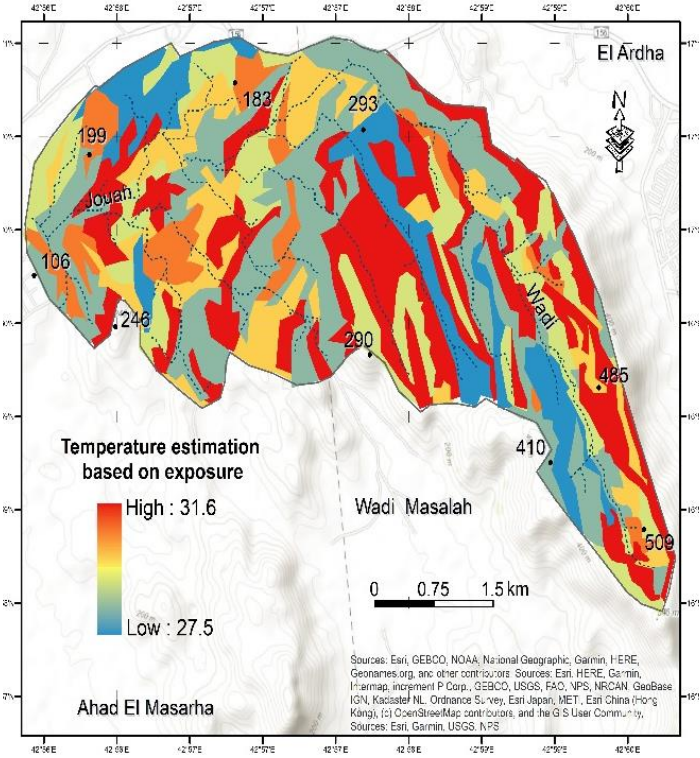

Fig. 4. Temperature estimation in wadi Jouah based on slope exposure.
Source: Geoprocessing of SRTM image (30 m).

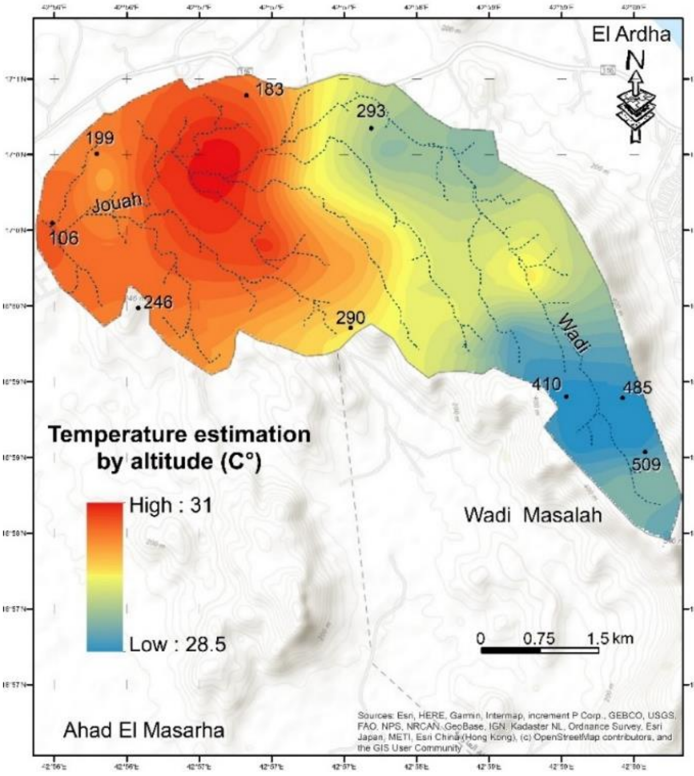

Fig. 5. Estimation of temperature based on the topographical gradient in wadi Jouah.
Source: Geoprocessing results for the input SRTM image on Arc Gis program.

