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Efficiency and sustainability assessment of terraces in the Qais Mountains basins using *Cesium 137 isotope* analysis

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THE CESIUM 137 isotope was tracked to monitor the degree of soil erosion and measure sedimentation levels based on the results of the different rates of activity, which enabled the classification of the sectors of the Jebel Kais basins according to the degree of soil stability to identify erosion hotspots and sedimentation sources. This study proved that the terracing system has enabled soil stabilisation ranging from 59 to 101 tonnes/ha/year. Even though the study area recorded the lowest levels of soil loss, which did not exceed 49.4 tonnes/ha/year as a maximum amount, compared to several neighbouring basins, where the losses exceeded 80 tonnes/ha/year. The radiometric analyses clearly show a balanced sediment budget, considering the difference between the eroded section and the sedimented one in terms of the drainage basin as a unit. This indicates that the basin's sedimentary system is in apparent dynamic stability. This fact is essential for forecasting the morphological dynamics of the basin. The results of this research will provide the basis for promoting new avenues of study incorporating other isotopes such as lead-210 and beryllium-7 to improve erosion prediction, from local analysis to global management of agricultural land in response to environmental challenges, particularly in arid zones in Saudi Arabia.

Keywords: Balance sediment, Cesium137, Agricultural terraces, Qais Mountain basin, Soli loss.

1. Introduction

Much has been written about the ecological and developmental role of agricultural terraces in harsh mountainous regions (Al Katmour, 2004; Mesrar et al., 2017; Chuxiong et al., 2021; Azbouche et al., 2023). These terraces took different forms depending on the local topo-climatic conditions. They extended in the form of narrow ribbon terraces from the top of the rocky ledges where the first headwaters of the rivers are located, increasing in width as they gradually descend into the valley beds, especially in areas where the tributaries converge with each other. In other areas, agricultural terraces were carved in a contouring manner, following various landform changes and slopes (Oueslati et al, 2019). These terraces were the first step for Asir's early inhabitants to sustainably manage the mountainous environment, marking a form of human response to the constraints of this type of environment (Azaiez, 2021a, b; 2024). The main objective of their establishment was to optimise water harvesting and provide additional land for agricultural activity, especially since the water balance of the tropical and subtropical highlands fluctuates between availability and scarcity due to the high variability and temporal concentration of rainfall (Gdiri et al., 2024). Thanks to these man-made terraces, different systems of farming have emerged, producing a variety of agricultural crops that are part of the subsistence economy. Over a relatively long period of time, these terraces have been credited with creating ecological balances, especially at the level of natural vegetation, which has intensified dramatically in recent decades. The diversity and prosperity of vegetation is one of the main factors that contributed to the establishment of the beekeeping and pastoral sectors and a strong connection to the land, which is reflected in the division of land into small and medium-sized family holdings managed by tightly distributed village communities.

Thanks to the system of agricultural terraces, these village communities were able to ensure a good environmental balance, although they were only able to achieve a subsistence-level of agricultural production without attaining a more integrated agricultural strategy that is open to the global economy (Azaiez et al., 2025). From a geomorphological point of view, these terraces have either prevented or slowed down the natural morphological evolution of the water basin due to the slow transport of rock fragments of different sizes between water basin sectors, resulting in a kind of morphological stability (Arnaez et al, 2015; Londono et al., 2017; Chuxiong et al, 2021;). On the contrary, modern dynamics such as slides and collapses were most severe on the neighbouring slopes that were not terraced. Several previous studies have shown the effectiveness of terraces in conserving water and soil and in sustaining vegetation cover and agricultural activity. Among the studies that

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relied on direct field measurements to determine the role of rocky barriers in reducing runoff is (Al-Ali and Shehata, 2015), which found that rocky terraces contributed to reducing the runoff coefficient by about four times on steep slopes that had stone terraces compared to those that were not terraced. The average runoff rate during the study period was 7.2 per cent for the terraced slopes compared to 27 per cent for the non-terraced ones. The Nasri study (Nasri, 2002) also found that the runoff rate decreased by 36% on the slopes over which earthen embankments were established in the Wadi Kawazin basin in central Tunisia, which also belongs to the semi-arid zone. Furthermore, (Al Ali et al, 2008) compared the protective efficiency between partially constructed and fully constructed earthen embankments for soil and water. The study of Azaiez (2016), and (2024) presented the difference in the amount of soil retained on the slopes of Wadi El Messine in northeastern Tunisia through tracking the radioactive tracer (Cesium 137) between earthen embankments that retained between 7 and 8 tonnes/ha/year and rock barriers that retained between 4 and 12 tonnes/ha/year. It was emphasised that the earthen embankments were efficient in water harvesting, while the rock barriers were better in soil retention but less efficient in water harvesting due to both their construction method and the precipitation regime which is characterised by highly concentrated precipitation both temporally and spatially. This means that there is a complementary relationship between these different structures, provided that each technique is applied in its proper place so that it does not have an opposite effect on soil, water, and plant resources (Azaiez et al., 2025).

The agricultural terraces in southwestern Saudi Arabia are the best testament to how the people of the Asir region have been able to adapt the harsh mountainous environment in favour of the humans for more than five centuries with a unique geometric planning that has been successfully employed to serve their living requirements. They have also represented a form of pre-emptive, protective measures to preserve the soil, increase its thickness, and optimise the use of water resources that are characterized by their fluctuating and limited availability. The agricultural terraces in Aseer are unique in that their units are distinguished according to their topographical position and their location in relation to watercourses and we distinguish between the upper terraces known as "Rakeeb‘’ and the lower terraces called ‘’ Al Jallah‘’ which receive the water coming from the slopes and valley banks. Different types of soils with different properties have settled on these different terraces. These include 'Al-Outhari’ which is dedicated to rain-fed agriculture, and the 'Masqawi' or 'Sakka’ soil for irrigated crops (azaiez et al., 2020). The mountain Qais basins in the village of Batila in Aseer region are one of the areas where agricultural terraces have taken on a heritage and developmental dimension and this study aims to highlight its importance through forms of planning and patterns of exploitation. An experimental approach based on the isotopic technique was applied to evaluate the effectiveness of these terraces in reducing erosion and dam silting. Some agricultural terraces in Rijal Almaa are currently undergoing deterioration due to the movement of people to live in major cities to be closer to basic educational and health services, especially since the region lacks university branches and colleges that are close to the province's students and that fulfil the needs of the population. Prior to the Kingdom's qualitative leap in establishing an education system that seeks to create a national elite on which the state relies on in various fields, the main activity of the population in Rijal Almaa revolved around the exploitation of agricultural terraces to produce millet, sesame, barley, corn and other subsistence crops under a predominantly rain-fed farming system (Qhtani, 2024). The population has also developed the quality and quantity of honey production, taking advantage of the diversity of vegetation, especially the Sidr plants that characterise the region (Al-Ghamdi and Nuru, 2013) . The contribution of the terracing system in securing the livelihoods of the first inhabitants and keeping them in their villages for centuries prompted us to conduct a quantitative assessment of the effectiveness of these terraces in preserving soil, water, vegetation cover and agricultural production (plant and animal), especially now that they have been chosen as a driving force to implement ambitious development projects by establishing rural and environmental tourism trails along heritage agricultural terraces and natural landscapes that blend mountain slopes and diverse vegetation formations (Naghdi et al., 2024; David Raj, 2025).

Thus, this study was conducted to evaluate the effectiveness of the constructed stone terraces and earthen embankments for water and soil conservation in the mountain Qais basins within Rijal Almaa Province by estimating the amount of soil erosion on the undeveloped slopes as well as the amount of sedimentation that was trapped behind the terrace barriers over an average period of 37 years using the isotopic method by tracking the Cesium 137 radium tracer. The predicted results were compared with neighbouring basins where the same technique was applied with rainfall simulation to track the rate of sediment movement.

2. Materials and Methods

The agricultural terraces in the mountain Qais basins in Al-Batila area were selected for this pilot study to evaluate the soil resources, including water, vegetation and agricultural resources, because both Wadi Abha and Wadi Jazan have had their share of experimenting with this technique, while accurate quantitative data on those basins are lacking. The study area extends over an area of 30 km² and includes the basins of the Kharar, Al-Salil, Mil Qais, and Al-Batila Wadis. These wadis represent the upper northeastern headwaters of Wadi Al Reem, which flows north of Al Shuqaiq beach (Fig 1). predominance of metamorphic rocks such as schist, slate and some sedimentary rocks such as limestone sand, sometimes interspersed with some barriers of igneous rocks (basalt, andesite and dacite). It is bordered to the east by Wadi Hasswa basin, to the north by Wadi Us basin, to the west by Tiah basin, and to the south by Rajab basin. The average height of the study area is 1350 m and the average slope is 35°. However, the maximum heights reached 1980 m and the maximum slopes reached 87°. The steep slopes are concentrated in the upper sectors of the water basins, especially from the north and east. The Baha Formation is one of the dominant geological formations in the study area. These diverse rocks are responsible for the different soil textures within the sub-basins, as well as for the different layout of the agricultural terraces in terms of their width and the height of their walls.

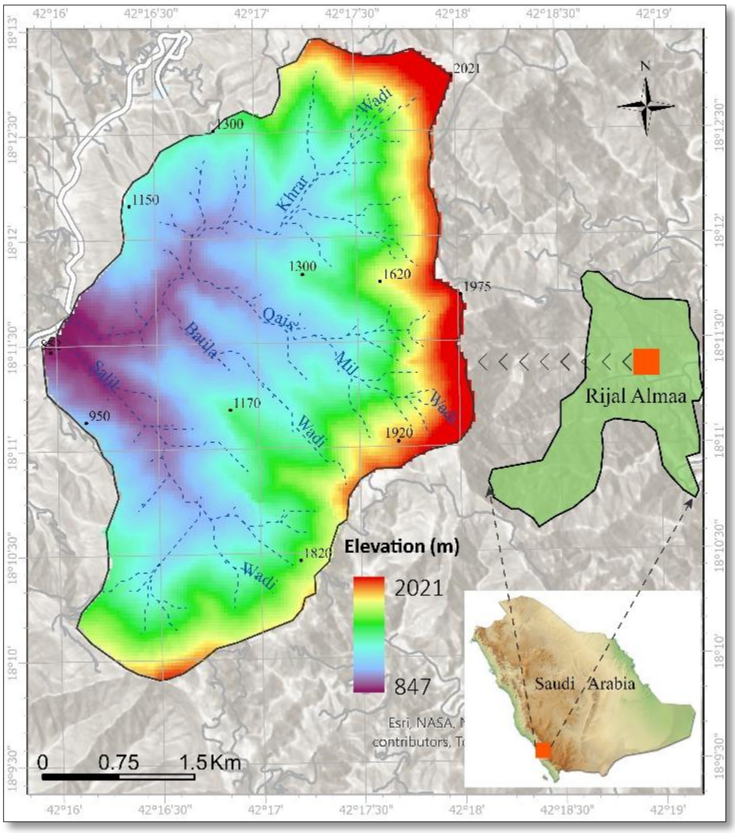

Fig. 1. Map location of the study area, source: SRTM image and open source.

