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Research article

Using Simulated Rainfall to Assess Water Erosion in the Aghrouz Watershed (Southern Rif, Morocco)

Uso de chuvas simuladas para avaliar a erosão da água na bacia hidrográfica de Aghrouz (Rif do Sul, Marrocos)

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Abstract: Water erosion is one of the most critical environmental problems of our time, posing a major threat to sustainable development. Various factors influence its appearance and progression, including soil properties, topography, geology, climate, and land use. This has a major impact on ecosystems, agriculture, and infrastructure. This research aims to analyse the risks of runoff and erosion in the Aghrouz Watershed (Northern Morocco prefecture) using a one-square-meter manual ramp irrigator. This study explores the linkages between factors influencing infiltration and runoff, taking into account soil typology, and also seeks to quantify soil loss according to different land occupations. Rain simulation tests reveal that the highest infiltration volumes (maximum: 77.44 mm/h) are recorded on machined plots. In contrast, abandoned plots have the lowest infiltration rates (minimum: 17.6 mm/h), while land in dirt shows intermediate values. Furthermore, measures of solid load depending on the type of land occupation reveal that ploughed plots have a high turbidity of up to 140 g/l in the autumn compared to other types of occupation. These results highlight the importance of water erosion and sedimentation in these areas. The study represents a very important scientific contribution to the field of geomorphology, hydrology, and the study of natural hazards. The results can help prioritize areas for intervention in erosion control.

Keywords: Erosion, Runoff, watershed, Aghrouz River, simulation.

Resumo: A erosão hídrica é um dos problemas ambientais mais críticos da atualidade, representando uma grande ameaça ao desenvolvimento sustentável. Vários fatores influenciam seu surgimento e progressão, incluindo as propriedades do solo, a topografia, a geologia, o clima e o uso da terra. Isso tem um grande

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impacto sobre os ecossistemas, a agricultura e a infraestrutura. Esta investigação tem por objetivo analisar os riscos de escoamento e de erosão na bacia do Aghrouz (província do Norte de Marrocos), utilizando um irrigador manual de rampa de um metro quadrado. Este estudo explora as relações entre os fatores que influenciam a infiltração e o escoamento superficial, tendo em conta a tipologia do solo, e procura também quantificar a perda de solo em função das diferentes ocupações do solo. Os ensaios de simulação de chuva revelam que os volumes de infiltração mais elevados (máximo: 77,44 mm/h) são registados nas parcelas trabalhadas. Em contrapartida, as parcelas abandonadas apresentam as taxas de infiltração mais baixas (mínimo: 17,6 mm/h), enquanto os terrenos em terra batida apresentam valores intermédios. Além disso, as medidas de carga sólida em função do tipo de ocupação do solo revelam que as parcelas lavradas apresentam uma turbidez elevada, que pode atingir 140 g/l no outono, em comparação com outros tipos de ocupação. Estes resultados evidenciam a importância da erosão hídrica e da sedimentação nestas zonas. Este estudo representa uma contribuição científica muito importante para o campo da geomorfologia, da hidrologia e do estudo de riscos naturais. Os resultados podem ajudar a priorizar áreas para intervenção no controle da erosão.

Palavras-chave: Erosão, escoamento superficial, bacia hidrográfica, Rio Aghrouz, simulação.

1. Introduction

Water erosion is a natural and universal phenomenon that contributes to soil degradation (Afenzar *et al.*, 2025; Achiban, 2020; Bou Kheir *et al.*, 2001; Valentin *et al.*, 2005). It is characterized by the detachment and transportation of soil particles from the top to the bottom (Ludwig, 2000). Its evolution is influenced by various natural and anthropogenic factors. It is one of the most complex environmental problems (Lal, 2001) that threatens ecosystems (Yang *et al.*, 2003), agricultural land productivity (Duan *et al.*, 2022), human health, water quality (Wuepper *et al.*, 2020), flood risk, and dam depletion (Lal, 1998; Cheggour *et al.*, 2008), with adverse consequences for the environment and human beings (Yang *et al.*, 2003).

