ASSESSING THE IMPACT OF CLIMATE CHANGE ON SOIL MOISTURE AND SOIL EROSION IN NORTHWEST MOROCCO BASED ON NUCLEAR TECHNIQUES (CAESIUM-137 RE-SAMPLING AND EXCESS LEAD-210 SEDIMENT DATING) AND REMOTE SENSING

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ABSTRACT
Climate change threatens soil and water resources in Africa. In Northwest Morocco, which is located at the extreme Northwest of Africa and typical of African Mediterranean areas, soil erosion is intense and the situation could have been triggered by the climate change impact. The annual long periods of drought decreases soil moisture and increases soil aridity in consequence which in turn makes soil more vulnerable to soil erosion.

The Caesium-137 technique was used in this study in combination with the re-sampling approach to evaluate changes in soil redistribution between two different periods 1954-2000/2001/2002 and 1954-2017/2018. Lead-210 in excess was used to assess changes in sedimentation rates within El Hachef dam. Moreover, data on soil moisture were obtained by Sentinel 1 for the period 2018-2022. The obtained data on soil moisture shows that soil moisture decreased from 0.184 to 0.169 cm³/cm³ in El Hachef watershed and from 0.203 to 0.192 cm³/cm³ in the Nakhla watershed and from 0.255 to 0.233 cm³/cm³ in the Raouz watershed. This shows that the tendency of soil aridity is toward increase in the three watersheds. Moreover, based on the Caesium-137 technique, the results show that the mean soil erosion rates decreased from 38.5 to 31.5 t.ha⁻¹.yr⁻¹ in the study sites of El Hachef watershed due to some beneficial changes in land use consisting of more frequent fallows and the regional crop rotation however, the decreasing tendency in the mean annual soil loss does not dominate in the whole El Hachef watershed since the sedimentation has increased by around 30% between the periods 1950-2002 and 1950-2015 due to probably climate change impact and intensive agriculture in other sites in the region. The mean soil erosion rates decreased from 36 to 29 t.ha⁻¹.yr⁻¹ in the study site of the Nakhla watershed due to the beneficial impact of agricultural practices and the implemented soil erosion control strategy and from 11.9 to 10.9 t.ha⁻¹.yr⁻¹ in the study sites of the Raouz watershed. Within this last watershed, soil erosion rates had slightly increased from 4.5 to 5.7 t.ha⁻¹.yr⁻¹ in one field where agricultural practices were not changed. This variation represents an increase of the soil erosion rate of about 26% between the two periods and could be due to climate change impact on soil erosion in this area. Furthermore, the results show that the Raouz watershed which recorded the highest values of soil moisture is the most stable (recorded the lowest erosion rates) in comparison with the other watersheds which recorded lower values of soil moisture and higher rates of soil erosion.

The results of this study proved the effectiveness of the used approach in assessing changes in soil erosion rates and soil moisture in the study area. They also showed that sustainable agricultural practices can mitigate the complex effects of climate change on soil loss.

Keywords: soil erosion, soil moisture, climate change, Caesium-137, remote sensing.

1. INTRODUCTION
Soil erosion has been the main threat of the natural resources, mainly soil and water, in Northwest Morocco. Indeed, the complex effects of soil erosion and climate change impacts negatively the sustainability of soil resources and water reservoirs in Northwest Morocco. This region is typical of extreme Northwest African Mediterranean areas submitted to several natural and anthropic pressures. Land use and climate change impacts are among the factors that trigger the situation in the area (Moustakim, 2021). Recent studies on vulnerability to climate change in Mediterranean areas in general and particularly in Morocco have shown a trend of increasing aridity leading to a decrease in soil moisture which in turn accelerates soil erosion (Mokssit, 2012). So, the annual long periods of drought contribute in increasing soil aridity in the area. The Northwest Morocco is also known by the clayey texture of soil permitting less infiltration and more runoff which enhances soil erosion by water (Ibrahimi, 2005). In this regard, the soil water content (SWC) is a key state variable in determining the partitioning of infiltration and surface runoff permitting making optimal water management decisions (Franz et al., 2016). It impacts a variety of applications, including agricultural management, climate and weather applications, flood and drought forecasting and groundwater recharge. Moreover, SWC is a key parameter in helping understand and predicting the timing and severity of natural disasters such as drought and landslides and controlling irrigation systems (Franz et al., 2016). However, it is still a difficult parameter to continuously monitor and measure at a catchment scale because of its heterogeneous characteristics.
Endeavors to find efficient methods of assessing the climate change impact on soil moisture and soil loss are continuing. In recent years, the cosmic ray probe (CRP), which is an in-situ technique, has been implemented in several countries across the globe and may fill the intermediate scale gap in soil moisture measurements. At large scales, remote sensing methods provide near-surface estimates of soil moisture but there is significant influence of surface conditions (Wagner et al., 2007) and a significant gap still exists between point observations with remote sensing. However, no single point measurement can be entirely representative of larger areas, because of the heterogeneity that exists in soil properties, topography, land cover and meteorological conditions.