This study was based on a quantitative and qualitative analytical approach at the same time. The quantitative analytical approach is founded on an experimental field and laboratory basis to track and measure the pattern of erosion and sedimentation, a pattern that was followed over 37 years by tracking the actual specific activity of the Cesium 137 tracer, and then the sedimentation processes were quantified using statistical tools and mathematical models, precisely Proportional and Mass Balance 2, whose accuracy has been proven in many previous studies (Al-Falih, 2010; Azaiez and Hamza, 2021; Zapata, 2002; Al Katmour, 2004; Al-Falih, 2010; Azaiez and Hamza, 2021); Zapata, 2002; Al Katmour, 2004;). The results were confirmed by internal comparison with neighbouring basins, and external comparison of Cesium 137 specific activity measurements and sedimentation pattern based on the results of other studies conducted in arid and semi-arid regions (Faleh, 2010; Azaiez, 2016; Azaiez, 2020; Azaiez, 2021 (a) and (b); Azaiez, 2023). As for the qualitative analytical approach, it was adopted to analyse Landsat 5 (1986) and Landsat 8 (2023) satellite imagery to derive vegetation indicators, soil moisture indicators, and ground surface temperature at a spatial resolution of 30 m.

The Spot 7 imagery of 2022 was also used to generate maps of land use, as its spatial resolution is 10 m, which is higher than Landsat 8. This high-resolution imagery was adopted to avoid confusion between cultivated terraces and those that have merged into the forest area after being abandoned by the local people. Vegetation, soil moisture and surface temperature indicators and their evolution over the last three decades were processed and analysed in Excel. Modelling, statistics and geospatial analysis techniques are the most important methods applied in the GIS context.

Bioclimatic characteristics of the study area

In terms of climate, the study area is in the southwest of the Kingdom of Saudi Arabia, which means in the course of the rainy southwest winds. However, the statistical treatment of the monthly and daily distribution of precipitation, as well as the wind direction and speed, proved that the rainfall is more of a progressive type than of a seasonal or thunderstorm type, as the largest daily rainfall did not exceed 65 mm. These rains spread throughout the months of the year, with a major spring rainfall peak and a secondary summer rainfall peak (Fig. 2).

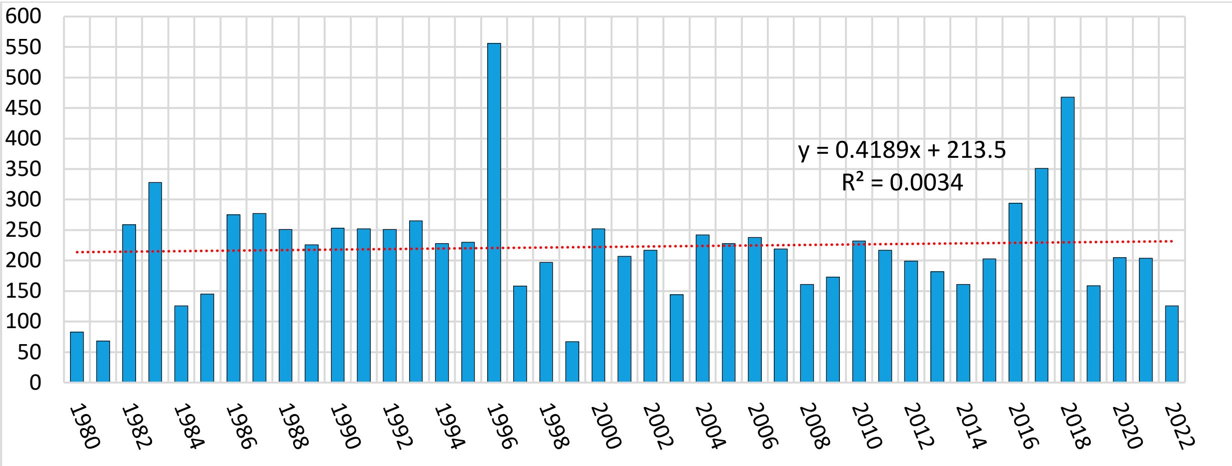

Fig. 2. Annual precipitation distribution in the Mountain Qais basins (1986-2023), Source: The Meteorological and Water Authority, 1986-2022.

The rain falls mostly in the form of light and continuous precipitation, and sometimes in the form of thunderstorms accompanied by concentrated and heavy showers, which are usually a cause of soil erosion, especially since the region is dominated by rugged slopes, and this is highlighted by the map of the spatial distribution of precipitation (Fig. 3), where the highest rainfall amounts are concentrated over the northern and eastern highlands, on the border with Wadi Haswa basin and Wadi Us basin. The average annual precipitation in the Jebel Qais basins during the period (1986-2023) was 225 mm, which is considered an important amount, especially since it is distributed throughout the months of the year (Fig.2). The highest daily rainfall amount was 64.8 mm at the beginning of April 1996, which was the wettest year up to 2023. The comparison between the first and last two decades showed that rainfall fluctuated more than before, but the overall trend showed a qualitative increase (Figs. 2 and 3). In terms of temperatures, the average temperature for the same period was 24.8°C. The average temperature, unlike precipitation, has not improved, as shown by the rising curve, where the average temperature for the first two decades (1980-2000) was recorded at 24.5°C, rising to 25.24°C during the last two decades (2001-2023), showing an increase of 3%. This is likely to affect the elements of the ecosystem, especially plants and crops, which are sensitive to temperature changes. Based on the analysis of the results of the temperature and precipitation data made according to the Gaussen rule, the Jebel Qais basins are subject to severe drought throughout the year since the monthly precipitation is not always accompanied with any temperature drop (Fig. 4).

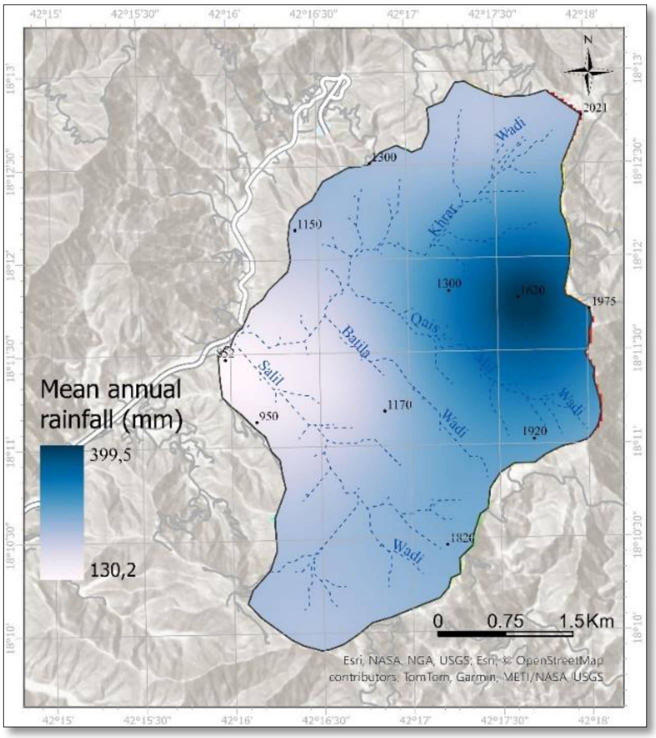

Fig. 3. Map of spatial distribution of mean annual rainfall over Kais Mountain basins, Source: The Meteorological and Water Authority, 1986-2024.

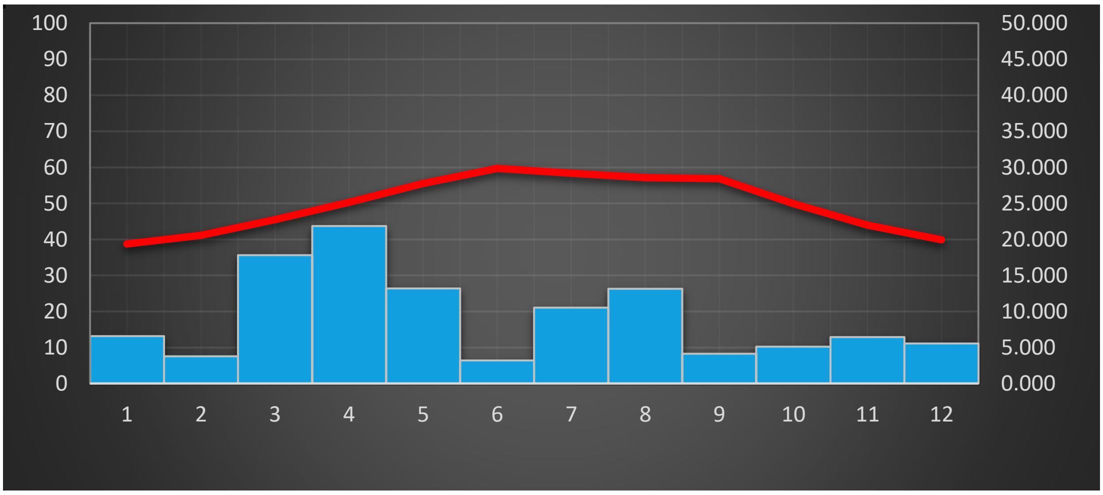

Fig. 4. precipitation and temperature (1986-2024) according to Gaussen's formula, Source: The Meteorological and Water Authority, 1986-2024.

This means that climatic conditions, especially rainfall, do not help the growth of a forest or woodland vegetation according to Gaussen's definition of drought. This contradicts the reality of the vegetation cover, as the study area is considered one of the most densely vegetated places. Seeing this contrast, it becomes necessary to study bioclimatic conditions in a more comprehensive framework, taking into account soil quality, topography, slope direction, development techniques, vegetation density, land use, and the effectiveness of all these elements in water harvesting and preserving soil moisture for as long as possible. To answer this inconsistency between measurements and field data, monthly and annual data available since 1980, taken from Meteo Blue and Climate Engine websites, as well as data for Rial Almaa taken from the National Meteorological Centre, were used to determine that the study area records one of the weakest evapotranspiration values compared to neighbouring areas, which ranged between 0.2 and 0.4 mm/m^2/day. This is due to the direction of the slopes, the importance of moisture in the soil and air, as well as the fog and daily rains that can form due to the heating of the air in the wadi beds and its subsequent rise and condensation. All these conditions helped the natural vegetation cover to grow, sometimes reaching 100 % coverage on many slopes, especially on the eastern and southeastern ones (Fig. 5 and Photo 1).