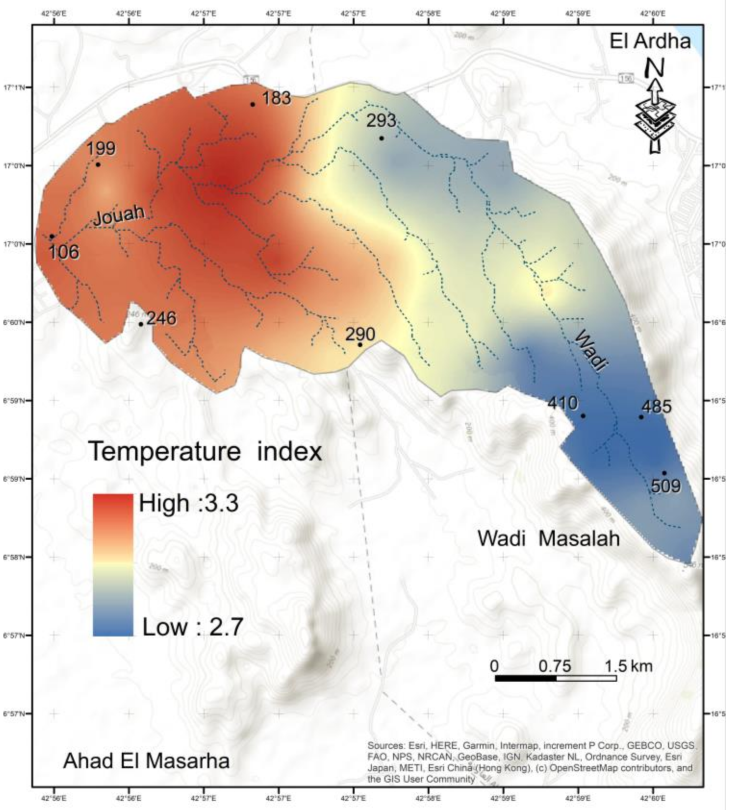

Fig. 6. temperature indexes in wadi Jouah.
Source: Geoprocessing results for the input SRTM image on Arc Gis program.

This index varied from 3.3 in the downstream to 2.7 in the upstream, according to the cartographic representation of the interpolation results obtained by applying the Kriging function (Figures. 3 and 4). The thermal index is obtained from the following equation:

$$T = (0.1 * t0) + 0.1$$

Where: t_0 = mean annual temperature

0.1 = fixed indicator

- **Erosion index (Z)**

This index incorporates additional qualitative information to determine the degree of vulnerability of the watershed's various sections to water erosion. It considers soil erodibility, average slope, and the most frequently observed forms of erosion, such as stripping, gullying and landslides (Figures. 7 and 8).

Fig. 7. Gully and scouring fields in the northern sector of the Jouah basin.
Source: Image Google Earth Pro, 2023.

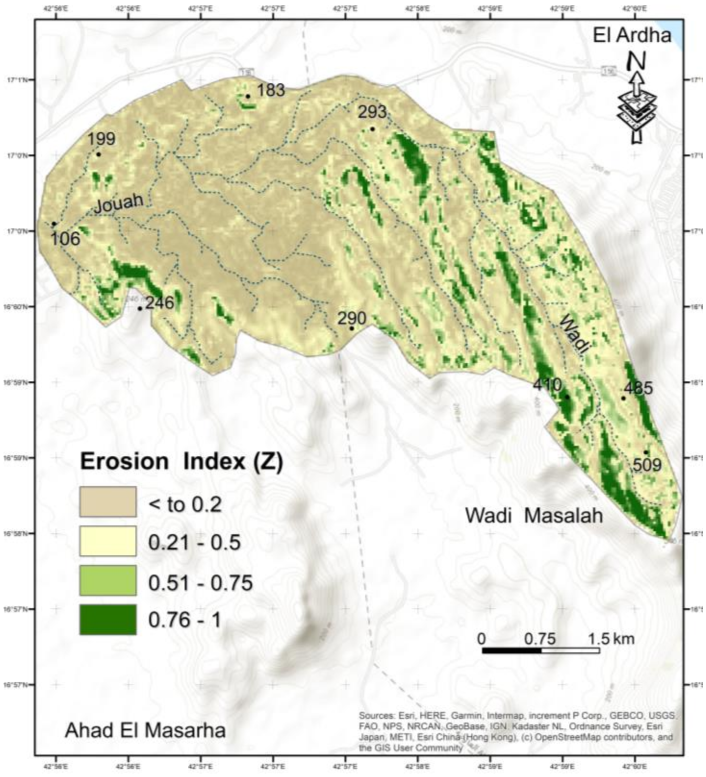

Fig. 8. Map of the coefficient (Z) in the wadi Jouah catchment area.
Source: Image Google Earth pro and Image Landsat 8-9 OLI/TIRS C2 L2", 2023.