In northern Morocco, the Rif region has undergone significant degradation (Sadiki, 2005), making it vulnerable to water erosion (Tribak *et al.*, 2012). Specific degradation potential exceeds 2,000 $t.km^{-2}.an^{-1}$ in the Rif slopes to the north and between 500 and 1,000 t. km-2.ann-1 in the Middle and Upper Atlas (Ghanam, 2003). Moreover, although the Rif mountains account for only 6% of the national territory, they record 60% of the volume of eroded sediment (Heusch, 1970).

The study of problems related to water erosion requires a precise understanding of soil permeability, thresholds to trigger the spill, the amount of water spilled, and, consequently, the solid load transported (Marston & Dolan, 1999; Morgan *et al.*, 1997). Monitoring of runoff and infiltration during natural precipitation poses great difficulties due to their long duration (Collinet & Lafforgue, 1979; Leonard & Andrieux, 1998). This is why the use of a rain simulator allows us to control the amount of precipitation and to obtain many scientific data directly in the field in an experimental manner in a shorter time, thus facilitating the study of the factors explaining the phenomenon of runoff and permeability (Casenave & Valentin, 1989).

Numerous studies have focused on the links between the risk of water erosion and various indicators measured by the rain simulator, such as soil surface condition, organic matter, initial humidity and soil occupation. Among these studies are Lafforgue (1977), Asseline & Valentin (1978), Collinet & Lafforgue (1979), Casenave (1982), Casenave & Valentin (1989), Marston & Dolan (1999), Morgan *et al.* (1997), Asseline (1997), Roose (1996), Cheggour *et al.* (2008), Abahrour (2009), Amhani (2022), Arari (2022), and El-Ommal (2023). These studies have shown that water erosion is strongly influenced by soil surface conditions. Crusting promotes runoff, while roughness and porosity increase infiltration. Organic matter and initial soil moisture reduce erosion by stabilizing aggregates and improving infiltration, which in turn reduces runoff turbidity and soil detachability. Finally, soil cover (vegetation, residues, etc.) significantly reduces soil loss by intercepting precipitation and improving infiltration, thus limiting soil degradation.

This paper aims to experimentally analyze the dynamics of runoff, infiltration, and solid transport using a manual ramp rainfall simulator. It explains the relationships between the factors controlling infiltration and runoff as a function of soil typology in the Aghrouz Watershed. It aims to highlight the effects of land use on soil infiltration capacity, taking into account surface conditions and soil properties.

2. Study Area

Aghrouz River is an affluent of the right bank of the Inaouène River, it drains part of the southern eastern Prefecture of Morocco to the west of the city of Taza between the latitudes 34,18° and 34,30° North and the longitudes 4,20° and 4,26° West (Fig. 1). It covers an area of 41 km^2. The area is characterized by the presence of hills of less elongated shape, separated by wide and deep valleys with a peak of 1,087 m at J. Errouda and a lowest point of 282 m at its confluence with the Inaouène River.

From a geological point of view, the lithology of the substrate is mainly composed of frail and waterproof marshes of the Miocene (54%), as well as flysches of the Eocene (34%), resulting in a highly developed hydrographic network.

In addition, the climate of the Watershed is of a Mediterranean type with Atlantic influence. It is situated in conditions of semi-arid bioclimate. The average annual rainfall for the period 1978–2021 ranges from 493 mm at the Oued Amlil station to 651 mm at Had Msila station. The rainy months are January and March. The coldest months are January and February, and the warmest months are July and August.

