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Original article

Quantitative analysis of rill erosion and contributing factors in the Oued Aghrouz catchment, Morocco

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ABSTRACT

Rill erosion represents a major form of soil degradation and loss, poses a significant environmental problem and is a serious threat to sustainable development. Various factors, including soil properties, topography, climate, and land use influence its occurrence and progression. Over the past decades, most soil erosion studies have focused on sheet erosion processes. However, research on rill erosion, both at the plot level and across broader spatial scales, remains relatively scarce. This article aimed to examine the impacts and consequences of rill erosion while seeking to identify the factors influencing elementary gully formation in the Oued Aghrouz catchment. Data were collected through measurements of rill dimensions on 12 plots. Descriptive statistics and correlation analyses were used to interpret the findings. The study revealed that the investigated catchment experienced an average soil loss due to rill erosion estimated at 64.9 t/ha, with values ranging from 15.9 t/ha on Vertisols to 151.13 t/ha on Raw Minerals Soil. These losses were recorded during a heavy rainfall event lasting 32 hours, with a maximum intensity of 7 mm/h.

KEY WORDS: water erosion, rills, catchment, Oued Aghrouz, soil loss, plots

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1. Introduction

Water erosion is a major environmental and socio-economic threat, adversely affecting water quality, crop yields, land productivity, and long-term ecosystem stability (Duan et al., 2022; Wuepper et al., 2020). Globally, it is considered one of the most alarming challenges due to its widespread impact on food security and agricultural sustainability (Lal, 2003; Ma et al., 2014; Duan et al., 2022). Erosive processes typically manifest in the form of sheet erosion, rill erosion, and gully erosion (Morgan, 2005).

Among these, rill erosion represents a transitional stage between sheet erosion and more advanced forms of concentrated flow erosion, often evolving into gullies under favourable conditions. It plays a pivotal role in the acceleration of sediment transport and soil degradation, particularly on cultivated or bare slopes (Shen et al., 2019). Rills begin as shallow, linear incisions resulting from concentrated surface runoff during heavy rainfall events and are highly sensitive to both environmental conditions and anthropogenic disturbances.

Rills develop as shallow, temporary surface incisions that appear during periods of intense rainfall events. Their formation is attributed to various natural factors such as desiccation cracks, ploughing furrows, collapses caused by suffusion, or remnants of mass movements (Bergsma, 1996; El Karkouri, 2003). However, human activities such as poor land management, the construction of roads and cattle tracks, and unprotected access paths also contribute significantly to their formation (Alemu et al., 2018; Montgomery, 1994; Wemple et al., 1996).

These rills typically appear when rainfall intensity exceeds the soil's infiltration capacity, resulting in concentrated runoff. They can reach depths of several tens of centimetres and are especially common in autumn or early winter when rainfall events are both abundant and intense (Govers et al., 2007; Abahrour, 2009; Di Stefano et al., 2022; Zhao et al., 2024).

The morphology and evolution of rills are governed by multiple factors, including lithology, slope gradient and length, surface roughness, and vegetation cover (Tribak, 2000). Over time, persistent rainfall may deepen and widen rills, potentially causing the collapse of their sidewalls and transforming them into more stable incipient gullies. As emphasized by Huang et al. 2025 understanding the mechanisms of sidewall collapse is critical to modelling this transition and anticipating sediment dynamics in vulnerable landscapes. However, certain practices, such as deep ploughing and frequent cattle movement, can reduce their impact (Faleh, 2004; Abahrour, 2009; El Karkouri, 2003).

Rill erosion has severe implications for soil heritage, notably through the loss of fertile topsoil and essential nutrients (Hancock et al., 2008; Cui et al., 2022). This degradation often results in declining crop yields and, in some cases, the abandonment of degraded agricultural lands (Abahrour, 2009).

In Morocco, sheet erosion has been extensively assessed using various methods, particularly the RUSLE model and direct field methods (Abahrour, 2009; El Karkouri, 2003; Amhani, 2022). In contrast, the evaluation of rill erosion remains largely under-explored.

In this context, the present study aims to: (1) identify the key environmental and topographic factors that control rill initiation and development in the marl-dominated Oued Aghrouz catchment (northern Morocco); (2) quantify soil losses caused by rill erosion during a specific extreme rainfall event lasting 32 hours with a peak intensity of 7 mm/h; and (3) assess the spatial variability of rill distribution across 12 experimental plots, to better understand how concentrated runoff contributes to localized erosion processes.

2. Study area

The Oued Aghrouz is a tributary located on the right bank of the Oued Inaouène, within the south-eastern Prerif region of Morocco. The study area is situated west of the city of Taza, between latitudes 34.18° and 34.30° North and longitudes 4.20° and 4.26° West (Fig. 1). This tributary drains a catchment covering an area of 41 km^2, characterized by lithology predominantly composed of marl formations.