This study is currently based on remote sensing data to assess the spatiotemporal change in soil moisture which may have occurred these last years. Moreover, it is based on the combination between the Caesium-137 technique and the re-sampling approach to assess changes in soil redistribution between two different time-intervals and Lead-210 in excess was used to assess changes in soil sedimentation rates in an important water reservoir in the region.

2. MATERIAL AND METHODS

The study sites were previously sampled between 2000 and 2003 (Ibrahimi, 2005) and re-sampled in 2017 and 2018. Consistently with the previous samplings, soil samples were collected along parallel or single transects within the fields following the slope gradient and the runoff directions in each field. From twenty to twenty two soil samples were collected from the agricultural fields of each watershed. Moreover, some samples were collected from the reference site, which is a stable site, in each watershed according to systematic grids. In general, the collected samples were two types either bulk cores or sectioned cores from 4 to 5cm increment. One to two sectioned cores were collected from the agricultural fields to tell about the tillage depth whereas in the reference sites, the sectioned cores are expected to confirm the stability of these sites since the period of the first sampling campaigns. In addition, a sediment core, 30 cm deep, was collected to establish the sedimentation history in the “9th of April Dam” using a corer 8.5 cm in inner diameter. Soil and sediment samples were oven dried at 60°C, disaggregated, manually and automatically ground, then sieved at 2 mm and homogenized. Sub-samples from each bulk and sectioned core were put in specific cylindrical pots and analyzed by gamma spectrometry using High Purity Germanium detectors (HPGe) of 50% and 30% efficiency for counting times reaching 100 000s.

The analysis of 210Pbex in the sediment core requires sealing samples for at least 21 days to prevent the escape of 222Rn and to establish secular equilibrium between 210Pbtot, 226Ra, and 214Bi. The 137Cs inventory (areal activity (Bq m−2)) in each sample was calculated. The relative uncertainties ranged between 6% and 50% for few samples with very low activities. The comparison of the inventories with the reference site inventory permit to determine points of soil loss and gain in the field. Then, the Mass Balance Model 2 (MBM2) (Walling et al., 2002) which takes into account both the temporal variation of the 137Cs fallout input and the fate of the freshly deposited 137Cs fallout prior to incorporation into the plough layer by tillage was used to convert the previous and the recent 137Cs inventories (t ha−1 yr−1) of both periods into erosion rates (t ha-1 yr-1). It can be used as follows:

\[ \frac{d(A)}{dt} = -(1-G)I(t) - \lambda PR/A(t) \]  

(1)

\( A(t) \) is the 137Cs inventories (Bq m−2); \( t \) is the time since the onset of 137Cs fallout (yr) considered in 1954; \( R \) is the soil erosion rate (kg m−2 yr−1) which can be converted to t ha−1 yr−1; \( d \) is the cumulative mass depth representing the average plough depth (kg m−2); \( \lambda \) is the decay constant for 137Cs (yr−1); \( I(t) \) is the annual 137Cs deposition flux at time t (Bq m−2 yr−1); \( G \) is the proportion of the recently deposited 137Cs removed by erosion before being incorporated into the plough layer; \( P \) is the particle size factor.

The obtained previous and recent erosion rates associated with each period were compared to evaluate changes that had occurred in soil redistribution.

The Constant Rate Supply (CRS) model (Appleby and Oldfield, 1978) was used to calculate the sedimentation rates (kg m−2 year−1 or t ha−1 yr−1) based on 210Pbex sediment dating techniques. The model is based on the following formula:

\[ R = \frac{I(z)}{A(z)} \]  

(2)

\( R \): sedimentation rate ( kg m−2 yr−1) associated with layer z; \( I(z) \): total 210Pbex inventory (Bq m−2) of the sediment core below depth z; \( \lambda \): radioactive decay constant of 0.03114 yr−1; \( A(z) \): 210Pbex activity (Bq m−2) at depth z.

The data on soil moisture in the three watersheds was obtained by Sentinel 1 satellite which permits to derive soil moisture data only from 2018 to 2022. Rainfall data are also necessary to support and explain changes in soil moisture but we previously obtained rainfall data only up to 2017 from the Hydraulic Basin Agency of Loukkos.
3. RESULTS AND DISCUSSION