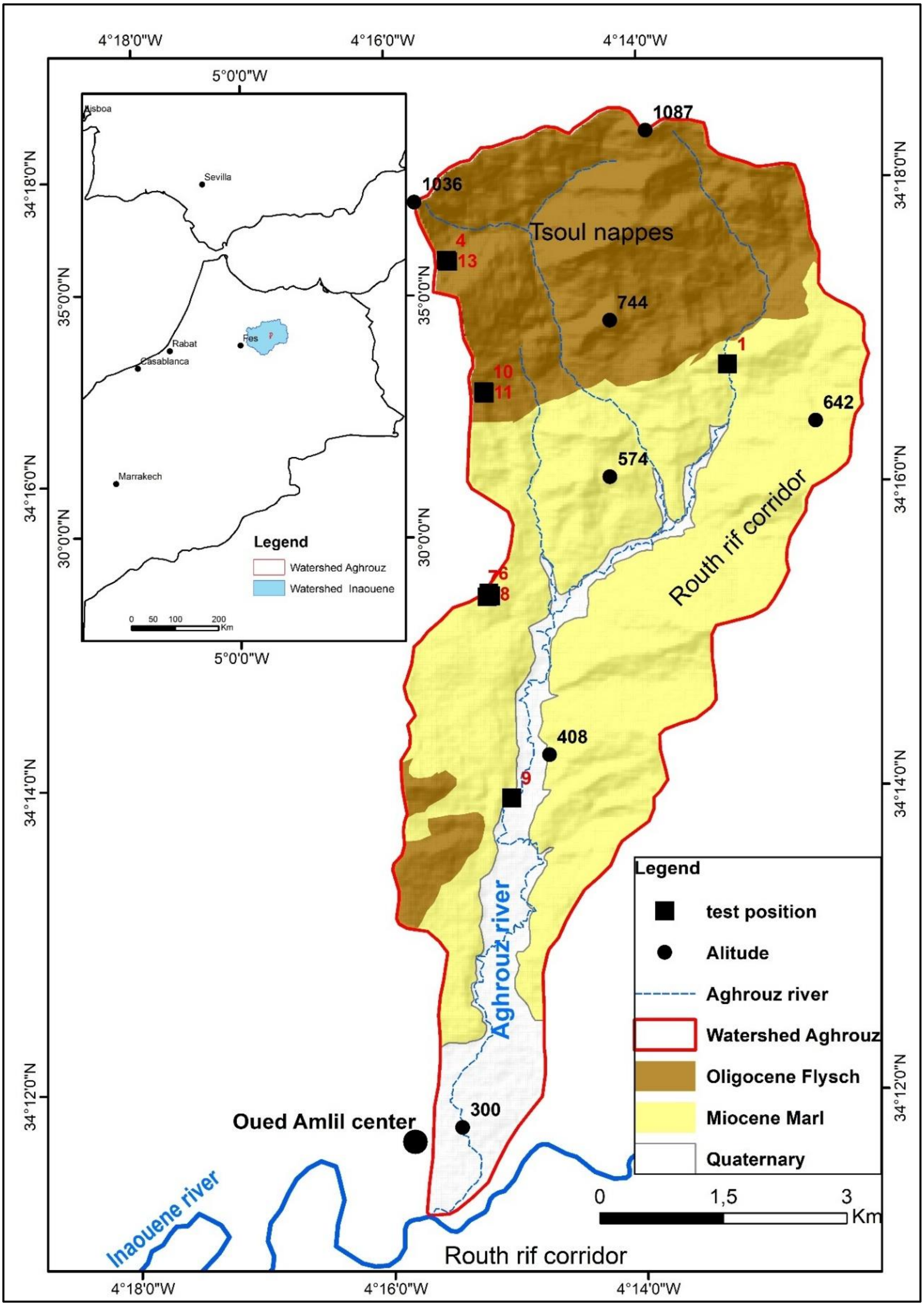

Figure 1. Geographical location of the Aghrouz River Watershed.

Figura 1. Localização geográfica da bacia hidrográfica do rio Aghrouz.

3. Materials and Methods

The device used in this study is a manual ramp irrigation simulator, which has been simplified (Roose, 1996; Roose & Smolikowski, 1997). It consists of generating artificial rain on a plot to measure the runoff and the associated soil losses (Barthès *et al.*, 1998). This simulator is based on a version developed by Asseline and Valentin (1978), and it allows it to be used on different slopes with a small amount of water (60 litres). The tests were carried out on a 1 m² plot delimited by a metal frame (1,66 m long, 0,60 m wide), and the irrigation system had an intensity of 80 mm/h (Fig. 2, A).

In total, we have selected 9 experimental plots for the simulations, pending the autumn of 2021. Of these, three have been established on calcimagnesic soils, with varied soil occupations such as fallow land, cereal cultivation, and abandoned soils. Three plates were selected on the vertices, covering the types of land of the type of cedar, abandoned, and cereal crops. Three more have been installed on poorly developed soils associated with the types of occupation of cereal-cultivated, fallow land, and abandoned soils.