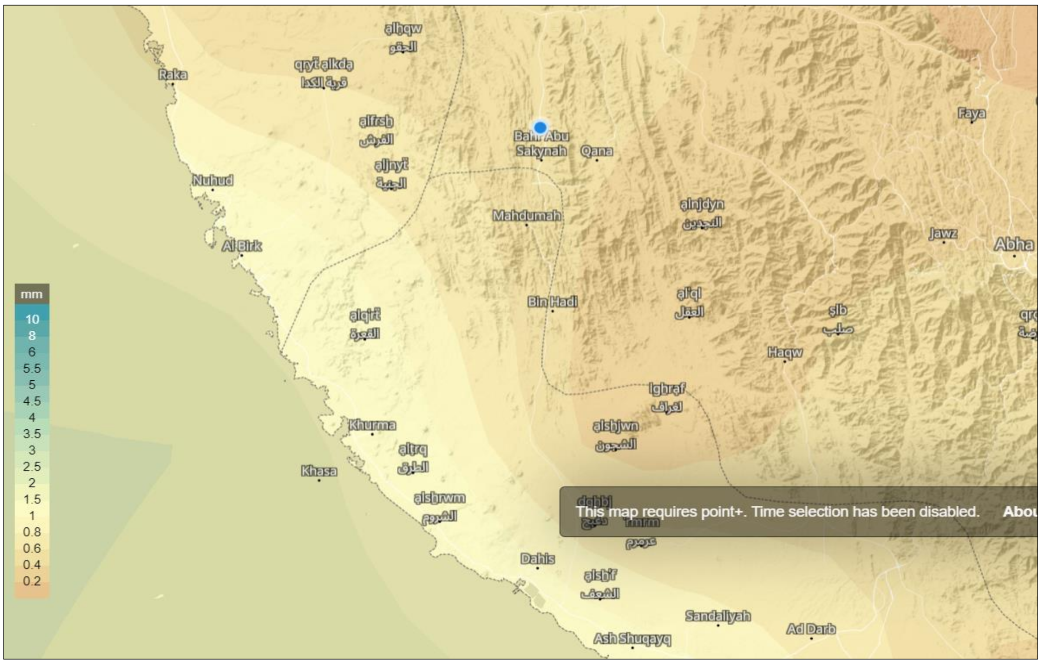

Fig. 5. Distribution of the evapotranspiration index for the Mountain Qais basins (1986-2024), source: Climate Engine and meteo-blue, 1986-2024.

Photo 1. Significant vegetation density in the Mountain Qais basins (upper sector of the Wadi Al Kharar basin), Source, Azaiez, 2025.

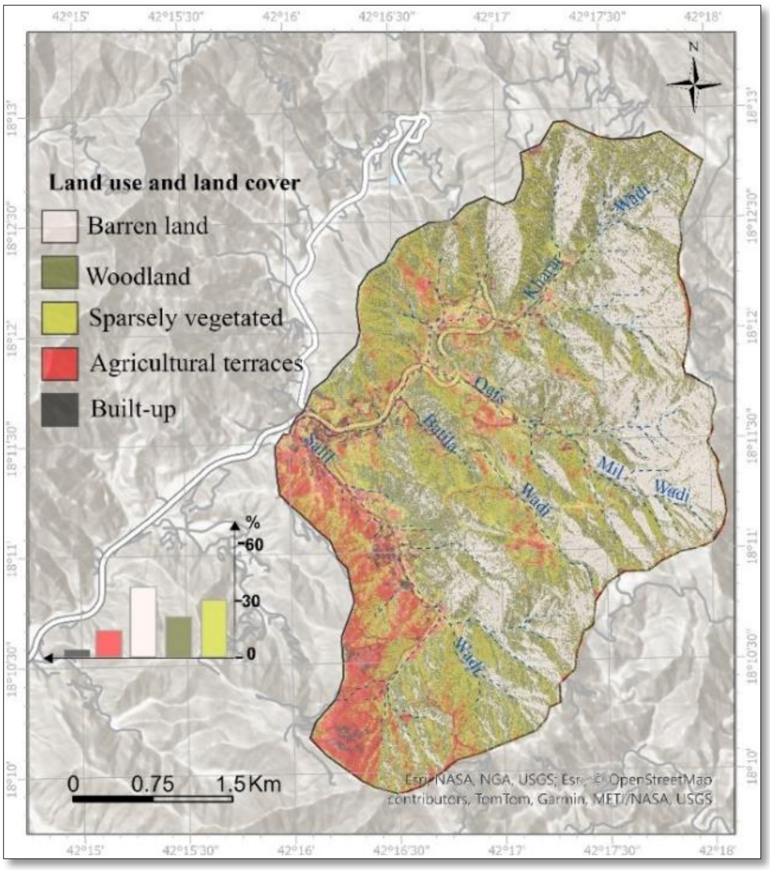

Fig. 6. Land use and Land cover in the Mountain Qais basins, source: geoprocessing of image Spot7, 2024.

Land use in the study area

Based on the field study as well as the land use map, which was derived from SPOT 7 of 2022 by applying the guided classification method, the study area is primarily agricultural in nature (Fig .6). The agricultural character can be confirmed by the widespread distribution of agricultural terraces, which extend over 23% of the total size of the study area, with about 70% of them concentrated in the Wadi Al-Salil basin. Most of the agricultural crops are rain-fed, with millet, sesame, maize, cereals, some types of vegetables, in addition to some types of fruit trees that residents have started to introduce in recent years, coinciding with the rehabilitation project for agricultural terraces launched by the Kingdom of Saudi Arabia in 2017. This initiative has been associated with the introduction of water development projects aimed at further controlling water resources so that farmers are not affected by the consequences of the fluctuating rainfall. The land-use map also highlighted the high distribution of dense forests consisting mainly of Sidr integrated with climbing plants, in addition to many aromatic plant species such as camphor, kadi, lavender, violets, samar, laurel, basil, rosemary etc...(Seraj et al., 2014). What must be emphasised is the overlap between the terracing system and the natural vegetation, especially in the valley floors. The vegetation has been steadily increasing over the past three decades, which emphasises the role of the terraces in improving environmental conditions, which in turn has helped sustain forests, water, and pastoral and agricultural resources as well as beekeeping (El-Juhany, 2009).

Soil properties

Based on routine analyses of soil samples, especially texture and permeability index, it was found that these water basins are characterised by loamy clay soils (Fig 7). They are shallow and undergo mass movements, slides and erosion over unprepared slopes, while over the terraces, their thickness ranges from 100 cm at the top of the terrace to 150 cm at the bottom. The thickness can reach or exceed 200 cm in the lower sedimentation areas (field investigation). This difference is due to the method of constructing the terraces with an external inclination, especially in El Kharar, Mil Qais and Batila, in contrast to the terraces in the Salil, which are mostly flat, with a slight inclination in some of them, especially at the mid- course level.

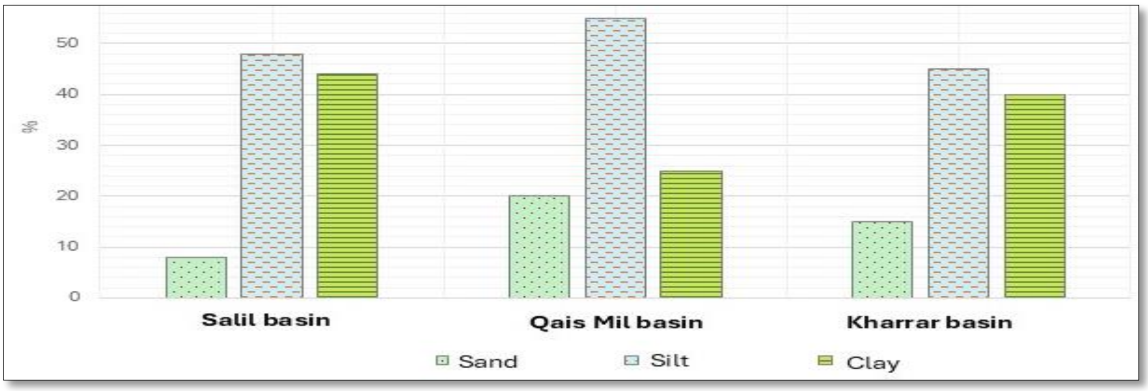

Fig. 7. Soil texture in the Mountain Qais basins, Source: Results of soil analysis, 2024.

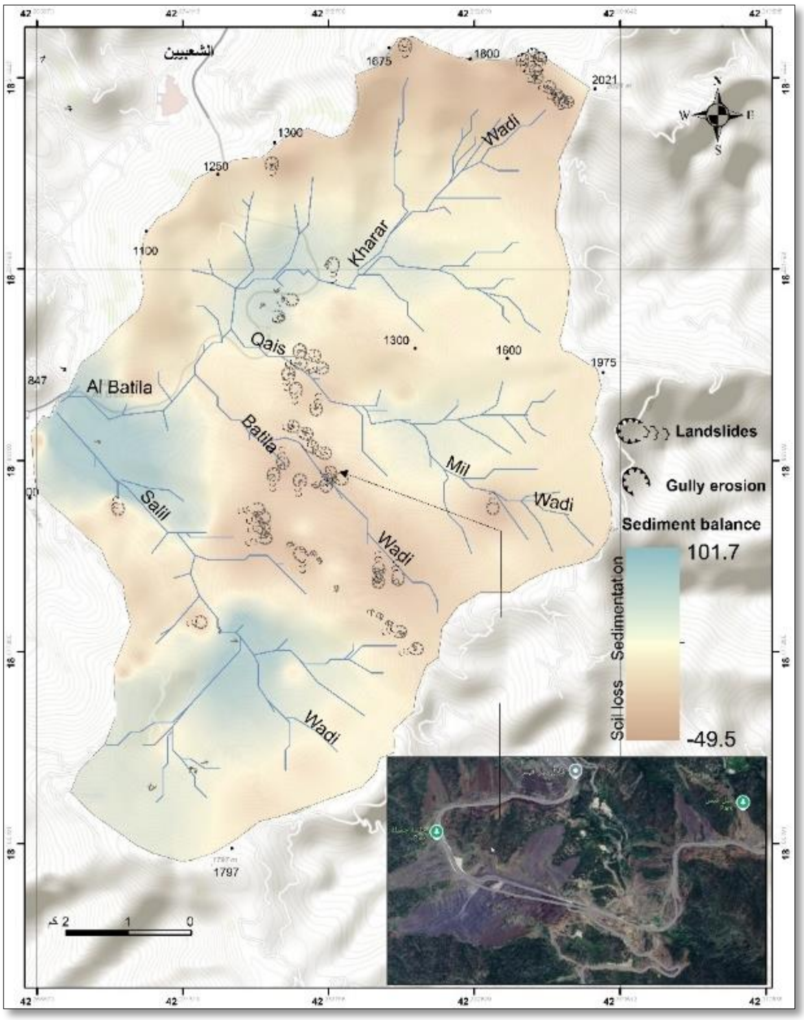

Fig. 8. Distribution of certain soil landslides over disturbed slopes in the Wadi Batila basin, source: Image, Google Earth Pro, 2024 and Cesium 137 analysis results.