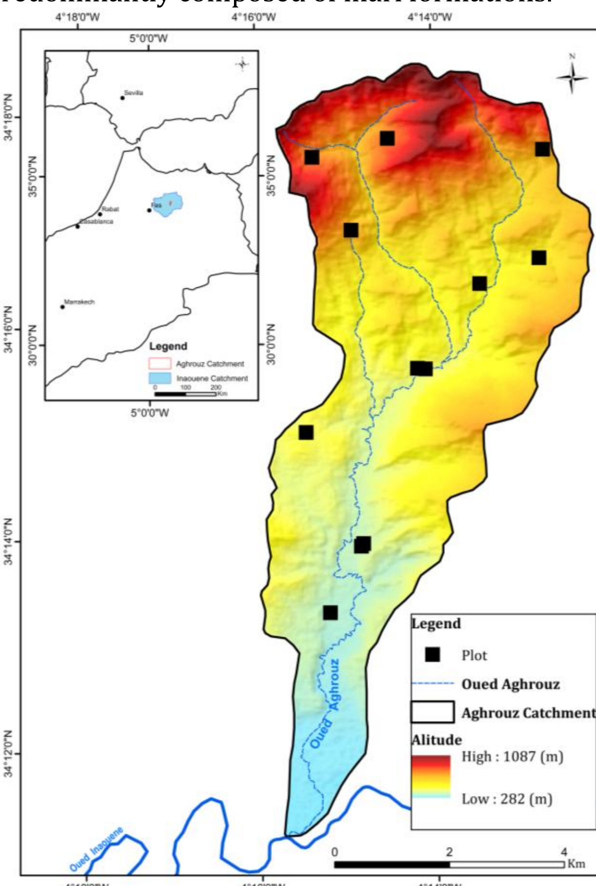

Fig. 1. Geographical location of the catchment of the Oued Aghrouz

The morphology of the territory is marked by gently rounded hills separated by wide and deeply incised valleys. The elevation ranges from a peak at 1,087 meters, located at Jebel Errouda, to the lowest point at 282 meters, at the confluence of the Oued Aghrouz with the Oued Inaouène. This topography endows the region with a complex hydrographic structure and offers significant research potential within the framework of geographical and hydrological studies.

From a geological perspective, the region's substrate is predominantly composed of friable and impermeable Miocene marls, which account for 54% of the lithology, along with Eocene flysch formations covering 34%. This composition promotes the development of a dense hydrographic network, characteristic of areas with impermeable and friable substrates.

Climatically, the catchment is situated within a Mediterranean regime with Atlantic influences, typical of the southern Rif corridor. It falls under a semi-arid bioclimatic zone, with average annual rainfall ranging between 540 mm and over 600 mm, depending on the location and year. Precipitation is concentrated mainly between January and March, which are the rainiest months. In terms of temperature, January and February are the coldest months, while July and August mark the hottest periods. These climatic conditions significantly influence the hydrological and ecological dynamics of the region.

A mix of extensive rangelands, cultivated plots, fallow lands, and small wooded patches characterise the land cover and land use within the Oued Aghrouz catchment. Agriculture is predominantly rainfed and seasonal, with cereal crops and legumes being the most common. The upper slopes are largely degraded and exposed, offering minimal vegetation cover, which increases their vulnerability to erosion. Grazing pressure is notable, especially on the steeper slopes, further contributing to vegetation depletion. The valley bottoms, on the other hand, are more intensively cultivated and may benefit from slightly higher moisture retention. The absence of permanent vegetation and the seasonal nature of cultivation significantly influence runoff concentration and rill formation during heavy rain events.

3. Data collection

To evaluate soil losses caused by the storm of December 14–15, 2022, in the Oued Aghrouz catchment, a field-based study was conducted using 12 representative plots. These plots were selected to reflect the variability in lithology, slope gradient, land use, and soil type across the catchment. Each plot had the same surface area of 500 m^2 (10 m × 50 m), ensuring data comparability and spatial representativeness.

The plots were distributed as follows:

- Mid-zone: Three plots (P1, P2, P3) were installed on vertisols with marl substrates, while two plots were placed on raw mineral soils, one on fallow land (P10) and the other on plooughed terrain (P6).
- Downstream zone: Three plots (P5, P7, P8) were located on weakly developed soils in fallow and ploughed lands resting on alluvial substrates, and one plot (P4) was installed on isohumic soils cultivated with cereals on a marl substrate.
- Upstream zone: Two plots (P9, P11) were placed on calcimagnesic soils in areas of arboriculture (olive groves), and one plot (P12) on ploughed soils. (Fig. 2).