3.1. Testing process

Before starting irrigation, it is necessary to perform a series of measurements and calculations to assess the factors related to the runoff, such as surface condition, soil roughness, and slope, as well as to take a soil sample for laboratory analysis (Tab. 1).

The surface state of the soil is measured using the square point method (Roose, 1996). Two diagonal transects are established inside the plot using a meter, then piquets are pushed every 2 cm (Fig. 2, B). For each point, the percentage of covered surfaces (CV% = weeds + litter + stones not integrated into the soil mass), the percentage of open surfaces (SO% = aggregates + cracks + fauna holes), or closed surfaces (SF% = surface crust due to compaction or erosion, sedimentation crust, compaction layer, and stones integrated into the soil mass) are noted. The sum of covered and bare surfaces equals 100%. Similarly, the sum of closed and open surfaces equals 100%.

The surface roughness is measured using a metal chain whose length is greater than the frame width. The roughness index (Ir%) is calculated by relating the length of the stretched chain to the measurement length. The plot is calculated as the average of six measurements carried out longitudinally and transversally (three times for one direction).

To determine the Imbibition rain (pi), a 10-liter watering machine was used, calculating the time and amount of water to be poured for the development of the first drop of stream at the bottom of the plot (Fig. 2, C).

After determining the Imbibition rain, the process continues without interruption. The ten liters of water are poured in 7 minutes and 30 seconds, with an intensity of 80 mm/h. For every 10 liters, the volume of water poured out of the plot is measured. This process is repeated, and the test ends when the same amount of water is recorded twice in a row, indicating a stable permeability value and maximum surface spill (stabilisation phase). To determine the solid load, it is necessary to collect the runoff water during the test (Fig. 2, D).

This rainfall simulator has several notable advantages, such as its ability to analyze the factors influencing the hydrodynamic behaviour of soils (moisture, soil type, surface condition), its efficiency in terms of cost and speed of obtaining results, its portability even on steep slopes, and its low water consumption. However, it does have certain limitations, notably the absence of kinetic energy from natural precipitation, the small size of the plots tested (scale effect), and wind disturbance during watering.

Figure 2: Photographic illustration of the precipitation simulation system used in the field. A: Experimental plot demarcated using a metal frame, B: Measurement of ground surface state using the quadrat point method, C: The first runoff drop appears at the downstream end of the plot, D: Collection of runoff water for solid load quantification.

Figura 2: Ilustração fotográfica do sistema de simulação de precipitação usado no campo. A: Parcela experimental demarcada usando uma estrutura metálica, B: Medição do estado da superfície do solo usando o método de ponto quadrado, C: A primeira gota de escoamento superficial aparece na extremidade a jusante da parcela, D: Coleta de água de escoamento superficial para quantificação da carga sólida.

3.2. Laboratory analyses

The samples were taken uniformly at a constant depth to enable comparisons to be made between the different samples taken (Nmiss *et al.*, 2025). The physical and chemical characteristics of the soil of the various experimental plates were evaluated by a granulometric analysis in the laboratory, including apparent density (da, g/cm3), initial humidity, soil porosity, ground texture (% of sand, % of lemon and% of clay) and organic material content (MO%).

Table 1. Description of the sites studied (P: Plot; MO: Organic matter).

Tabela 1. Descrição dos sítios estudados (P: Lote; MO: Matéria orgânica).

P	Coordinats (m)			Sol	Occupation	MO %	Clay %	Silt %	Sable %	Pente %
	X	Y	Z							
1	608486	409216	540	Calcimagnesic	Fallows	1,2	29,2	46	24,8	39
4	605068	410482	880	Calcimagnesic	Cereal farming	2	41	27	32	28
6	605588	406433	482	Vertisoils	Abandoned	2,1	50	35	15	12
7	605565	406388	481	Vertisoils	Cereal farming	1,6	47	36	17	13
8	605608	406397	484	Vertisoils	Fallows	2,5	49	39	12	4
9	605868	403944	355	weakly developed	Abandoned	1,5	24,2	41	34,8	10
10	605524	408882	630	weakly developed	Abandoned	0,6	21,2	45	33,8	28
11	605533	408863	625	weakly developed	Cereal farming	1,9	25,2	39	35,8	20
13	605087	410464	686	Calcimagnesic	Abandoned	0,9	39,5	25	35,5	32

4. Results

4.1. Imbibition Rain

Values the Imbibition rain varies considerably from one soil type to another, and depending on the type of soil occupation. During autumn, the trigger limit of the runoff ranges from 20.1 to 3.4 mm on the vertices. Several parameters, such as the previous humidity of the first centimeters of soil, surface condition, and surface roughness, can explain these results (Ludwig, 2000), which are similar to those of other studies carried out in the same region (El-Ommal, 2021; Abahrour *et al.*, 2015).