It also includes protective measures designed to improve slope stability and manage water resources, particularly the old terraces. The Z coefficient is obtained by applying the following equation:

$$Z = Y * Xa\ (\delta + \sqrt{J_a})$$

Where :

Y: Coefficient of the soil's aptitude for water erosion. It depends on the nature of the parent rock, the type of soil and the climate. This coefficient varies between 0.05 in the least sensitive sectors and 1 in the most affected sectors.

Xa: Soil protection coefficient. Only a few agricultural terraces are identified in the north-west and south-west compartments. Their beneficial effect was developed by (Houshia et al, 2022) in the Palestinian territory.

δ: This coefficient expresses the forms and qualitative aspects of water erosion. It refers to the visible forms and processes of water erosion in the catchment.

Ja: Average slope index of the study area (in %) (Damnati et al, 2012, Azaiez, 2016). The coefficient (Z) varies from 0.12 in the least sloping sectors, generally shaped into terraces, to 1 in the most rugged and unprotected ones (Figure. 8).

The multiplication of three terms in the EPM model made it possible to obtain soil losses by considering average climatic conditions, but without giving any emphasis to inter-annual, seasonal, and daily variability, which can play a decisive role in varying the rate of erosion. Exceptional climatic events capable of mobilizing large quantities of arable land have been increasing in magnitude over the last few decades.

This risk weighs heavily on the region's agricultural potential. Once the empirical model had been established, it was easy to select a representative top-down transect to collect soil samples for analysis based on variations in Caesium- 137 activity.

The graphical representation showed that isotopic activity is closely linked to soil condition (Navas et al. 2011; Azaiez, 2016).

The highest activity levels are found in downstream areas and on slopes shaped into agricultural terraces, ranging from 1020 to 2514 bq/m$^{2-1}$. This is due to decantation processes that entrap the silty-clay residues that accumulate on the sides of the terraces. The lowest values, or even zero, were observed on the slopes that are most exposed to erosion.

In some areas, the soil layer was destroyed by the mining activity in the center and north-east of the catchment (Figure 9), where open-cast mines have been exploited over the last two decades.

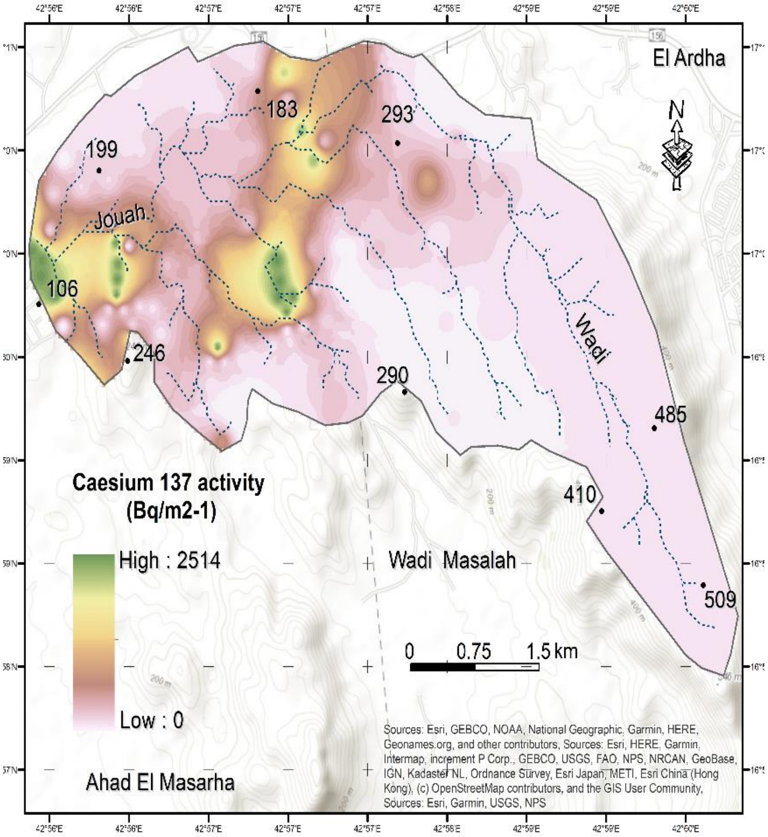

Fig. 9. Distribution of Caesium-137 activity in the wadi Jouah catchment area.
Source: results of isotope analyses of soil samples.