The efficiency of agricultural terraces in soil resilience and the sustainability of associated resources. This part of the analysis will evaluate the soil resource in relation to the agricultural terraces, including an indirect evaluation of the rest of the resources that are directly affected by the improvement of the soil condition, in particular vegetation cover, water, agriculture, pastoralism and beekeeping (Fig. 8).

3. Results

Quantifying sediment over agricultural terraces by monitoring Cesium 137 tracers

The process of sedimentation over agricultural terraces began many centuries ago, and tracing its pattern can only be done in two ways, either by using isotopes, which in turn are divided into stable and unstable isotopes, or by direct field measurements, which require repeated field trips over several years, choosing different locations to reach reliable results. As for radionuclides, there are different ways of using them depending on the objectives of the study. The use of stable isotopes can help determine the age of the sediments and the bioclimatic conditions that accompanied the period during which the sedimentation process took place in its various stages. On the other hand, unstable isotopes are a very important tool not only in determining the age of the sediment, but also in accurately calculating its quantity in the short, medium and long terms, depending on the type of nuclides to be traced. Due to the high cost of radiometric analyses, the quantification of the deposits in the medium term, over the 37 years between April 1986 and January 2024, will be carried out using the Cesium 137 tracer. The year 1986 is considered the reference year for Cesium 137 projections because the projections of the late 1950s and the peak projections of 1963 have disappeared from the soil after undergoing total radioactive decay as Cesium 137 nuclides lose their half-life in 30.1 years. In 61 years (between 1986 and 2024), these nuclides will have undergone complete degradation. Thus, the nuclides whose activity was measured in the samples taken in 2024 are mainly from the projections of 26 April 1986 associated with the Chernobyl reactor explosion. For sampling, the transect survey method was applied; where the study area was divided from top to bottom into units according to slope, precipitation, vegetation cover, and morphological units to ensure that the samples are representative of the entire Jebel Qais basin, despite its limited extent. In order to quantify the soil tension, 10 samples were selected in the study area, 6 of which were taken on agricultural terraces with different topographic positions, crops and slopes. 3 of them were taken on eroded slopes. The reference sample was taken from a stable reference site that was carefully selected in accordance with the criteria and conditions that must be met by the reference site, namely that it must not have been subjected to ploughing or agricultural exploitation, nor subjected to erosion, and must be one of the higher areas of the basin. Stable reference sites are less common in mountainous water basins, especially those that have been subjected to human intervention. Based on all these conditions, the identification of the reference site in the study area required significant field investigation and exploration, because the success of the modelling process and the accuracy of its results depend on the accurate identification of the stable site (Table 1).

Table 1. The characteristics of the sampling sites used for radiometric analysis.

Sample number	Basin	Slope (°)	Type of soil	Additional Notes
1	Upper sector of Wadi Kharar	8	Sandy loam rich in organic matter	Terraced plowed against slope direction
2	Middle sector of Wadi Mil Qais basin	3	Loamy	Terraces planted with sesame
3	Batila basin	2	Loamy/Clayey	Eroded slope
4	Upper sector of Wadi Salil	4	Loamy/Clayey	Terraced plowed
5	Middle sector of Wadi Salil basin	3	Loamy/Clayey rich in organic matter	Planted Terraces
6	Batila basin	13	Loamy	Eroded slope
7	Reference site (Batila basin)	0	Clayey/Loamy	Not plowed or cultivated for decades, sampled around remnants of an old house.
8	Upper sector of Wadi Kharar	25	Sandy loam	Eroded slope
9	Middle sector of Wadi Salil	35	Sandy loam	Eroded slope
10	Middle sector of Wadi Kharar	22	loam	Eroded slope

Although the results comply with the conditions of the experimental protocol, it cannot be asserted that the results of the analysis of the six samples can give comprehensive and representative results for the entire study area since interpolation methods will be used to generalise the measurements to the remaining unsampled sites, but it is nevertheless one of the first serious attempts to trace the redistribution of sediments in the Batila area to highlight the efficiency of agricultural terraces in soil retention during the last 37 years. All samples were taken with a corer at a depth of 25 cm (plough layer). The choice of this depth can be justified by the fact that Cesium 137 is mostly deposited by rainfall on the soil surface and at low depths (only a few centimetres), especially in the absence of deep ploughing. Once deposited on the soil, these nuclides are quickly absorbed by clay particles and can only be removed primarily by hydro-mechanical erosion and secondarily by wind erosion. All samples were then subjected to a physiological preparation process to separate the fine soil particles (less than 0.2 mm) from the coarse components (greater than 0.2 mm) after drying and grinding, after which the density of both fine and coarse soils was calculated. These calculation steps are necessary to provide a quantitative estimate of the sediments accumulated behind the terrace walls. In the laboratory phase, gamma spectroscopy with high-resolution germanium detectors was used for all samples for 24 hours after the sample contents were homogenized before being filled with a 3D mixer and placed in sealed capsules. The homogenization test of reference samples must meet certain criteria, which can be achieved in three different ways. One of them should be adopted depending on the justifications and difficulties encountered by the researcher, because each study area has its own difficulties and obstacles:

-The first method is based on the use of 3 to 6 reference samples whose radiation is measured on the same day using the same instrument.

-The second method relies on the analysis of several isotopes of the same reference sample, and then the reference value is determined in multiple laboratories, in other words, using different instruments, and then comparing the different results to choose the results that are close and remain within the acceptable margin of error. This method can be applied in countries with many laboratories specialised in radiometric analysis.

-The third method relies on performing comparisons with reference samples from neighbouring areas that underwent quantification of radioactivity in the same period, or at least within close intervals, and whose reports or results have been published in scientific papers. This is the most used method, especially by researchers. Due to the high cost of analyses for the current study, homogenisation was done with reference samples taken from other neighbouring water basins (Wadi Abha). This method was used because it is the most common and widely used by researchers, especially for unfunded research, as it is the least expensive and has proven to be effective. Based on the results of the sample analysis, it was found that the values of the specific activity of the Cesium -137 tracer ranged from 9.57 Bq/kg at the reference site to 56.9 Bq/kg in the terraces with the highest levels of sedimentation. It was also observed that the specific activity of Cesium 137 was higher on the terraces located in the centre and at the bottom of the water basins. In the upper reaches, the relative importance of Cesium 137 activity is explained by precipitation, which is the main source of its stabilisation in the soil, and the potential for flooding in the upper terraces is rare and exceptional because the headwaters of the rivers are usually weak and the water flow is moderate, which explains why the largest possible percentage of Cesium 137 nuclides remain attached to fine soil particles, but these upper terraces do not benefit from any supply other than rainfall. In contrast, in the central sector of the basin, the complexity of the water network increases as we rise in the grade of the rivers and with it the width and depth of the water tributaries increase due to the intensity of the flow of streams descending from the upper slopes, making flooding more likely, which leads to a greater and faster movement of sediments with Cesium 137 nuclides between the terraces after they are filled, in addition to those fixed by precipitation. The significant increase in Cesium 137 activity in the terraces at the bottom of the basins, specifically in the Batila area where the waters of all the tributaries (Salil, El Kharar, Mil Qais...) meet, is due both to the pre-existing initial precipitation of Cesium 137 deposits (via rain) and to the lateral and longitudinal supply that takes place across the various wadi sectors after the terraces are filled. To further refine the conditions for the experimental estimation process, the overall characteristics of the sampling sites are summarised in Table 1. After obtaining the results of the Cesium-137 specific radioactivity for each sample, generalisation was made by finding isotopes for the sampling sites by relying on the method of homogeneous units. All terraces with the same characteristics in terms of slope, soil type, topographic position, annual precipitation amount, vegetation density, and land use were assigned the same specific activity for Cesium 137. Using geospatial interpolation tools, sediment distribution models were obtained in the form of a final prediction map, for which two methods were used. Kriging 'and IDW (Inverse Distance Weighted) were used as suitable geostatistical interpolation methods, despite the slight differences between them. The 'Kriging'' method is considered the most suitable for generating accurate or adjusted (smoothed) spatial mathematical models, as it relies mainly on the assumption of internal correlations between different elements of the sample and not only between neighbouring samples. It is also based on modelling and analysing measurement errors because it considers the relationship between the maximum possible number of neighbouring points in terms of value and distance and is also characterised by flexibility and the possibility of examining the internal correlation between the results of the specific radioactivity of all samples, thus accurately predicting the unknown values of the unsampled areas. The second interpolation method, Inverse Distance Weighted (IDW), is more suitable for samples that have a uniform distribution in the study area, because it correlates the different elements of the sample by considering the distance between them without considering the value of specific activity assigned to them. It should be noted that the relationship between the distribution of specific radioactivity and the sedimentation process in the study area is a proportional relationship, but with some exceptions. The sedimentation values sometimes increase or decrease, but not at the same rate as the specific activity. It was found that the rate of sedimentation was also related to the density of fine soil particles (below 0.2 mm). The density ranged from 0.69 for soils characterised by silt and sandy loam and 1.89 for soils with clay and clay/silt textures. To translate the specific radioactivity into soil fertilisation or loss, customised conversion models were used. The proportional transformation model is considered the most suitable for the Batila area, because in this study the focus was on agricultural terraces. This model was developed by (Kachanoski, 1993) to determine the percentage of soil loss or fertilisation in ploughed slopes. The proportional model is calculated according to the following equation (Azaiez, 2024):

$$\mathbf{Y = 10*D*BX/(100*T)} \qquad \mathbf{(1)}$$

Y = soil loss (t ha-1an-1); D = plow layer thickness (m); = B density of fine particles (below 0.2 mm) (kg/m^3)

= X Percentage enrichment or reduction of ^{137}Cs activity expressed by the following equation: (Aref-A/Aref) 100); T = the number of years elapsed from the reference year of maximum Cesium-137 projections (1986) and the sampling date (2024); Aref = specific activity of Cesium 137 at the reference site (Bq/m2); A = specific activity of Cesium 137 from the soil sample taken in Bq/m^2.