All the visible rills present on the plot were identified and measured exhaustively, without selective sampling, best to represent all the erosive processes active on the plot. The length (L) of each rill was measured along its actual course, from its point of departure (upstream) to its downstream point or its point of confluence with another rill, following its natural sinuosity, as these forms are generally not rectilinear. However, to improve accuracy, we first measured the average width of each rill section, then calculated the overall mean width from all measured sections. This approach helps to reduce potential over-estimation by integrating field-based measurements rather than relying on a fixed or assumed width. The width (l) and depth (P) were measured every 10 cm along the length of each rill. From these measurements, specific averages for each rill were calculated to obtain more accurate estimates. The volume of soil loss per rill (Vr, in cm^3) was calculated using the following formula:

$$\mathrm{Vr}\ (\mathrm{cm}^3) = \mathrm{l.\,L.\,P}$$

The total soil loss per plot (Vt) was calculated by summing the volumes of all individual rills:

$$\mathrm{Vt} = \sum \mathrm{Vr}$$

Quantifying soil loss first requires determination of the bulk density using the oven-drying method. Samples were collected using a 269.255 cm^3 cylinder (h = 7 cm; r = 3.5 cm), then dried at 105°C for 24 hours before taking measurements. Soil loss in tonnes per hectare was then estimated using the equation:

$$P\ (t/ha) = Vt * DA/S$$

Where:
P: Soil loss in tonnes per hectare (t/ha)
Vt: Total soil loss volume per plot (cm^3)
DA: Bulk density of the soil (g/cm^3),
S: Plot surface area (ha)

Rill density (Dr), defined as the total rill length per unit area (m/m^2), was calculated following LEMMA ET AL. (2017):

$$\mathrm{Dr} = L/S$$

Where:
L: Total rill length in the plot (m)
S: Plot area in m^2 (500 m^2)

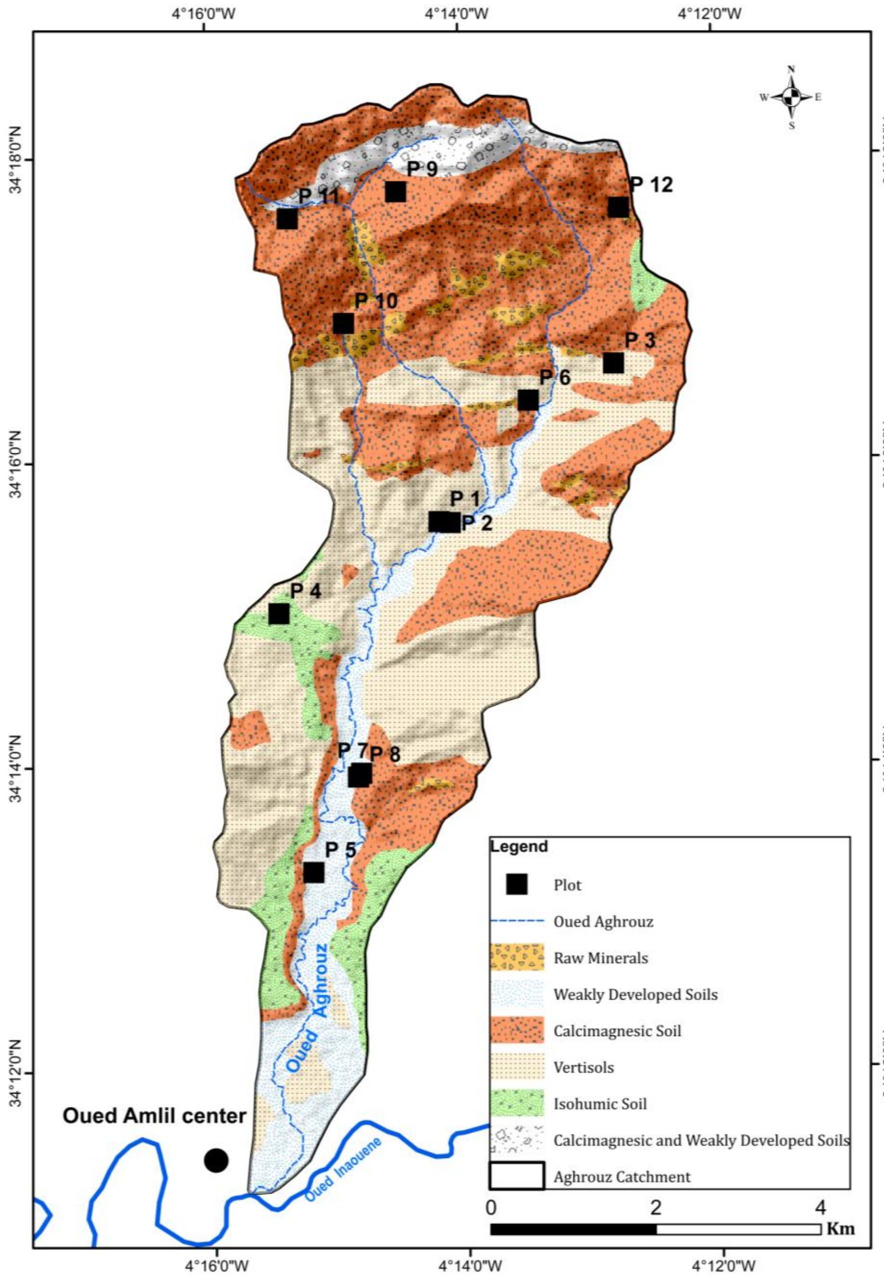

Fig. 2. Distribution of plots based on soil type in the Oued Aghrouz catchment area

3.1. Soil analysis

The physical and chemical properties of the soil were analysed for each plot. The parameters measured included porosity (%), determined using the gravimetric method, and soil texture, defined by granulometric analysis and expressed as the percentage of sand, silt and clay. Finally, the organic matter content (OM%) was calculated using the calcination method (loss on ignition).