Table 2. Soil surface condition.

Tabela 2. Estado da superfície do solo.

Plots	Ir (%)	surface state (%)				DA (g/cm^3)	P (%)	H (%)	PI (mm)
		Covered	nu	Opened	Closed				
1	4,0	28,8	71,3	45,0	55,0	1,54	42,9	4,1	4,8
4	6,0	38,0	62,0	45,0	55,0	1,4	49,3	5,8	10,0
6	2,1	34,3	65,7	46,5	53,5	1,47	48,3	6,6	3,4
7	15	25	75	77,3	22,69	1,22	54,5	2,76	20,1
8	6	40	60	70	30	1,2	54	5,8	14
9	6	44,0	56,0	51,7	48,3	1,53	44,6	4,9	12,6
10	1,6	38,3	61,7	42,8	57,2	1,5	42,9	4,4	4,4
11	12,0	47,1	52,9	59,9	40,1	1,3	51,67	6,3	18,2
13	3,0	26,9	73,1	40,0	60,0	1,49	48,9	6,7	4,0

With: roughness index (Ir%), Apparent density (DA), Porosity(P), Humidity (H), Imbibition rain (Pi)

The plots initially harvested in the early autumn (P7 = 20.1 mm) record maximum Imbibition rain values due to the low initial humidity (2.76%). As well as soil harvesting increases porosity (P7 = 54.5%), roughness (15%), and the opening of the soil surface (P7% = 77.3%), which improves their ability to infiltrate. Although these values are high, they correspond to the measurements carried out by Collinet & Lafforgue (1979). In general, agricultural activities have a significant impact on all flow and erosion processes (Auzet *et al.*, 1987; 1992).

Abandoned land has very low imbibition values, not exceeding 4.4 mm. According to (Arabi & Roose, 2004), if the soil is dry, the runoff begins after 20 minutes of rain or after 3 mm if it is compact or damp, due to their initial humidity, their percentage of naked surface that exceeds 65.7% and their very high apparent density (> 1.47 g/cm^3). Moreover, high runoff intensities occur only when all these conditions are met.

4.2 Runoff and infiltration

According to the various simulations carried out, it is clear that the runoff coefficient is relatively high, reaching 48.4% for plot 6, while lower values are recorded for plot 11, which does not exceed 10% (Tab. 3). This exceptional runoff is due to factors such as animal hardening and compacting of the soil surface, low plant coverage and low roughness. Other researchers have also pointed out that the flow of a soil is strongly influenced by the physical characteristics of its surface condition and plant cover (Sabir *et al.*, 2004; Morsli *et al.*, 2004).

Table 3. Distribution Table of the coefficient of runoff and the final infiltration.

Tabela 3. Tabela de distribuição do coeficiente de escoamento superficial e da infiltração final.

Plots	1	4	6	7	8	9	10	11	13
final infiltration mm/h	38,7	49	32	37	36,6	36	33,2	70,5	30
coefficient of runoff (%)	20,22	19,8	48,45	13,9	20,4	13,3	40,9	10	30

Abandoned land and fallow land have a higher runoff coefficient, reaching 48.4 % for vertices. On the other hand, cereal-growing lands record lower values (10%). Similar studies conducted in comparable environments (Arabi, 1991) showed that bare, compact soils have runoff rates of approximately 30%. The minimum flow values on cereal-growing land are due to the presence of crop residues (foams). The fluctuations between soil occupations are visible for the final infiltration (from 32 to 70,5 mm/h). Most of the maximum values are recorded on agricultural land, with a peak observed on weakly developed soils (P11 = 70,5 mm/h), which is explained by the surface condition favourable to infiltration, mainly due to ploughing that increases roughness and low initial humidity. These results are consistent with those of other studies carried out in the same region (Al Karkouri, 2000). Thus, soil work plays an important role in infiltration by changing the roughness, increasing the porosity, and allowing the surface storage of part of the water (Gómez *et al.*, 2005) (Fig. 3).