Samples taken from eroded and stabilised sites were treated according to the Mass and Balance Model 2 (MBM2), whose law (Zapata et al., 2002) was explained in a manual funded by the World Food and Agriculture Organisation (FAO) and published under the supervision of Springer. Unlike the proportional model, the mass and balance 2 model takes into account the selective displacement of soil microcomponents by surface runoff, to which the proportional model pays no attention because the process of ploughing and turning the soil prevents soil transport but makes the Cesium

137 nuclides migrate towards the second horizon of the soil layer, depending on the depth of ploughing and the ploughing methods adopted.

$$\mathbf{Y = 10*d.b/p[1-(1-X/100)1/(t-1986)} \qquad \mathbf{(2)}$$

Y: Soil loss tons/ha/year; D: Soil depth (m); B: Density of fine particles (below 0.2 mm) (kg/m3); T: Number of years elapsed from the Cesium 137 reference year; P: Index of selective displacement of fine soil constituents.

X: Percentage enrichment or reduction of Cesium 137 activity.

Many researchers have also applied other models to cultivated slopes, such as the Mass and Balance 1 and 3 models, but they have been applied under different conditions as part of more accurate studies that take into account the degree of agricultural stress (such as frequent seasonal crops) as well as the methods and means of land management such as agricultural rotation and fallow, the method of ploughing and the means used for it.

The spatial modelling of soil fertilisation and loss

Cartographic interpretation of the displacement and sedimentation values in the Jebel Qais basins showed that the agricultural terracing system played and continues to play a major role in the distribution of sediment and soil tension on the slopes. Together with vegetation, they have also contributed to reducing water erosion. A comparison of the results of soil loss modelling with other neighbouring water basins such as Al Badla basin, Wadi Marbah basin, the middle course of Wadi Abha, and to a lesser extent Wadi Al Hayat basin - because it is somewhat further away from the study area - shows that Jebel Qais basins recorded the lowest levels of erosion despite extreme steepness. The maximum soil loss in the study area was 49.5 tonnes/hectare/year (Fig. 9), which is considered one of the lowest maximum amounts, only partially exceeding the threshold of 40 tonnes/hectare/year (Nasri, 2002; Azaiez, 2016) permitted in semi-arid areas (Nasri, 2002; Azaiez, 2016).

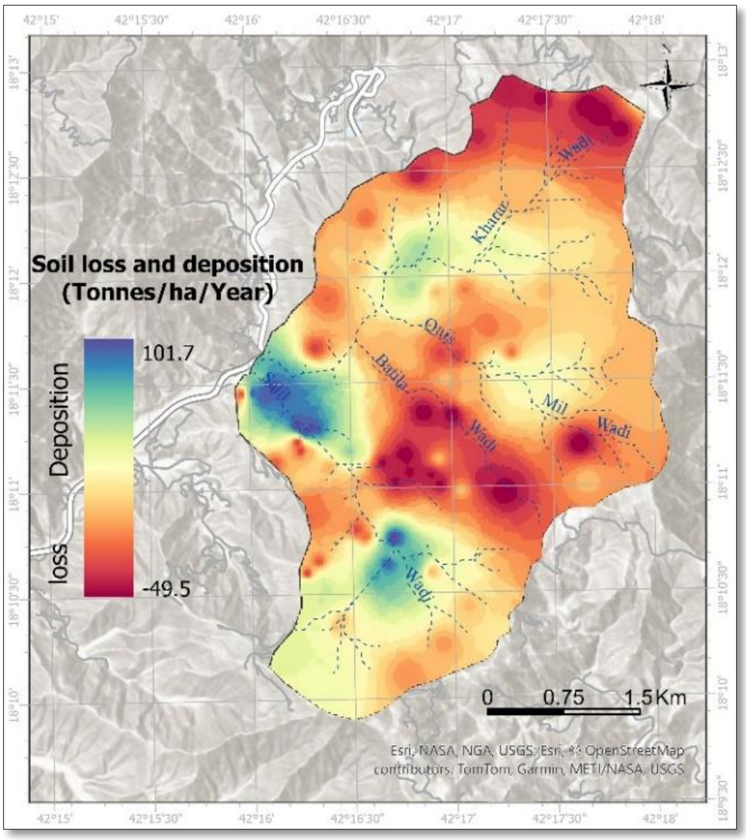

Fig. 9. Spatial distribution of soil loss and sedimentation values in the Mountain Qais basins (1986-2024), Source: Prepared by the author based on the results of radiometric analyses.

This means that when soil loss reaches 40 tonnes, natural regeneration through various weathering processes is possible, but only if precautions are taken. This confirms that the ancient protective measures of terraces and dikes were well suited to the characteristics of the studied water basins in terms of nature of the soil, the quality of the vegetation cover and the slope in the different sectors of the water basins, and they also provided a favourable ground for the establishment of a dense vegetation cover that increased the resources of the region in terms of improved vegetation cover, pasture and increasing production of biological honey. What was proven by the field study is that sedimentation processes recorded the highest rates in the Wadi Salil basin compared to the basins of Wadi Mil Qais and Wadi Kharrar. Sedimentation levels reached a threshold of 101.5 tonnes/ha/year in the middle and lower parts of the basin. The volume of soil sedimentation was measured over a period of 37 years since 1986, but the construction of these terraces dates back several centuries, so the amount of sedimentation measured represents only a fraction of the total sediment trapped behind the walls of the terraces.

In the rest of the basin sectors, sedimentation ranged from 5 tonnes/ha/year to 78 tonnes/ha/year. The importance of sedimentation in Wadi Al-Salil can be explained by several factors, including the moderate slope compared to the basins of Wadis Kharar, Mil Qais, and Al-Batila (Fig. 9). It is also due to the importance of the area occupied by the terraces, and the density and diversity of the natural vegetation cover. This is in addition to the density of the terraces and the integration of their units between the upper slopes and the valley floors, with the predominance of narrow terraces that have a very slight inclination in the direction of the slope, as more than 75% of the terraces in Wadi Al-Salil do not exceed 8 m in width (Figs. 10 and 11).

All these favourable conditions ensured a fair distribution of soils between the upper, middle and lower terraces, although the maximum sedimentation levels were recorded at the bottom of the water basins in the area where all the tributaries meet and where the soils are clayey and the width of the terraces reaches a maximum of 35 m. By contrast, the terraces are wider and steeper in the upper parts of the basins of the Kharar, Mil Qais and Btila Wadis. These conditions contribute to the passage of most of the sediments towards the lower reaches, and even the sediments held above the upper terraces are of sandy and sandy loam texture. The rest of the basins are dominated by terraces that range in width from 8 to 20 metres. In addition, the extended length of the slope provides favourable conditions for the movement of materials over the long and inclined terraces towards the bottom of the slope. Previous studies have confirmed that increasing the length of the slope increases the reinforcement of surface water erosion methods.

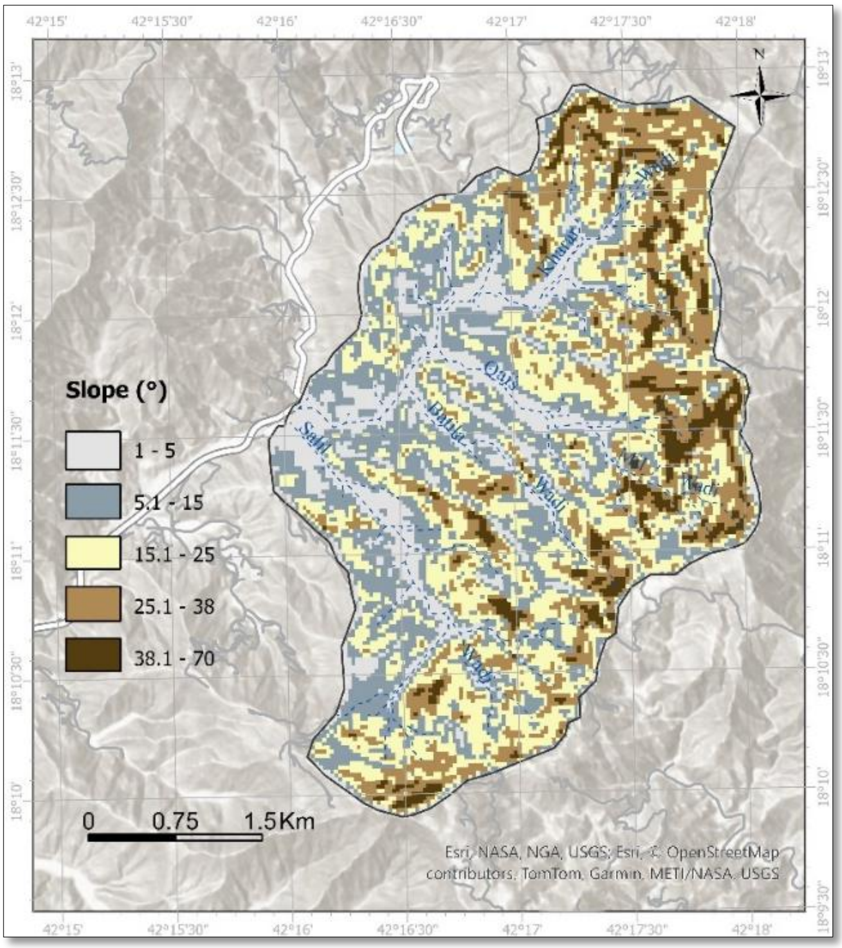

Fig. 10. Distribution of slopes across the different sectors of the Jebel Qais basins, Source: Prepared by the author based on the satellite image of Alos Palsar, 12.5 m.

Variation of sedimentation values in terms of width, slope and direction

On steep slopes, terraces are surrounded by dry stone walls, which are narrow and nearly horizontal. However, terraces in valley bottoms are surrounded by unbuilt rocky barriers interspersed with fast-spread climbing plants. The field visit showed that most of the terraces supported by natural vegetation are in a more stable condition than terraces that are not supported by a natural vegetation cover that is able to resist the force of the flow and to trap sediment, and this was confirmed by the modelling (Fig. 12). Soil texture analyses carried out on several soil samples taken from agricultural terraces selected at different topographic positions show that the irrigated terraces tend to have a medium and semi-coarse texture because they are the ones where the first sedimentation processes take place, mainly involving larger and heavier grains. These terraces are usually narrower and steeper, and their soils are also characterised by high aeration because the drainage process is smoother due to the relative steepness and the higher level of solar radiation compared to the valley bottoms. These upper terraces are dedicated to crops that require relative warmth and take less time to germinate because they benefit from the high porosity and good soil structure. Crops produced in irrigated terraces ripen earlier than crops from terraces in the valley bottoms, especially in the rainy season. These upper terraces benefit from the relatively warm daily winds during the night, which result from the sliding of cold mountain air towards the valley bottoms as the upper slopes lose their ground radiation faster than the lowlands, which contributes to lifting warm air from the lowlands and valley bottoms towards the upper terraces.