3.2. Statistical analysis

A statistical analysis was conducted to explore the relationships between soil loss and contributing factors such as slope, rill density, porosity, and organic matter. Pearson correlation coefficients were calculated using Statgraphics XVII X64 for Windows (https://www.statgraphics.com/download-statgraphics-centurion-xvii), with a significance threshold of $p < 0.05$. The statistical results were interpreted in conjunction with field observations to identify key explanatory variables and interactions.

4. Results and discussion

4.1. The Impact of precipitation on rill formation

4.1.1. Meteorological conditions

Precipitation, along with the resulting runoff, is a key driver in rill development (Yan et al., 2024). The rainfall event of December 14–15, 2022, in the Oued Aghrouz catchment caused significant degradation. Before this date, no rills were observed in the study area, highlighting the exceptional impact of this meteorological event. Due to the extensive damage caused, this precipitation can be classified as unusual. The rill formation rapidly expanded on a large scale, generating significant impacts on the landscape and soil.

Meteorological analyses revealed that a period of atmospheric stability prevailed until December 13, 2022, under the influence of high atmospheric pressure. However, instability set in from midnight onwards (Fig. 3 and 4). This instability was caused by the anticyclone's southwesterly displacement and the formation of a cold front over the North Atlantic Ocean. This front, resulting from the interaction of warm tropical maritime air masses with cold polar air masses, allowed polar disturbances to reach Moroccan territory (Bahou, 2002). This event particularly affected the northern and central regions, producing significant rainfall. These conditions intensified hydrological erosion processes, promoting rill formation in vulnerable areas of the catchment.

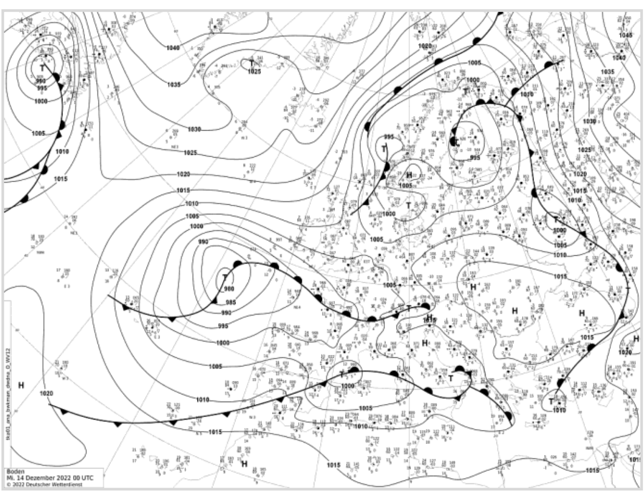

Fig. 3. Surface meteorological conditions on December 15, 2022 (Source: https://www1.wetter3.de)

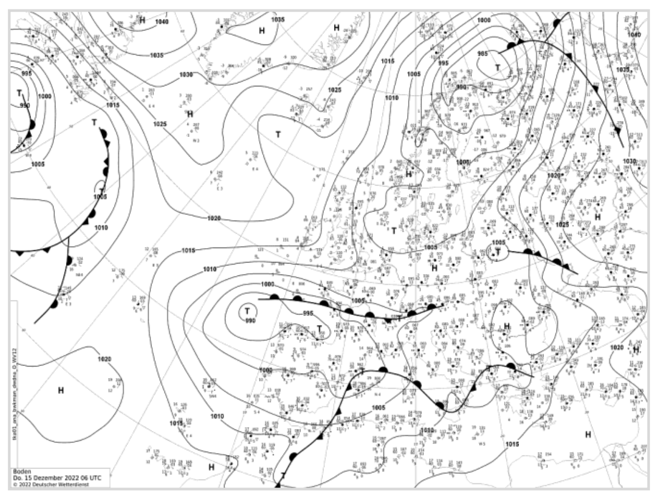

Fig. 4. Surface meteorological conditions on December 14, 2022 (Source: https://www1.wetter3.de)

4.1.2. Total precipitation evolution during the depressive episode

The study area was impacted by an atmospheric depression that caused continuous rainfall over 32 hours before a return to stable meteorological conditions (Fig. 5).