The infiltration rates of fallows are higher than those of abandoned land and lower than those of laboured land. The highest value was recorded on Calcimagnesian soils (P1=38.7 mm/h), and the lowest was registered on vertisols (36mm/h). These findings show that this practice of chasing helps to minimize runoff and promotes infiltration, as has also been observed in other studies (Abahrour, 2009; Boli & Roose, 2004; Diallo *et al.*, 2012; El-Ommal & Tribak, 2023; Laouina, 2000; Zaher *et al.*, 2021).

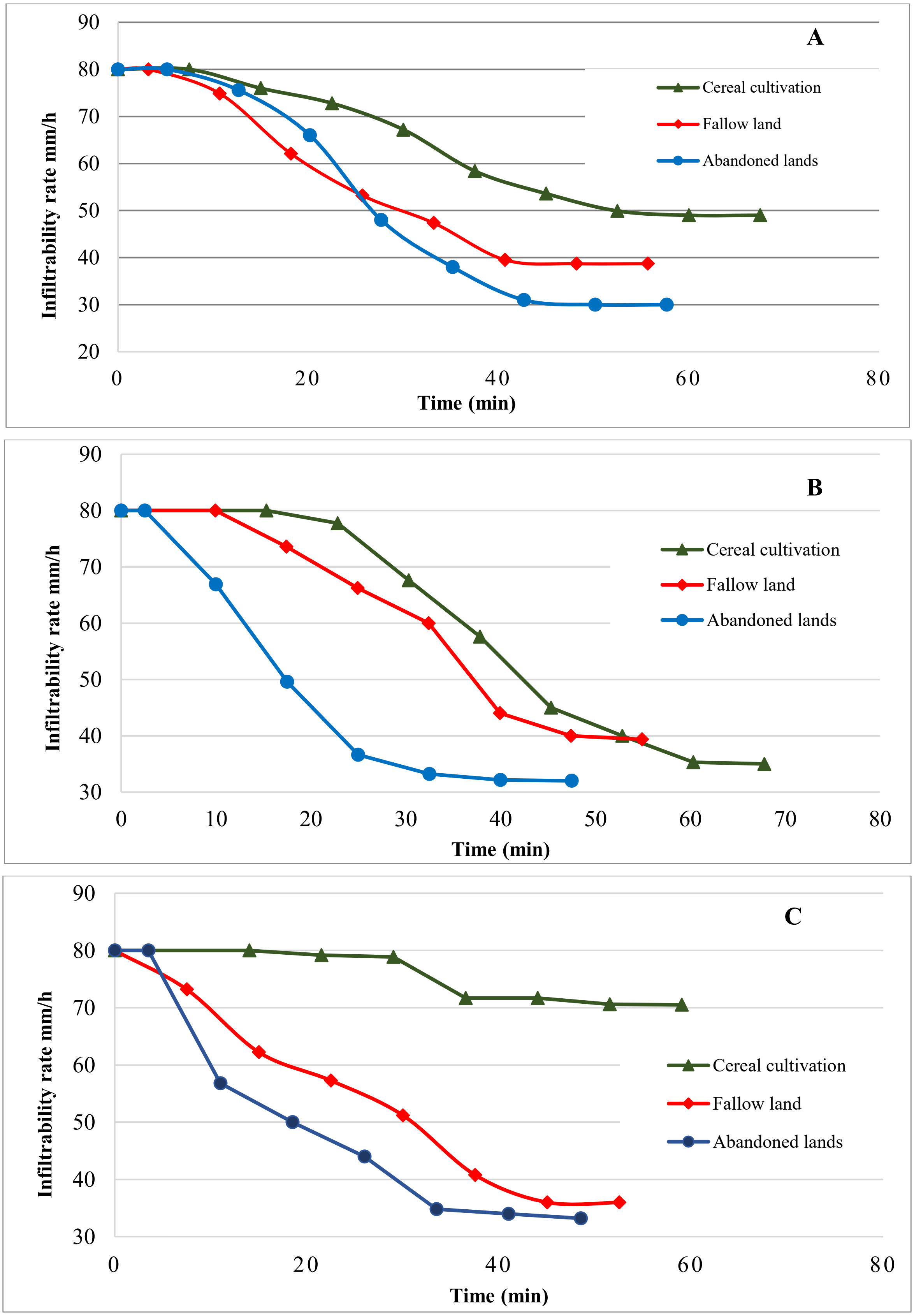

Figure 3. Evolution of the infiltration measured by the rain simulation according to the soils occupation and Soil type, (A) Calcimagnesic soils, (B) Vertisols, (C) weakly developed soils.

Figura 3. Evolução da infiltração medida pela simulação de chuva em função da ocupação do solo e do tipo de solo, (A) Calcimagnésico, (B) Vertissolos, (C) solos pouco desenvolvidos.

Soil type plays a significant role in the flow and infiltration process. On vertisoils, the final infiltration is modest on abandoned land, not exceeding 32 mm/h, while it is very high on cereal-growing land, reaching 37 mm/hr. Vertisoils are characterized by large amounts of inflatable clay and surface cracks, which causes the fissures to close during moistening and thus reduce infiltration.

For weakly developed soils (Tab. 3), the highest values are recorded on grassland, exceeding 70,5 mm/h. These values are in the same order of magnitude as those measured in other studies on the 1-meter scale (Amhani, 2022). Minimum values are recorded on abandoned land. In comparison, infiltrations in arable land are two times higher than in abandoned land For Cereal cultivated land (P11 = 70,5 mm/h and P6 = 32mm/h).

4.3 Soil erosion and loss

In general, the maximum autumn erosive is an average of 36.7 g/L. The average turbidities for each soil type vary from 72.9 g/L for vertisoils, 21.8 g/L for weakly developed soils and 15.5 g/L for calcimagnesic soils.

Maximum sedimentary yield values for each soil type are recorded respectively in the vertisoils (P8: 140 g/L), calcimagnesic soils in cereal growing (P11: 19.6 g/L) and weakly developed soils in abandoned land (P9: 20 g/ L). This situation is due to the initial humidity, the low grass cover and the fragility of the first horizons of the soil because of the long period of sunshine, as well as a widespread desertification of soils at the end of the dry season. These findings are consistent with those found by other researchers such as (Roose *et al.*, 2012; Laouina, 2000; Morsli *et al.*, 2004).