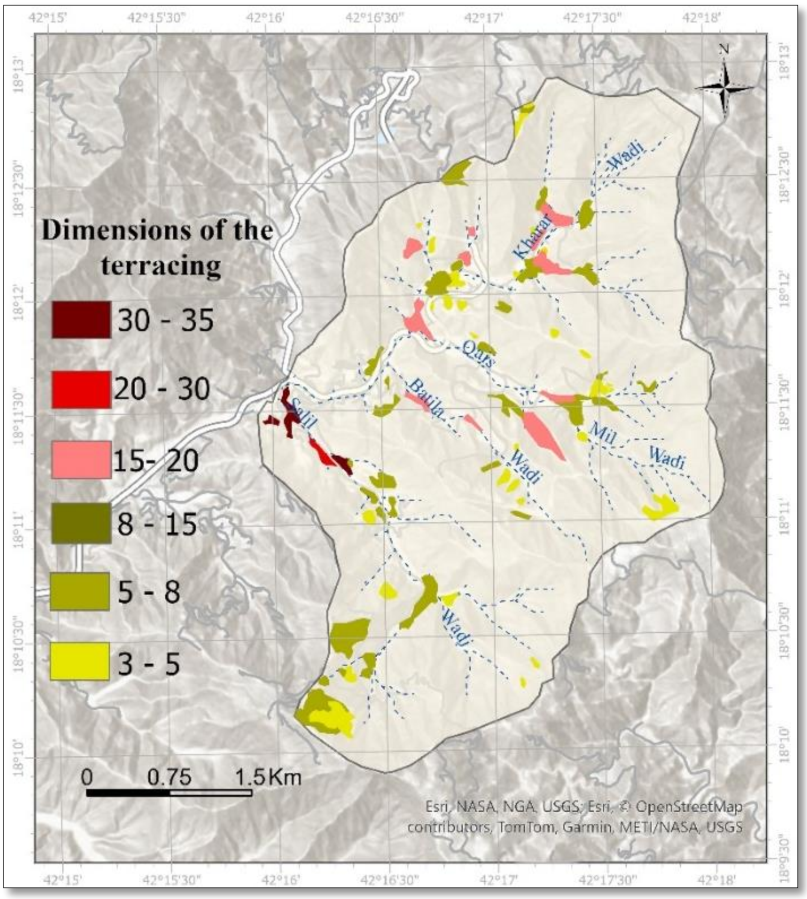

Fig. 11. Spatial distribution and classification of terraces according to their different dimensions, Source: Image, Google Earth Pro, 2024 and field study.

This makes the vegetation cover more abundant and diverse because the middle and upper terraces benefit from this heat flux, whereas crops in the lower slopes and valley bottoms are often at risk of freezing in the last hours of the night and the first hours of the morning. One agricultural technique that contributes to stabilising the soil on these terraces is surface ploughing in the opposite direction of the slope (Photo 2), a method that can slow down the concentration of runoff, especially when the terraces are large enough.

Photo 2. Surface tillage in reverse as a soil conservation technique, Source: Photo taken by the author 2024.

There is also a relationship between hydro-agricultural structures (terraces) and the direction of the slopes, which reflects the experience gained by the early inhabitants in agricultural management, especially at the level of the Kharar and Salil basins, which account for 75% of the total number of terraces in the study area, with the highest concentration in the basin of Wadi Salil. The terraces that occupy the south-facing slopes benefit more from warmth. They also benefit from rainfall, especially summer rains. This characteristic includes all south-facing slopes between (130° and 290°) (Fig. 13). These slopes receive additional radiation, resulting in a warmer and drier weather, and creating temperature differences between day and night. These terraces also experience greater evaporation, causing the soil's water reserves to deplete very quickly. Most of these terraces are dedicated to crops that can cope with high temperatures. In contrast, the slopes facing north, north-west and north-east are cooler, more humid and have soil that retain more water due to the lack of sunshine and the importance of shading. These topo-climatic conditions are more favourable for mountain plant species, which explains the high prevalence of dense forests on these slopes.

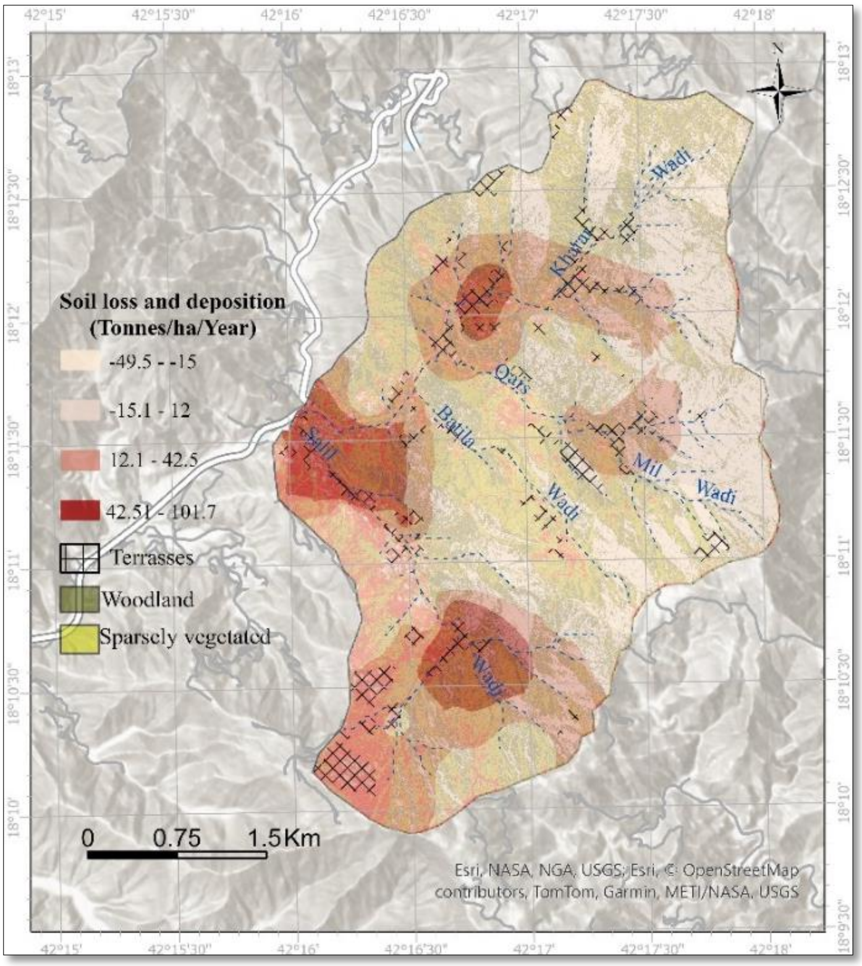

Fig. 12. The pattern of sedimentation depends on the topographic position and the density of vegetation, Source: Authors' work based on the results of modeling and targeted classification of SPOT 7, 2024.

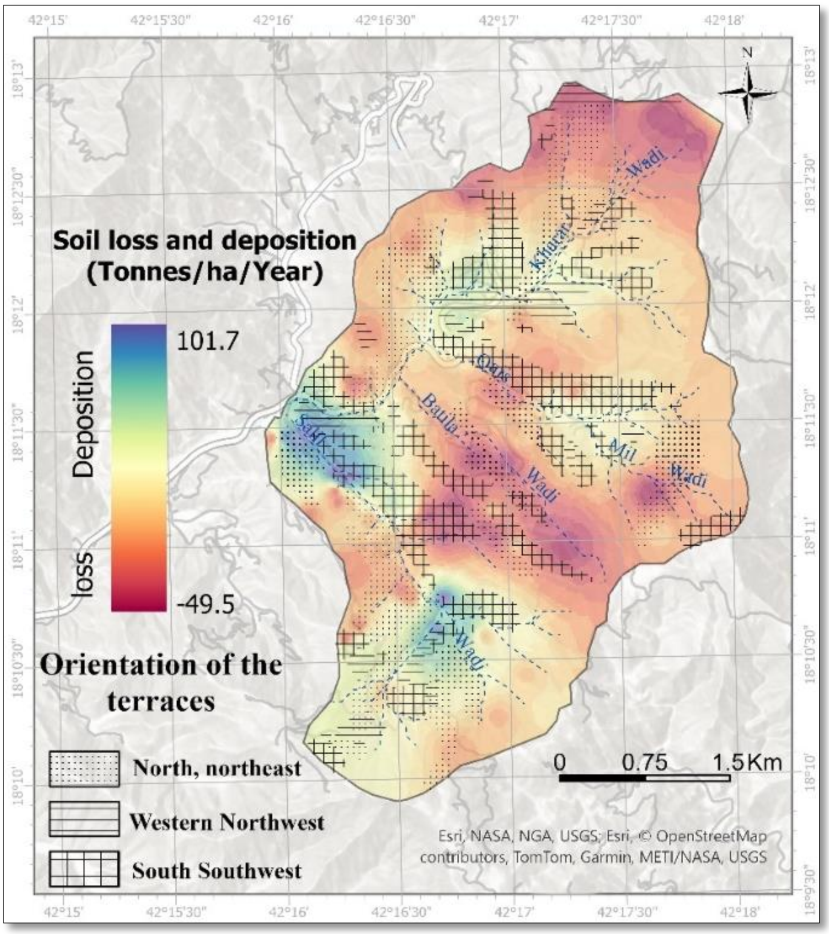

Fig. 13. The pattern of sedimentation in the terraces depends on the direction of the slopes, source: Developed by the author based on the modeling results.

The deep wadi bottoms are the most vulnerable to the accumulation and stagnation of cold air resulting from the cold mountain breeze sliding towards the valley bottoms during especially clear nights, where this night-time movement can cause severe late frost, and thus cause serious damage to the crops located in the wadi bottoms. This is illustrated by the formation of fog as a frequent phenomenon. All these conditions (direction, slope and length) contributed to ensuring a fair distribution of sediments between the different sectors of the basin, especially at the bottom of the basin. As for the upper sectors, at least they prevented the upper slopes from being completely stripped of their soils. Even if the sedimentation process is weaker than at the bottom of the basins, the stability of a dense vegetation cover would further stimulate the biological and chemical weathering processes, so that in the long term a fertile soil could be formed.