Rainfall began on December 14 at 2:00 PM, with an initial downpour of 5 mm recorded in the first hour. The intensity increased in the following hour, reaching a peak of 7 mm/h, the highest value for this event. During the first three hours, cumulative rainfall reached 17.5 mm. The precipitation continued uninterrupted until the end of the day, with a total of 45 mm recorded over 10 hours, corresponding to an average intensity of 4.5 mm/h.

After a four-hour break, rainfall resumed and persisted for an additional 14 hours. On the second day (December 15), 41 mm of precipitation was recorded.

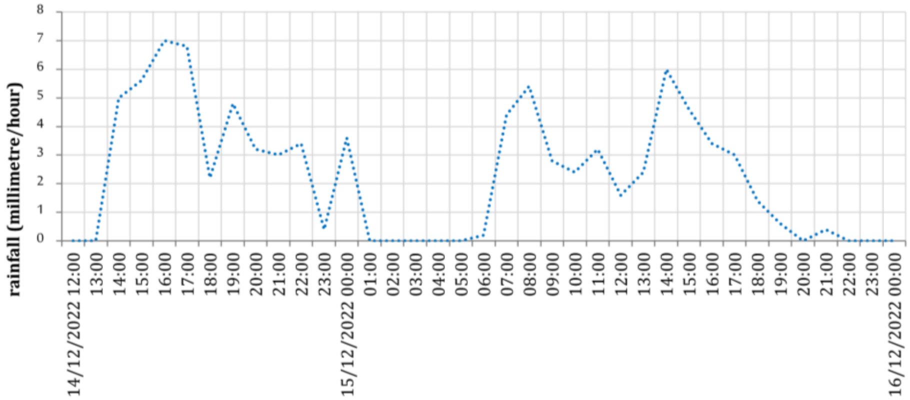

Fig. 5. Temporal variation in precipitation on December 14 and 15, 2022, at Oued Amlil station

Thus, the depressive episode consisted of 10 hours of continuous rainfall on the first day, followed by 14 hours of rain on the second day, resulting in a total of 86.8 mm over 32 hours.

This prolonged rainfall over more than a day align with the observations of TRIBAK (2000), who noted that significant rill formation is often associated with continuous precipitation over at least two consecutive days in late autumn or early winter. This configuration promotes soil saturation and intense surface runoff, amplifying hydrological erosion processes and rill formation in vulnerable areas.

4.2. The contribution of slope to rill formation

Slope is a key morphometric factor influencing surface runoff behaviour, flow velocity, and thus the intensity of rill erosion. In the Oued Aghrouz catchment, the development of rills was primarily observed on slopes exceeding 6°, with the highest rill densities recorded on very steep terrain, particularly those above 35° (Fig. 6).

For example, plot P6, situated on a 38° slope, experienced the highest soil loss in the study (151.13 t/ha), along with a rill density of 2.92 m/m^2. The combination of steep gradient, low organic matter content, and poor soil structure enhanced flow velocity, promoting both detachment and transport of fine particles.

However, while steep slopes often correlate with increased erosion, the relationship is not always linear or exclusive. In some cases, gentle slopes may also exhibit high soil losses depending on other factors such as land use, surface sealing, and rainfall characteristics. For instance, plot P3, located on a 33° slope, recorded a soil loss of 85.76 t/ha. In contrast, plot P4, on a gentler slope but with low bulk density and surface crusting, showed significant incision depth (24 cm), despite a relatively low rill density (0.36 m/m^2). These findings are consistent with the work of HEUSCH (1969) in the Sebou catchment, who observed that erosion intensity does not always increase with slope due to compensating effects such as improved infiltration or higher vegetation density on steep terrains.

Moreover, TRIBAK (2000) emphasized that rill erosion becomes notable when slope gradients exceed 10%, and intensifies with increasing slope steepness, especially when combined with bare or disturbed soil surfaces. Similarly, BERGSMA (1996) reported that rills typically emerge on slopes ranging between 2° and 12°, and may intensify rapidly beyond this threshold, particularly in the presence of continuous rainfall and insufficient vegetative cover.

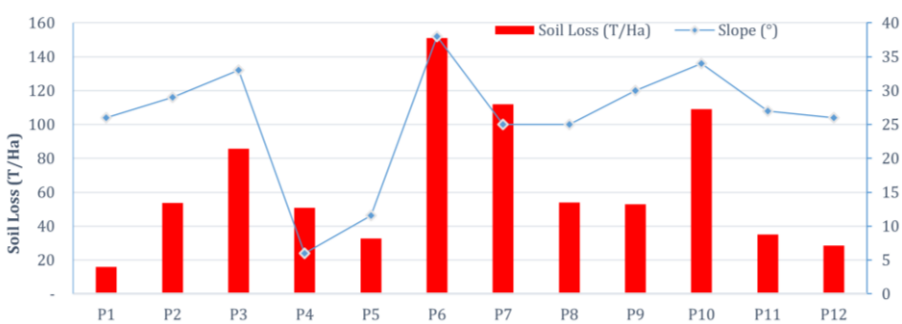

Fig. 6. The quantity of soil lost on the plots studied as a function of slope

Overall, the results of this study underscore that while slope is a critical factor in rill development, its effect is modulated by a complex interplay of soil properties, land use practices, and rainfall intensity. The observed heterogeneity between plots confirms that no single variable can fully explain the spatial variability of rill erosion in Mediterranean semi-arid environments.