The comparison of the Caesium- 137 activity obtained at the 9 sites with reference site activity has revealed areas of degradation and areas of enrichment in Caesium- 137. This suggests the presence of a proportionality between soil losses and the reduction in Caesium- 137 activity in the soil, and between deposition and enrichment in Caesium-137 within the same catchment area (Figure 10). This principle of proportionality was justified in previous studies by the fact that Caesium- 137 particles can only be removed with run-off water or wind in the presence of active mechanical erosion processes, whether hydric or wind-driven (Porto et al, 2014; Zhang, 2018; Azaiez and Hamza, 2021; Azaiez, 2021b). Caesium- 137 enrichment zones were mainly identified in the downstream and middle sections, where the average slope is around 2.5° and steep slopes do not exceed 5°. (Figure. 11).

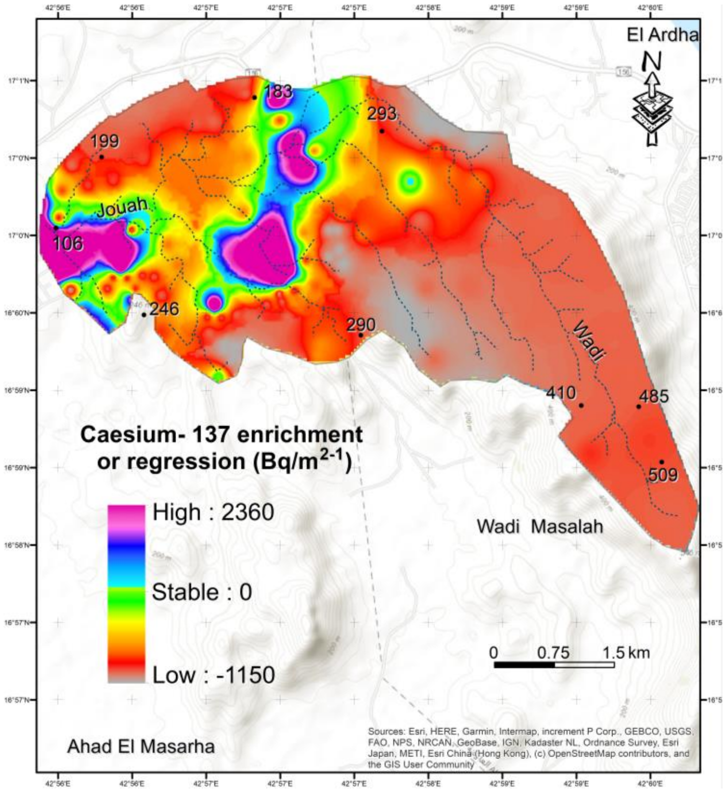

Fig. 10. Highlighting areas of enrichment and degradation of Caesium- 137 in the wadi Jouah catchment area.
Source: Results of Caesium- 137 analyses obtained in 2023.

As a result, much of the soil that was detached from upstream was deposited on the meanders and terraces before reaching the outlet (the junction of Wadi Jouah and Wadi Jīzān), as the Wadi Jouah watercourse is wedged between two ridges, making it difficult for sediment to pass through (Figure 11).

It should be noted, however, that riparian vegetation seems to have a significant effect on sediment trapping. The few terraces that exist on the middle and lower courses have, for their part, enabled silt and clay decantation (Figure. 12).

Soil losses in the Wadi Jouah watershed were calculated based on the year 1986 instead of 1963, because the Caesium- 137 fallouts from the 1960s is at their peril given that the lifetime and final decay rate of Caesium- 137 as defined by specialists was estimated at around 60.2 years. The Jīzān station recorded rainfall between April 26 and 30, with quantities of 20, 30 and 35 mm respectively on April 26, 27 and 28, 1986. These precipitations were sufficient to bring down the Caesium- 137 particles suspended in the upper troposphere. There is no reason to be overly concerned about the origin of the precipitation and the trajectory of the air masses, as it's very likely that there will be a dry deposit in the subtropical zones, due to the adiabatic descent of the air under the pressure of the Jet Stream current and the dominance of anticyclonic situations. In addition to the fallout from 1986, other releases of Caesium-137 were made by reactors currently operating in

Eastern Europe, but in quantities that are still limited. While the distribution of Caesium- 137 fallout was homogeneous during the reference year, the redistribution of this isotopic tracer was not. This is due to soil mobility and the influence of morphogenesis agents, notably run-off water, but this does not exclude the possibility that sediments may have been reshuffled and redistributed by strong winds. Regretfully, wind action was not considered in the calculation of the results due to its high spatio-temporal variability. However, the wind factor could be the subject of another more targeted study based on more advanced reflections and tools. It should be highlighted that the region is prone to rainstorms that cause irreversible land degradation, but with variations between cultivated and uncultivated areas in terms of quantity and quality. For this reason, two conversion models of loss rate were applied to take account of the selective loss of fine soil elements in the no-tilled plots, which are not covered by vegetation either. The proportional model was applied to the limited number of agricultural terraces covering only 5% of the total watershed area. For the rest of the Jouah watershed, the mass balance 2 model was chosen to calculate soil loss.