Qualitative and quantitative improvement of environmental and bioclimatic indicators as a response to the sustainability of the agricultural terracing system

The terraces were designed in such a way that, over the centuries, they have been able to distribute the water and heat reserves needed by the plants. This has contributed to the sustainability of many resources that have been sequentially supported starting from the soil to beekeeping and pastoralism. Based on the tested results, the study area witnessed an improvement in many environmental indicators that have been positively reflected on many resources in the region. This improvement in the performance of the ecosystem was evident on several levels: The soil as a foundation for agriculture and as a habitat for natural vegetation, as well as the improvement of soil moisture, surface temperature, and vegetation cover. The qualitative improvement in climatic conditions over the last four decades cannot be overlooked, especially considering that the world is witnessing climate change that climate scientists believe is undermining and threatening the prevailing ecosystems. This improvement is particularly evident in rainfall, which has shown a clear tendency to increase. This is evident in the precipitation trend curve (Fig. 2), as well as in terms of its annual distribution. This precipitation is characterised by its continuity throughout the year. Although it remains below the double of the temperature throughout the year according to Gossan's definition of drought, it is considered enough to protect existing ecosystems, but with the need for a strategy of sustainable development by adopting all methods that would increase valorisation of water and maximise resources. In contrast, a clear decline in the land surface temperature index (LST) was recorded, which is due to the importance of soil moisture which, in turn, is related to the seasonal distribution of rainfall that peaks in spring, as well as the daily precipitation pattern that peaks between afternoon and midnight in the autumn, winter and spring seasons, which reduces the chances of water loss through evapotranspiration. This means that the discrepancy between the daily rainfall peak and the daily thermal peak played a crucial role in preventing the loss of moisture. Except in the summer due to the influence of the summer monsoon. The dense natural forest vegetation has also contributed to the increase in shading and the absorption of solar radiation in the process of photosynthesis. It is worth noting that one of the characteristics of the natural vegetation cover in the Qais Mountains is that it is of a perennial type with numerous branches. Jujube trees and climbing plants, which are considered one of the most important plants that provide food for bees, are widespread, and the Rijal Almaa region, to which the mountain Qais basins belong, is one of the most important areas for producing and exporting high-quality honey (Photo 3). It should be noted that the diversification of the local population's income, especially as some of them engage in various economic activities such as rural tourism, commerce, and others, has contributed to greater care for the agricultural terraces. Also, the impact of the project to rehabilitate agricultural terraces launched by the Kingdom of Saudi Arabia in 2016, which targets Asir, Jizan regions and aims to revitalise the cultivation of the terraces.

Photo 3. Diversity and intensity of vegetation cover in the Salil and Batila basins, source: Photo taken by the author 2024.

Rijal Almaa has benefited from this effort, with a series of workshops for farmers to raise awareness of the importance of following the agroforestry method and encourage people to choose field crops, fruit trees and fodder plants suitable for the region. In this way, the farmer achieves the maximum benefit from the trees by fertilising the soil in a biological way through falling leaves. They also provide pasture and minimise evaporation due to the shade that the trees provide on the slopes. This leads to improving the local climate, lowering temperatures and reducing the wind speed near the ground surface by increasing the surface roughness index. The effectiveness of these methods that were applied in the study area can be confirmed by several factors, including the Land Surface Temperature (LST), soil moisture index (NDWI), Normalized Difference Vegetation Index (NDVI), and SAVI, which is based on a coefficient that minimises the effects of soil brightness. By analysing the surface temperature data, it was found that there has been a clear decline during the last two decades, which is highlighted by the descending trend curve of the LST index (Fig. 14). In contrast to the LST, the NDVI showed a clear increase in green biomass and chlorophyll concentration, which can only be a direct result of improved bioclimatic conditions and the effectiveness of land management methods, in which agricultural terraces are the key factor in improving the performance of the ecosystem. They are one of the most widespread landscapes in the study area. Although some caution should be taken in using the results of the vegetation index analysis in dry areas due to the high reflectivity of dry soils, the Batila region is characterized by high soil moisture. To highlight this, the (LST) Index was derived for the period between 1986 and 2023, which showed a clear decline in land surface temperature of 27.5, from 36.5 to 28.3 on average. These results are illustrated by the temperature trend curve and the median (Figure 14). The cartographic representation shows the clear inverse correlation between the LST, NDWI and NDVI indicators.

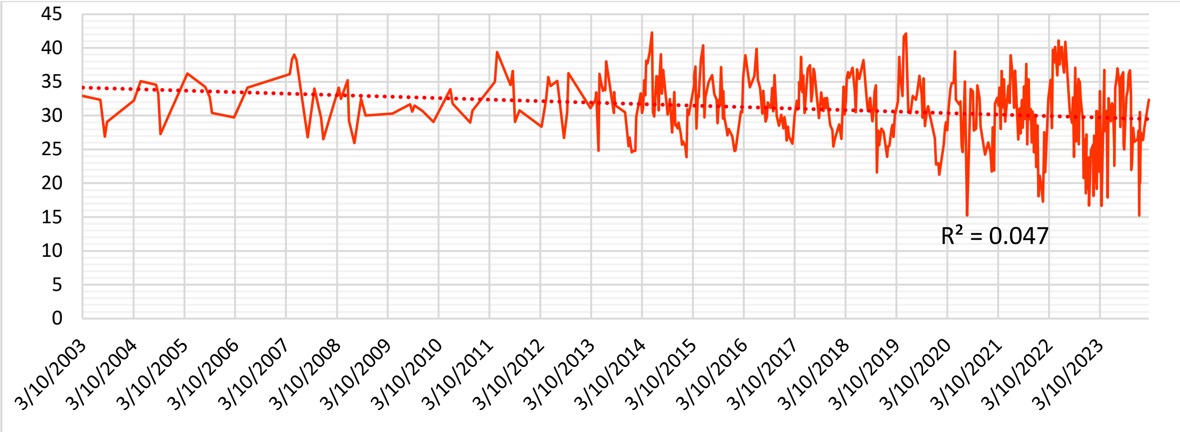

Fig. 14. Evolution of Land Surface Temperature (LST) for the period January 2003-March 2024, Source: Website of Climate engine, Based on Landsat images (5, 7, 8, 9 SR).

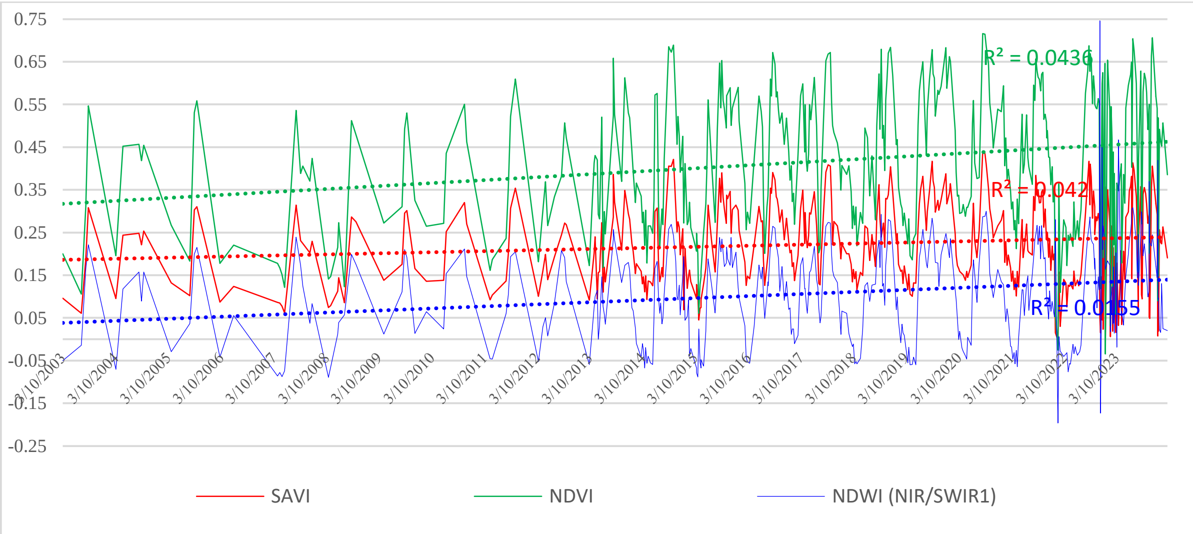

Fig. 15. Evolution of vegetation and soil indices (SAVI, NDVI, NDWI) in the study area (2003-2024), Source: Website of Climate engine, Based on Landsat images (5, 7, 8, 9 SR).

In fact, the areas with the least surface temperature in the Jebel Qais basins are the most humid and have the highest vegetation cover. This decline is an inevitable result of improved climatic conditions and increased soil moisture on the one hand and the efficiency of terraces and land use methods and tools on the other. By linking the growth of the Land Surface Temperature Derivative Index (LSDI) with the growth of the SAVI, NDVI and NDWI indicators for the period (2003-2024), there is an inverse relationship between them as shown in the Trend Curve (Fig 14 and 15). The levels of soil moisture (NDWI), Normalized Difference Vegetation Index (NDVI), and Soil Adjusted Vegetation Index (SAVI) have increased. Here, it is important to note that there are other local climatic factors that the terrain has helped to shape, namely the phenomenon of mountain breeze and valley breeze which, at the local level, have helped to determine the temperature distribution between day and night and between the upper slopes and valley bottoms, which constitutes a kind of interaction between air movements and terrain to form a complex biological system that has benefited the terraces and natural vegetation cover, especially plants that need a balanced temperature for their survival. The construction of concrete reservoirs, dams and the drilling of surface wells with the support of the state also played a key role in explaining these distinctive environmental conditions. It is worth noting that the state provides adequate support to farmers through the Agricultural Development Fund. The Kingdom of Saudi Arabia has undertaken several initiatives to rehabilitate agricultural terraces in the Asir region through the water harvesting policies that have been applied. These include the introduction of water-saving irrigation techniques, as well as harvesting surplus rainwater and directing it to nearby wells to replenish the surface water table and then use it for agriculture during periods of low precipitation. Other techniques include the construction of concrete reservoirs to harvest rainwater as well as small earthen dams to reduce surface runoff and collect floodwater after rainfall to irrigate crops in the terraces. Agricultural terraces are indeed ancestral constructions, but their benefits are reaped by descendants several centuries after their construction, as their effects are not immediate but rather long-lasting. It is not possible to abandon this precious heritage while the fruits come to fruition. In view of all these results, every rehabilitation attempt must be based on a comprehensive approach that considers the general framework in which the terraces were created, socio-economic changes, as well as the aspirations of the local people who are considered the key players in the implementation of the various stages of the rehabilitation process.