4.3. The role of land use in rill development

4.3.1. Cultivated lands

Cultivated lands exhibit high levels of soil loss, with values ranging from 35 t/ha to 151 t/ha and an average of 74.5 t/ha. These levels are concerning, as ploughing amplifies several processes that increase erosion: it creates open spaces, fragments soil particles, increases porosity, and reduces bulk density. These changes weaken the soil's resistance to water erosion. Additionally, ploughing creates surface roughness, which, while it can temporarily slow runoff by retaining water, becomes vulnerable during continuous rainfall. Prolonged precipitation leads to the formation of surface crusts, reducing permeability and increasing surface runoff, thus promoting rill formation (Roose, 1994).

The variability of erosion observed on cultivated land also depends on several interdependent factors, including the direction and method of ploughing (parallel or perpendicular to contours), ploughing methods and timing, timing of tillage with rainfall, ploughing methods and timing, tools and techniques used, and the physical and chemical properties of the soil. Freshly ploughed lands, particularly susceptible to runoff, displayed heightened vulnerability during the 2022-2023 agricultural season. In contrast, unploughed lands maintain higher bulk density, which partially limits soil losses.

Plot 8, which was not ploughed during the season, showed a relative decrease in erosion compared to the adjacent plot 7 (Fig. 7), which was ploughed. Specifically, ploughed lands oriented perpendicular to contour lines (plot 7) recorded losses of up to 112 t/ha, with an average rill loss of 3.5 t/ha (Fig. 8). Perpendicular ploughing encourages water accumulation in furrows, which develop into rills proportional to the number of ploughing lines, transporting significant sediment downstream as deposition cones. Despite similar slope and soil characteristics, plot 8 recorded lower losses (53.9 t/ha) due to its reduced porosity, which offered greater resistance to runoff.

These results confirm that cultivated lands, especially when poorly managed, are the most erosion-prone land use type, particularly during early-season rainfall events. The presence of long furrows acts as preferential flow paths that enhance runoff concentration, accelerating rill development and sediment export.

Fig. 7. The evolution of rills on land that has not yet been ploughed during the new agricultural season (photo by M. Afenzar, 17/12/2022)

Fig. 8. Transformation of ploughing into furrows on land cultivated in parallel lines opposite the contour lines (photo by M. Afenzar, 17/12/2022)

4.3.2. Fallow lands

Fallow lands recorded moderate levels of rill erosion, with soil losses ranging from 15.9 t/ha to 109.2 t/ha and an average of 46.59 t/ha. Although these lands are not ploughed, their compaction due to repeated grazing and trampling results in high bulk density values (between 1.42 g/cm^3 and 1.6 g/cm^3), which reduce infiltration and promote surface runoff.

However, this compaction also acts as a protective factor, limiting the depth and width of rills and thus reducing sediment volume. For instance, plot 5 (fallow land) recorded a moderate soil loss of 32.7 t/ha, with rills that were shallow and short. These observations are supported by previous studies (Abahrour, 2009; El Karkouri, 2003), which showed that while fallow lands are prone to diffuse runoff, they experience lower soil detachment compared to cultivated lands.

Nevertheless, it is worth noting that in the absence of vegetative cover or ploughing, prolonged exposure of fallow lands to rainfall may lead to the gradual deepening of rills and, over time, the transition to gully formation, particularly on steep or convex slopes (Tribak, 2000). As noted by Laouina et al. (2010), biomass presence on fallow lands may reduce erosivity, but the lack of infiltration capacity and compaction by livestock still make them vulnerable to initial forms of erosion, especially under storm conditions.

4.4. The role of soil type in rill development

Field observations revealed that soil loss varies according to several factors, including soil type, land use patterns, physico-chemical properties, surface conditions, and slope morphology. On vertisols, plot P1 recorded the lowest rill density and minimal erosion. This outcome can be attributed to its relatively high bulk density (1.42 g/cm^3) and lower porosity compared to other plots with the same soil type. Additionally, plot P1 is notable for its organic matter content of 3.1% (Table 1). which enhances soil particle cohesion and significantly reduces erosion. These conditions resulted in the formation of seven rills confined to a narrow area, with an average depth of 6.5 cm and a width of 7 cm.