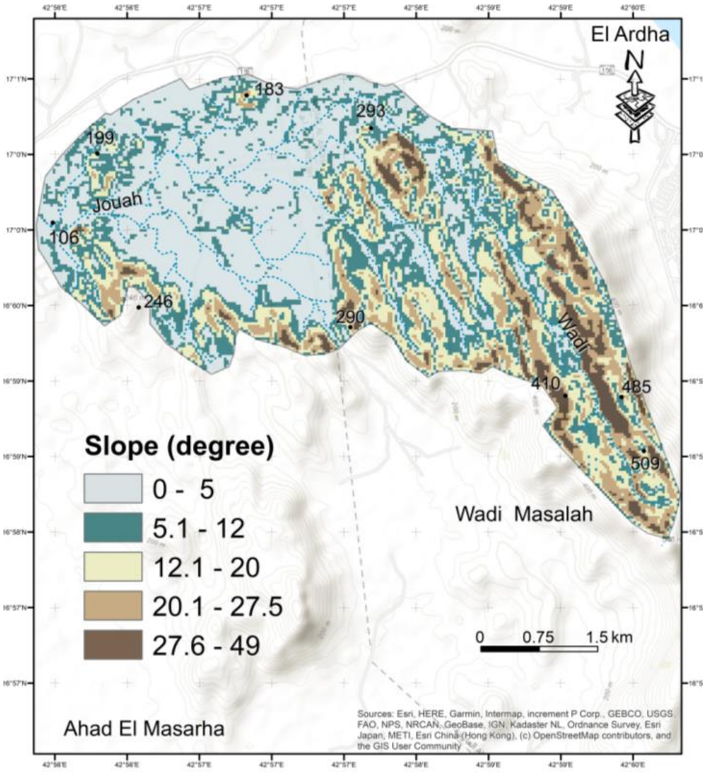

Fig. 11. Slope map of Jouah basin.
Source: SRTM image (Precision 30 m), and topographical map of Jīzān at 1/50000.

The persistence of Caesium- 137 at the soil surface, rather than at depth, is due to its strong, almost irreversible adsorption by the clay elements in the soil. On the other hand, the decrease in its surface activity in other areas is due to superficial degradation of the soil, controlled by a diffuse run-off that is capable of carrying away more than 62 t $ha^{-1}yr^{-1}$ from the soil in extreme cases in the most vulnerable areas. The part of the soil loss related to landslides, gullies and suffosion has not been considered in the present calculation, because the radiometric method only quantifies superficial and rill erosion.

It is also necessary to highlight certain measurement difficulties when applying the isotopic tracer method. This difficulty consists in the absence of a certified reference site for the entire southwestern area of Saudi Arabia and the absence of previous studies in nearby watersheds to be able to assess the reliability of the isotopic method. Thus, as a procedure for verifying the results, a double comparison was opted for to ensure that land degradation was placed in its regional context. The results of the isotopic modelling are first compared with the results of the empirical model (EPM), which showed a certain consistency, even if they were not strictly identical.

The loss rates obtained could be slightly underestimated or overestimated (Figures 10 and 11). Nevertheless, the difference between the two models does not appear to exceed 12.5 t $ha^{-1}yr^{-1}$, knowing that the maximum loss obtained from the EPM model is around 74.9 t $ha^{-1}yr^{-1}$ and that of Caesium -137 is around 62.49 t $ha^{-1}yr^{-1}$. (Figures. 12 and 13).

The east and center of the Jouah basin were the most adversely affected. The two models illustrated a similar spatial distribution, but with a subtle difference in the maxima and minima and the degree of severity across the whole catchment area. However, the empirical model showed a low to moderate erosion rate of around 72% and severely affected areas accounted for only 13.38% (Table. 1, Figures 13 and 14).