The significant losses observed on ploughed land indicate that this practice exposes the soil to erosion. Indeed, cultivated land generally has higher erodability rates of one to three orders of magnitude compared to covered land. (Abahrour *et al.*, 2015; Boli & Roose, 2004; Diallo *et al.*, 2012; El-Ommal, 2021; Laouina, 2000). These very high values in ploughed land correspond to the results obtained by Amhani (2022), in the Lahdar catchment, adjacent to the Aghrouz catchment, where the solid load exceeded 56.5 g/l on average.

The measured turbidities (Tab. 4) show a clear effect between turbidity and the negative covered surface state and a positive correlation with the bare surface state. However, the correlation between turbidities and runoff is weak. Several authors have already highlighted the positive effect of plant cover on reducing soil losses and runoff, such as (Laouina, 1992; Moufaddal, 2001; Sabir *et al.*, 2007).

Table 4. Turbidity of runoff waters from the tests conducted.

Tabela 4. Turbidez das águas de escoamento dos ensaios efetuados.

Plots	1	4	6	7	8	9	10	11	13
Soil loss (g/l)	13	19,6	55	140	58,1	20,6	6,2	18,2	14

5. Discussion

Typically, the runoff process can be divided into three successive phases: the embryonic phase, the transitory phase, and the steady state phase. (Lafforgue, 1977). During the first phase, the capacity of infiltration into the plot is greater than the intensity of the rain that reaches the ground. The water present in the plot leads to the formation of a slaking crust, thereby reducing the capacity of infiltration and decreasing the roughness of the surface of the soil (Boiffin, 1984). The water begins to flow and fill the depressions present in the plot. In time, the flakes overflow, and the moving water reaches the exit. This development promotes the triggering of the runoff and marks the beginning of the transitory phase (Casenave & Valentin, 1989). During this phase, the intensity of infiltration decreases, and the average height of the water spilled to the surface of the plot increases. Therefore, the roughness of the soil surface gradually decreases with the accumulation of water. The steady state phase is characterized by a minimum infiltration more or less constant marking each type of soil situation and a maximum stream that continues until the end of the rain.