Table 1. Summary of the characteristics of the studied plots

Plot	Bulk density (g/cm^3)	Porosity (%)	OM (%)	Sand (%)	Silt (%)	Clay (%)
P1	1.42	47.21	3.1	18.3	41.4	40.6
P2	1.24	53.90	2.5	11.3	41.1	47.1
P3	1.12	58.36	2.1	14.6	40.5	48.3
P4	0.97	63.50	2.7	34.2	48.6	17.2
P5	1.60	40.52	2.6	32.3	48.6	19.1
P6	1.40	47.96	0.7	36.0	43.0	21.0
P7	1.02	62.08	2.1	29.4	46.3	24.3
P8	1.50	44.24	2.1	29.4	46.3	24.3
P9	1.02	62.08	2.8	43.4	39.3	30.3
P10	1.60	40.52	0.9	32.0	40.0	24.0
P11	1.20	55.39	2.8	46.4	28.3	25.3
P12	1.60	40.52	2.7	49.4	33.3	27.3

In contrast, plot P3 exhibited a marked increase in erosion, with a rill density of 2.72 m/m^2 and a main rill measuring 17.30 metres in length. This dynamic is explained by a reduced bulk density (1.12 g/cm^3) due to ploughing, which makes the soil particularly vulnerable. While this reduction initially increases permeability, heavy rainfall or prolonged saturation promotes intense runoff. Furthermore, the steep slope of 33° amplifies flow velocity, intensifying erosion. The textural composition of this soil, dominated by fine particles (clay and silt comprising 88.9%), also contributed to a high volume of solid load.

On weakly developed soils, plot P5 recorded the lowest erosion level. This resilience can be attributed to a high organic matter content and a high bulk density (1.6 g/cm^3). These observations align with the findings of TRIBAK (2000) and ABAHROUR (2009), who demonstrated that increased bulk density reduces rill depth, thereby limiting erosion while accelerating runoff.

Calcimagnesic soils showed the lowest soil loss among all studied soil types, with an average of 38.8 t/ha. This low erosion is linked to a high proportion of sand (over 43%), which increases permeability and limits surface runoff. Plot P9 exemplifies this dynamic, recording a very low rill density (0.13 m/m^2). Additionally, as noted by ABAHROUR (2009), these soils contain a significant proportion of calcium carbonate, which enhances their resistance to erosion.

Conversely, on raw mineral soils, losses ranged from 109.2 t/ha in plot P6 to 151.13 t/ha in plot P10. These high values are associated with greater rill density (2.9 m/m^2). Several factors explain these results, including the steep slopes of plots P6 and P10 (over 30°), low organic matter content (0.9%), and a high clay proportion (over 40%) in these soils. These combined conditions result in rapid erosion and increased mobilization of fine particles.

4.5. Quantification of soil lost by rill erosion

The studied catchment recorded an average soil loss due to rill erosion estimated at 64.9 t/ha, indicating a significant erosive impact. However, this average masks substantial variability between plots, with values ranging from 15.9 t/ha in plot P1 to a maximum of 151.13 t/ha in plot P6 (Table 2). Rill characteristics varied notably across sites: the maximum average width recorded was 23 cm, and the maximum average depth reached 21 cm.

Rill density also showed wide variation, with the highest number of rills observed in plot P6 (2.92 m/m^2), reflecting intense surface incision processes. Conversely, plot P11 recorded the lowest density (0.14 m/m^2). Across the catchment, the mean rill density was 1.13 m/m^2, highlighting the spatial heterogeneity of erosion processes driven by land use, soil properties, and topography.

Table 2. Soil loss by rill erosion of the studied plots

Plot	Soil type	Land use	Soil loss (t/ha)	Density (m/m^2)	Avg. depth (cm)	Standard deviation	Avg. width (cm)	Standard deviation	Avg. length (m)	Standard deviation
P1	Vertisols	Fallow land	15.94	0.56	6.50	1.15	7.05	1.4	11.0	2.2
P2	Vertisols	Cultivated lands	53.87	1.60	7.60	1.3	6.30	0.9	17.0	1.2
P3	Vertisols	Cultivated lands	85.76	2.72	10.00	1.8	9.00	2.05	17.0	2.6
P4	Isohumic soil	Cultivated lands	50.80	0.36	24.00	3.1	19.00	3.7	10.0	1.7
P5	Weakly developed soils	Fallow land	32.70	1.00	7.17	1.5	7.00	1.3	10.0	0.3
P6	Raw minerals soil	Cultivated lands	151.13	2.92	15.00	2.9	15.00	2.5	17.0	0.8
P7	Weakly weveloped soils	Cultivated lands	112	1.70	21.00	4.01	15.00	3.8	50.0	2.5
P8	Weakly developed soils	Cultivated lands	50.80	0.36	8.00	1.23	18.00	3.7	50.0	1.1
P9	Calcimagnesic soil	Cultivated lands	53	0.60	11.00	1.9	11.20	1.7	43.0	7.9
P10	Raw minerals	Fallow land	109.20	1.30	14.00	1.2	16.00	1.5	23.0	0.7
P11	Calcimagnesic soil	Cultivated lands	35.10	0.14	12.00	3.01	23.00	2.5	21.0	3.01
P12	Raw minerals soil	Fallow land	28.50	0.21	9.30	1.33	18.60	2.4	35.0	2.5

These values are comparable to those recorded by Abahrour (2009) in the Oued Tleta catchment (Eastern Prérif), where heavy rainfall in November 2004 caused a loss varying between 53.5 and 140 t/ha. Furthermore, the results of measurements carried out by El Ommal in the Oued Sra basin (Central Rif) reveal an erosion rate of 35 t/ha during a very intense rainfall event (El Ommal, 2021). In a study carried out in the Oued Lahdar catchment, located in the Eastern Prérif region, it was found that the quantities of soil evacuated amounted to 73 t/ha (Amhani , 2022).