The results show that the mean soil erosion rates decreased in the Nakhla site from 36 to 29 t ha−1 yr−1 (Table 1) during the period between the two sampling campaigns (2002–2017) due to the beneficial impact of agricultural practices and the soil erosion control strategy that was implemented within the framework of the "PREM" project (Moustakim et al., 2019). This latter was established by the Moroccan government to mitigate the in-site and off-site effects of soil erosion for a sustainable management of soil and especially water resources in the Nakhla watershed. Indeed, the storage capacity of the Nakhla dam, which contributed to the water supply of Tetouan city since 1962, has progressively decreased due to the accelerated erosion in the watershed, described by numerous studies. In 1997, the direct interventions targeted in the upstream part of the Nakhla watershed were based on the plantation of olive trees in contour lines and then, the mechanical and biological stabilization of gullies. Our study site benefited from more frequent fallow with natural vegetation and olive plantations (Moustakim et al., 2019). In the study sites of El Hachef watershed, the results show that the mean soil erosion rates had decreased from 38.5 to 31.5 t ha-1 yr-1 due to some beneficial changes in land use consisting of more frequent fallows and the regional crop rotation. However, the decreasing tendency in the mean annual soil loss does not dominate in the whole El Hachef watershed since the sedimentation has increased from 0.20 g cm−2 yr−1 in 1950 to 0.80 g cm−2 yr−1 in 2015 in the water reservoir. An increase of the mean sedimentation rate of around 30% was observed between the periods 1950-2002 and 1950-2015. This increase was attributed to the combined impacts of climate change and intensive agriculture in some fields in the region (Moustakim et al., 2022). Indeed, soil erosion is intense in the region but land use and climate change impacts are among the main factors that trigger the situation there (Moustakim, 2021). In the study sites of the Raouz watershed, the mean soil erosion rates decreased from 11.9 to 10.9 t ha−1 yr−1 (Table 1). Soil erosion rates had slightly increased from 4.5 to 5.7 t ha−1 yr−1 in one field where agricultural practices were not changed (Moustakim et al., 2022). This slight variation represents an increase of the soil erosion rate of about 26% between the two periods and could be due to climate change impact on soil erosion in this area.

Table 1. Mean erosion rates in the study sites of the three watersheds.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Mean erosion rates (t ha−1 yr−1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nakhla</td>
<td>36.1</td>
</tr>
<tr>
<td>El Hachef</td>
<td>Site 1: 26.3</td>
</tr>
<tr>
<td></td>
<td>Site 2: 50.8</td>
</tr>
<tr>
<td>Raouz</td>
<td>Site 1: 19.4</td>
</tr>
<tr>
<td></td>
<td>Site 2: 4.5</td>
</tr>
</tbody>
</table>

The data derived from Sentinel 1 from 2018 to 2022 show that soil moisture generally decreased which could be due to the rises in temperature increasing water loss through evapotranspiration and causing in consequence moisture stress in soil (figure 1). Indeed, it decreased from 0.184 (2018) to 0.169 cm3/cm3 (2022) in El Hachef watershed and from 0.203 to 0.192 cm3/cm3 in the Nakhla watershed and from 0.255 to 0.233 cm3/cm3 in the Raouz watershed. This means that soil aridity is increasing in the study area. This fact means that soil will be more vulnerable to erosion in the study area. Indeed, correlations between the mean erosion rates for the periods 1954-2017/2018 and soil moisture data show that the highest mean erosion rates of about 31.4 t ha−1 yr−1 (1954-2017) and the lowest mean annual soil moisture of 0.17 cm3/cm3 were recorded in El Hachef watershed whereas the Raouz watershed recorded the lowest mean soil erosion rates of 10.9 t ha−1 yr−1 (1954-2018) and accordingly the highest soil moisture of 0.24 cm3/cm3. This confirms that soil moisture has an impact on soil stability. The decreases in soil moisture and increases soil aridity in consequence making soil more vulnerable to erosion threatens more the sustainability of water reservoirs in the region.
4. CONCLUSIONS

This study is the first in Morocco assessing the impact of climate change of soil erosion and sedimentation and soil moisture based on nuclear techniques and remote sensing. The results showed that the tendency is toward aridity and sustainable agricultural practices permitted to mitigate the negative impact of erosion and climate change on soil loss in the study sites. As it was reported in the PREM project, the programs of soil and water management should first raise the awareness of farmers about the importance of soil conservation strategies and nowadays about the impact of climate change on the natural resources. They must also be defined within the socio-economic context of the population and their practices, then integrate their participation to select the suitable soil conservation strategies.

Cosmic Ray Probe could be calibrated and installed in the area to obtain accurate in situ data. It is already installed and calibrated in the Merchouch area in Morocco and permitted to obtain the average soil moisture content over hundreds of square metres there. Perspectives are toward installing this tool in all Morocco to obtain accurate data on soil moisture using nuclear techniques. The current challenges facing the natural resources mainly water requires a continuing innovation in diagnosing tools to obtain reliable datasets as well as on climate change impact for sustainable management of soil and water.

Acknowledgement

This study was carried within the framework of a Research Contract between Centre National de l'Energie, des Sciences et des Techniques Nucléaires (CNESTEN) in Morocco and the International Atomic Energy Agency (IAEA) in Austria which partially funded this research work within the project CRP D1.50.17 entitled “Nuclear Techniques For a Better Understanding of the Impact of Climate Change on Soil Erosion in Upland Agro-ecosystem”. This study was always conducted within the framework of the project RAF 5086 entitled “Enhancing Crop Nutrition and Soil and Water Management and Technology Transfer in Irrigated Systems for Increased Food Production”.

REFERENCES


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