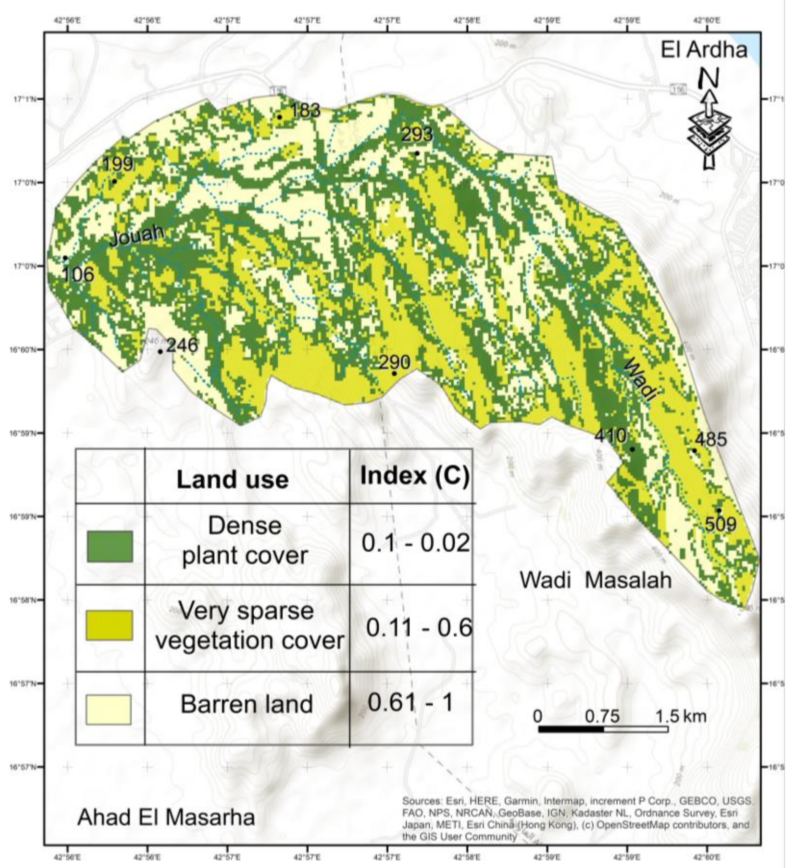

Fig. 12. Map of the coefficient (C) in the wadi Jouah catchment.
Source: Image Landsat 8-9 OLI/TIRS C2 L2"., 2023.

Table .1 Numeric soil loss range, area coverage, and severity class.
(L = Low; M= moderate; H= High; VH = very High)

Loss range t $ha^{-1}yr^{-1}$	Severity	Soil loss			
		EPM model		Caesium- 137 tracer	
		km^2	%	km^2	%
0-10	L	11.47	38.5	8	26.76
1-20	M	13	43.5	12	40.16
20 -40	H	4	13.38	5	16.74
>40	VH	1.38	4.62	4.88	16.34

Source: Geoprocessing results for the input parameters and results of isotope analyses of soil samples

These results are closely attributable to the input parameters, which are based on averages rather than on measurable and quantifiable indices. A major part of the catchment area seems to be intensely affected, i.e., 33 %, according to the isotopic method for Caesium- 137, compared with 18% according to the EPM model. This is considered considerable for a catchment with a moderate topography.