4.6. Statistical analysis of the relationship between soil loss and contributing factors

The statistical analysis of the results highlights the complexity of interactions between various indicators and variables influencing soil loss distribution. These factors, including soil types and land use, require detailed interpretation to understand their respective contributions. To clarify these interactions, the correlation coefficients between controlling factors and soil loss were analysed.

Organic Matter (OM): A strong negative correlation (R=−0.88, p-value = 0.0001) was observed between soil loss and organic matter content. This confirms that increased organic matter significantly reduces soil loss, consistent with findings by Roose et al. (1993). Soils rich in organic matter exhibit more stable aggregates, lower bulk density, and enhanced resistance to erosive rainfall (Zhao et al., 2024; Burylo et al., 2012; Zhang et al., 2015; Wang et al., 2018).

Rill Density (DR): A strong and significant positive correlation (R=0.80, P-value = 0.002) was identified between rill density and soil loss. This result confirms that areas with high rill density experience increased erosion.

Slope: Slope showed a significant positive correlation with soil loss (R=0.60, P-value = 0.03). Steeper slopes amplify erosion by increasing flow velocity and intensity, consistent with findings by Bryndal et al. (2017), Guo et al. (2019), and Cui et al. (2022).

Porosity: A significant negative correlation was recorded between porosity and rill incision capacity (R=−0.67, p-value = 0.02). On the other hand, a positive, but non-significant, correlation was observed between porosity and organic matter. This indicates that soils with higher porosity allow for deeper infiltration, reducing erosion intensity. This phenomenon was particularly evident in plot 4, where lower bulk density facilitated increased infiltration. This has been corroborated by Zhang et al. (2008), Li et al. (2015), and Geng et al. (2021).

Other factors: Correlations with soil texture (clay, sand, and silt) and rill width were not statistically significant (p-values > 0.05), although they may indirectly influence erosion dynamics under specific local conditions.

These results highlight the crucial influence of organic matter, rill density, slope, and porosity on soil loss. Organic matter, in particular, acts as a major protective factor, while rill density and topography significantly intensify water erosion processes.

5. Conclusions

This study demonstrates that rill erosion constitutes a significant mechanism of soil degradation in the Oued Aghrouz catchment, particularly under the influence of early-season storm events. The rainfall episode of December 14–15, 2022, which accounted for over 17% of the annual precipitation, triggered substantial rill formation across cultivatedand fallowlands.

The findings indicate significant spatial variability in erosion intensity, with soil losses ranging from 15.9 to 151.13 t/ha, contingent on soil type, land use, slope gradient, and the physical and chemical characteristics of soils. The development of rills was predominantly observed on slopes exceeding 6°. The highest recorded rill densities were found in terrains of a gradient greater than 35°. Calcimagnesic soils with high sand content demonstrated the lowest levels of loss, while raw mineral soils on steep slopes exhibited the highest susceptibility due to their fine texture and low cohesion.

Land use emerged as a key driver, with cultivated lands showing significantly higher rill density and soil loss than fallow lands. Poor tillage practices, such as ploughing perpendicular to contour lines, amplified erosion by creating preferential flow paths and sediment accumulation zones.

While this study focused on rill-scale processes, field observations suggest that some incisions may represent the initial stages of gully development, especially where rills exceed 30 cm in depth and show signs of lateral expansion. However, in the absence of sustained incision and bank collapse, these features were conservatively categorized as rills. Further work is needed to refine the criteria for rill–gully transition thresholds in similar geomorphological contexts.

This study highlights the impact of human interventions on accelerating water erosion in the Oued Aghrouz watershed. Sustainable land management, based on adapted agricultural methods, could reduce these impacts and contribute to soil preservation. Conversely, inappropriate practices exacerbate soil degradation, worsening issues related to water erosion.

The results underline the importance of targeted strategies to reduce soil degradation in vulnerable areas. They highlight the need to combat water erosion in rural areas by adopting an integrated approach that takes account of environmental, social, and economic issues to protect the land and improve living conditions. For sustainable solutions, involving farmers in decision-making and strengthening research and institutional partnerships are essential.

This contribution provides relevant information on rill erosion, useful for the effective management of catchment correction and stabilisation projects. It also opens up new research prospects that could be extended to similar topics, such as sheet erosion and the potential transfer of sediments downstream, particularly towards the Idris I dam.

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