Improving the pastoral sector

The improved vegetation cover, which benefited from the levelling of the slopes on the one hand and the increase in humidity on the other, led to the growth of livestock farming, especially the cattle breeding sector, which benefited greatly from improved pastures, abundant vegetation and an increase in the varieties preferred by livestock. The sustainability of these pastures is attributed to the local meteorological characteristics of the region. The rise of warm and humid air towards the mountain peaks contributes to the frequency precipitation, and even if they are in limited quantities, they are sufficient and in combination with soil moisture ensure that the vegetation remains in a state of equilibrium. This daily process can contribute to additional water sources for natural vegetation and can also support subsistence farming. The alternation of mountain and valley breezes also contributes to maintaining the temperature balance for many plants for their survival, thanks to the constant exchange of thermal surpluses between night and day and between the upper slopes and valley bottoms, which in turn increases the diversity of agricultural crops and provides diverse pasture for bees. However, it should be noted that some of the slopes have deteriorated due to the migration of residents because of the lack of services such as university education and adequate health services, which force citizens to migrate from their province to some large cities, in addition to the lack of labour for the maintenance of the rocky structures. Some of the terraces look almost destroyed, which may prevent the development projects that the study area aims to implement. This applies to the agricultural terraces surrounding some of the historic villages in the Kharar basin (photo. 4 and fig. 16). ensure that they are repaired and rehabilitated to adapt to the climatic and economic changes taking place in the region. Some other terraces in the different basins have been overtaken by natural vegetation cover.

Photo 4. Examples of bovine livestock farming under the open pastoral system in the Batila region, source: Photo taken by the author 2024.

Fig. 16. The natural vegetation of the terrace system in the Kharar basin and its integration into the forested area, source: Google Earth Pro, 2025.

4. Discussion

Regional comparisons are essential to combating water erosion efficiently. They identify common factors (such as climate, geology and land use) and unique regional differences, enabling stakeholders to create customized solutions such as terracing, reforestation or sustainable agriculture. This approach promotes inter-regional cooperation, links local erosion problems to broader climatic and socio-economic challenges and facilitates the exchange of knowledge between communities and political decision-makers. However, successful implementation depends on the existence of standardized data, the adaptation of solutions to local contexts and adherence to effective governance structures. Ultimately, regional comparisons help link local actions to global sustainability goals, improving resource management and resilience against environmental degradation due to erosion. By comparing the specific activity of Cesium 137 with neighbouring areas and with semi-arid areas in general where the same technique has been applied in previous studies (Al-Qhtani, 2024; Azaiez, 2021 and Azaiez, 2023), it was observed that the rates remain close, with a lower specific activity recorded in the current study area. The Qais basins are considered less eroded, despite being located on steeper slopes than the Wadi Abha basin. This is explained by the expiration of the radioactive decay period for all the projections associated with the nuclear tests of the years between 1958 and 1963. Although Wadi Abha is settled on less steep hillsides than Qais mountain basins, it recorded higher soil loss in terms of peak values (81.3 Tonnes/ha/year) compared to (49.5 Tonnes/ha/year) only in Qais mountain basins. This is due to different land use, Topo-climatic difference, vegetation density, and the distribution of terraces. So maintaining a plant cover is essential to preserve soil quality, avoid soil degradation and promote sustainable agricultural practices. Techniques such as agroforestry, mulching and cover crops (green manures) are all solutions for protecting and improving soils. Further investigation is needed to establish a possible causal link between low plant density and higher erosion rate. Consideration must also be given to the disadvantages or challenges associated with the application of Cesium 137. Indeed, the initial rather heterogeneous distribution of fallout could complicate any cross-regional comparisons. What's more, in some places, such as the tropics, heavy rainfall may have caused immediate runoff, so that Cesium 137 did not accumulate in the same way as in temperate zones (Navas et al., 2005; Falah, 2010; Kumar et al., 2024, Salah et al., 2024). Another point concerns temporal resolution: Cesium 137 considers erosion over several decades, so it is unsuitable for targeting short-term changes. In this regard, it would be advisable to consider berylium 7 and field validation as a complements to assess the seasonal rhythm in relation to various crops (Ben Mansour et al., 2000; Mabit et al., 2018; Azaiez and Hamza, 2021).

In addition, the inability to capture all erosion processes is a major drawback. Cesium 137 primarily tracks water-driven sheet erosion, neglecting wind erosion, gullying, or landslides. It also fails to quantify nutrient loss or chemical degradation, critical for agricultural productivity. Thus, complementary methods (e.g., isotopic tracers like Lead-210 or process-based models) are essential for holistic assessments. While Cesium 137 remains a valuable tool for historical erosion analysis, its limitations underscore the need for multidisciplinary approaches, emerging technologies and interdisciplinary collaboration. Integrating Cesium 137 with short-lived isotopes (e.g., Beryllium-7), remote sensing, and participatory field data can enhance spatial and temporal resolution (Ben Mansour et al., 2000; Navas et al., 2005; Faleh,2010; Mabit et al., 2018; Mabit and Blake, 2019; Azaiez and Hamza, 2021; Azbouche et al., 2023; Azaiez, 2024).It is also necessary to emphasize the spatial and logistical constraints that hinder the identification of soil erosion processes at the plot level. There are other soil constraints that must be taken into account such as granular texture and organic content.While rich soil effectively retains Cs-137 mud, soil chemistry plays an insufficient role by researchers along the lines of: the ability of some soil ingredients to exchange cationic (CEC), where low quantitative concentration soil (such as sandy soil or highly weathered tropical soil) does not retain good Cs-137, reducing the value of erosion.

pH and rival ions: Acid soil (pH < 5) or potassium-rich ones (Cs chemical isotope) can replace Cs-137, causing erroneous corrosion signals. In Brazil's Cerrado region, aluminium-rich soil increases the complexity of binding dynamics, and peat organic soil may be fraught with Cs-137 nuclides in surface layers despite erosion, resulting in contradictory results (Elizeu et al, 2019). All these constraints need to be taken seriously and considerable efforts must be made to develop and explore new avenues of research in this field, in order to elucidate the other aspects and dimensions of water erosion, which remains the major problem facing agricultural land.

The results in terms of preliminary recognition of the fact of erosion is considerably potential in awaiting the adoption of exauhsitive sampling, because Cesium 137 constitutes a strong spatiotemporal marker in the soil, although sometimes it seems indisponsible and preferable to promote other adherent methods in order to provide more accuracy, especially for slopes that undergoing mass movements and prone to gully erosion. This study is not the end of research on soil erosion in the Jabal Qais basins, but rather a first step towards a deeper understanding that could make a difference in the sustainability of our environment for future generations.

Differences in soil erosion rates across all slope classes represented in the basin were not considered because we were constrained to a limited number of samples. To estimate them more reliably, a larger number of samples would have to be taken. Thus, there is a lot of opportunity for future research to explore the impact of both the topography and the different characteristics of the soil types existing. Future research could include these differences to provide a more comprehensive understanding. Furthermore, the relationships between different soil properties, soil erosion rates, and Cesium-137 concentrations are still not well understood in southwestern Saudi Arabia due to the complexity of its topography and diversity of soils. To ensure that the reference site is representative and minimize uncertainties in its data, it should be sampled at multiple time periods to validate its stability (Tagami et al., 2019; Raj et al., 2025). Future studies can incorporate optimization factors to make soil erosion estimates more accurate. Some researchers have suggested that a standardized correction factor could be used for different grain sizes in the absence of detailed soil texture data.

All of the previous issues mentioned above can in themselves be a starting point for future research topics that complement the current study. For example, a comprehensive understanding of sediment dynamics cannot be achieved in relation to water processes only, because it is also affected by wind processes, and this dimension of erosion was not taken into account in this study. The topic of wind erosion could be a new research topic that complements this current study; the products of erosion and sedimentation in the study area are the result of water and wind processes, and even if they differ in distribution and relative weight, in favor of water processes, this does not mean a complete neglection of the role of winds, at least in certain months of the year when local winds are active and able to dispel and displace dust and soil elements. This type of study would highlighting the interactions between wind and precipitation in the erosion process.

5. Conclusion

This study has highlighted - even if partially - the importance of applying the isotopic technique in assessing the role of agricultural terraces in maintaining the proper functioning of mountain ecosystems and the sustainability of their resources. This study showed that the unstable isotope technique is a useful tool to track and measure the quantity range of sediments behind the terraces according to their topographic position, orientation, width, slope, and construction method. It was observed that sediment distribution follows two patterns: a lateral one, under the influence of slope and water flow, and a vertical one, under the influence of land use, especially ploughing methods and tools. However, it must be noted that the reliability of the results will still depend on the representativeness and accuracy of the reference sample, which increases with the number of homogeneities tests whose results must be within acceptable margins of error. The remote sensing technique also demonstrated its effectiveness in verifying the results of the theoretical technique by monitoring the response of some environmental indicators to the results of water harvesting and soil tension. The indicators (LST, NDWI, SAVI, NDVI) have all shown a clear improvement over the last three decades. This study aims to help fill the knowledge gap in the efficiency of agricultural terraces in soil tension in a direct quantitative way, as well as to predict their capacity to continue receiving sediments and to identify future measures needed for them to cope with various bioclimatic and socio-economic changes. However, the movement of some of the residents to settle in major cities may expose these terraces to deterioration in the long term. Neglecting and abandoning the terraces may lead to the collapse of the stone walls, which in turn creates mass movement of the soil, erosion of the surface horizon, and the formation of gullies and rills. Thus, it is necessary to explore this topic further by paving the way for joint research between stakeholders interested in agriculture and specialists in soil and water to reinforce the results of this study over longer periods of time, especially given the rapid climatic changes that the world is witnessing. In addition, the fact that the region contains multiple types of terraces makes it even more important to test their effectiveness. In addition to stone terraces, there are also earthen clusters and other patterns that incorporate vegetation as an essential component of the construction of the terraces. Some of these patterns were not included in the current pilot study due to the limited number of samples used for radiometric analysis. Perhaps by expanding experimental research on as many terraces as possible in the future to compare the effectiveness of all existing types of stone terraces in order to distinguish their strengths and weaknesses (Azaiez, 2021; Chuxiong et al, 2021), we can reach better ecological facts that can identify and classify the sources of sediment on slopes, determine the direction and pattern of sedimentation, and identify the best locations for the construction of terraces (Akplo et al, 2022). The study also recommends that further work is needed to determine the reference value of Cesium 137 by analyzing isotopes from the reference sample in at least 5 accredited laboratories to be adopted by future researchers in the Batila area and its neighbouring basins (Ben Mansour et al., 2000; Navas et al., 2005; Faleh,2010; Azaiez and Hamza, 2021; Azbouche et al., 2023). All these stages are essential inputs to plan a sustainable development strategy that takes into account the opinions of the local residents and their effective contribution based on their accumulated experience on the best types of terraces that can be built as well as agricultural options and land service methods that would further improve the performance of the ecosystem in all its components and increase its benefits to the local population.

List of abbreviations:

Cs^{137}: Cesium 137
LST: Land Surface Temperature
NDVI : Normalized Difference Vegetation Index
NDWI: soil moisture
SAVI : Adjusted Vegetation Index

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

Competing interests: The author declares that she doesn’t have any conflicts of interest in the

publication.

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