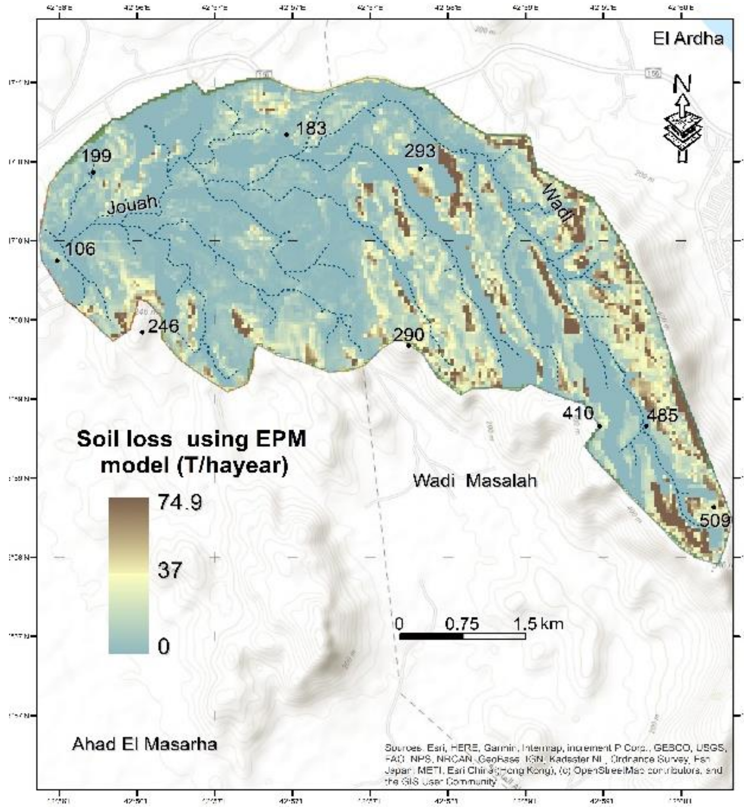

Fig. 13. Soil loss obtained by EPM Model.
Source: Geoprocessing of results for the input parameters of the empirical EPM model

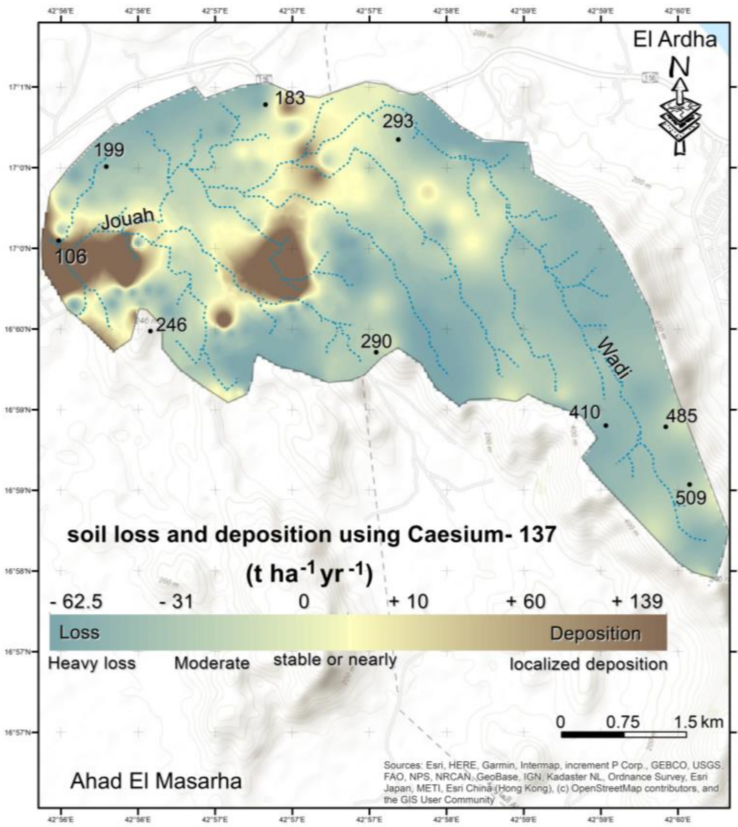

Fig. 14. Soil loss obtained by Caesium- 137 as radiometric tracer.
Source: Geoprocessing of results for the input parameters and results of isotope analyses of soil samples, 2023.

The second comparison is made between the Caesium- 137 activity of the selected samples and those previously studied in the El Arine region on the middle course of Wadi Abha. A difference of 2 t ha^{-1} yr^{-1} to 6.3 t $ha^{-1}yr^{-1}$ was obtained between the agricultural terraces in the El Arine region and those in the Wadi Jouah watershed (Azaiez, 2021b).

4. Discussion

This research may provide new insights into the applicability of the Caesium- 137 isotopic pattern in Saudi Arabia, to identify the different forms of water erosion and estimate their contribution to the sediment budget (transport as well as deposition) (Navas et al, 2018; Azaiez and Hamza, 2021). In terms of soil degradation, gullying and land movement were observed in the northern and southern parts of the watershed.

In fact, each quantification procedure has its own requirements, advantages, and limitations (Ikenoue et al, 2020). No model can be defined as the ideal model to apply (Zapata and Nguyen, 2009; Navas et al, 2011; Ben Mansour et al, 2012; Damnati et al, 2012; Azaiez, 2016; Azaiez and Hamza, 2021). As a result, the integration of two different models was a carefully considered choice based on the target soils to be studied for protection against water erosion. A comparison between the sequence of eroded and deposited soil revealed that sedimentation was significantly exceeded. Considering the erosion-sedimentation cycle mentioned by (Guzman et al, 2013; Mouri, 2020), it was observed that the cycle is generally balanced.

As certain compartments of the catchment are made up of old earthworks, fine soil elements were decanted into the downstream course of the wadi Jouah, which explains the enrichment in Caesium-137. However, not all the elements removed from the slopes and then carried into the various compartments of the catchment reached the outlet. A significant proportion of these particles were certainly retained and captured in the meanders, against the banks and against the dense riparian vegetation. This suggests much more significant sedimentation.

The overestimation of sedimentation compared with loss can be explained by the definition of the limit of application of two models, EPM and Caesium- 137. Both models can only estimate soil losses caused by sheet erosion and gullies, which are responsible for the total losses of the 5 samples taken from eroded slopes, accounting for only 66% of the elements deposited. It is very probable that the residual 34% of sediment comes from other erosion processes, such as gullying, landslides, Tunnel erosion, piping, and suffusion, which are very well known in the study area, despite being very localized. Other previous studies have also demonstrated that diffuse run-off accounts for 75% of soil degradation. This is indeed an erosive process that occurs silently, but its long-term impact is very significant (Navas et al, 2011; Azaiez, 2016; Xu et al, 2019; Azaiez and Hamza, 2021; Azaiez, 2021; Yoon et al. 2021).

There are still recommendations that have not been fully implemented and discussed in the research carried out, at least on a Saudi Arabian scale (Azaiez et al, 2021). It will be appropriate to select test (pilot) catchment areas in the different sectors of Saudi Arabia, where all models can be tested as part of academic research projects to provide an overview of the climatic-edaphic conditions and develop a strategy for managing water and soil resources. (Roose, 2004 ; Mabit et, 2013 ; Toumi, 2013 ; Azaiez, 2016 ; Ikenoue et al, 2020, Azaiez, 2021b).

The best results will depend on the huge investments and efforts made to easily reach a decision on the issue of land degradation by setting standards and thresholds that make it easier to compare and define efficient and effective soil consolidation strategies for each location (Mabit et al, 2013; Ikenoue et al, 2020; Azaiez, 2021a, b).

There is a need to develop simple models capable of quantifying the losses caused by gully erosion, currently measured directly in the field, which is considered a difficult operation to carry out at different spatio-temporal scales (Zapata and Nguyen, 2009; Azaiez, 2016; Mesrar et al, 2017; at different spatio-temporal scales (Zhang et al, 2018; Taylor et al, 2019; Ikenoue et al, 2020; Azaiez and Hamza, 2021; Akplo et al, 2022).

5. Conclusion

The aim of this research was to establish a state-of-the-art knowledge of the applicability of the Caesium- 137 isotope method and Gavrilovic's empirical model (EPM) in quantifying soil losses based on the mass spectrometry of the Caesium- 137 tracer. Evaluation of the results by the empirical model (EPM) revealed very similar loss values, although the spatial distribution appears slightly different.

This difference is expressed in both a spatial and a temporal dimension, because the two methods deal with the manifestation of water erosion, but on two different time scales. From the point of view of systemic modelling, the wadi Jouah watershed was found to be at substantial risk of erosion, which remains a major problem throughout the south-western region, particularly in the rugged mountain areas.

In fact, the maximum loss of 64 t $ha^{-1}yr^{-1}$ only concerns losses caused by diffuse run-off. It is even more so if we consider other erosion processes, such as gullying, mass movements and hypodermic erosion in the deep soil horizons. All these forms of degradation are not considered by the isotopic method or by the erosion potential model. It is therefore essential to identify the various sources of destabilization of watersheds and the different forms of erosion, to choose the most appropriate quantification method for each area of the watershed. It is becoming increasingly important to adopt a wide range of empirical and experimental models to gain new insights into the state of the soil in this agricultural heartland, and to learn new skills in terms of dealing with erosion. All the studies carried out in Saudi Arabia conclude that soil loss has a major impact on the agricultural potential of the south-western region. The most stable watersheds with the lowest losses (2-6 t $ha^{-1}yr^{-1}$) are those managed through terraced farming. This ancient know-how needs to be preserved, enhanced, and developed according to the morphoclimatic context and land use.

Conflicts of interest

The author declares that There are no conflicts of interest to declare.

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