Rain simulations show that on dry soil, high amounts of rain are required to cause the runoff. This relationship is consistent with previous studies by Al Karkouri (2000), Morsli *et al.* (2012), and Roose (1996). In addition, a positive correlation is observed between Imbibition rain and surface roughness, as the presence of barriers and holes (flakes) in the soil microtopography prevents runoff. This is also supported by the work of Roose (1996). Finally, a positive effect is observed with the open surface state, while a negative correlation is seen with the closed surface state. Indeed, the percentage of covered area plays a crucial role in triggering drainage and erosion, as demonstrated by several researchers such as Bensalah *et al.* (2012), Dahmani *et al.* (2015), El-Ommal (2021), Moufaddal (2001), and Wischmeier & Smith (1978). Furthermore, a positive relationship is observed between Imbibition rain and organic content, which means that the higher the percentage of organic matter, the longer the time required to trigger the spill. This positive correlation is consistent with the results found by Cheggour *et al.* (2008) in the Rhéraya Watershed of the Western High Atlas.

The findings of the study demonstrated a significant effect between the final infiltration capacity and the state of the covered surface. This observation suggests that covered surfaces, such as vegetation, organic residues, or other materials, encourage optimum infiltration of water into the soil. On the other hand, a negative correlation was observed between the final infiltration capacity and the state of the bare surface. Indeed, surfaces bare of vegetation, or any other organic material, appear to reduce infiltration capacity due to the formation of a surface crust that limits water penetration. In addition, Infiltration capacity has been observed to be positively influenced by surface roughness. This result suggests that infiltration capacity is high when the soil surface has a marked roughness, characterised by the presence of micro-roughness. This observation suggests that the roughness of the soil may encourage water to be retained on its surface, thereby promoting more gradual and efficient infiltration.

The results show that bare soils are more likely to generate high turbidity, but it is not always directly related to runoff intensity. This indicates that other factors, such as the granulometric composition of the soil and the slope, can influence turbidity independently of the volume of water runoff (Morgan *et al.*, 1997).

Finally, the state of the surface is a key factor influencing the hydrodynamic properties of the soil, in particular, its infiltration capacity. This can have important implications for soil management, particularly in agricultural contexts, stormwater management, or erosion prevention.

6. Conclusions

This study measured erosion, runoff and infiltration in different soils throughout the year, taking into account seasonal variations. The results obtained highlight the complexity of the processes studied and the number of parameters involved in the formation of runoff and erosion.

The use of the simulator in this area of study has proved to be ideal for studying the influence of runoff, infiltration, and above all, the impact of cultivation practices on soil response to simulated constant intensity precipitation. It enables detailed analysis of soil hydrodynamic behaviour and assessment of risks of runoff and erosion on slopes.

Understanding soil hydrodynamic behaviour is essential to diagnosing the risks of runoff and erosion on a slope. It is crucial to identify the factors that influence the onset of the flooding, such as soil surface condition, initial humidity and plant coverage, and soil infiltration capacity and deep horizon saturation risks associated with land-use practices.

Among these factors, surface condition, initial humidity, and plant cover play a major role in soil infiltration capacity and increase in the amount of infiltered water. Thus, the infiltration capacity may vary from one plot to another depending on the type of land use. Farmland, due to its open surfaces and surface roughness, generally has a higher infiltration capacity than other types of land use.

In conclusion, this study emphasizes the importance of taking into account several factors in the assessment of the risks of water runoff and erosion. It highlights the impact of cropping practices on soil hydrodynamic behaviour and highlights the crucial role of surface condition, initial soil moisture, and vegetative cover in soil infiltration capacity. These findings provide valuable insights for sustainable land management and the implementation of appropriate agricultural practices to reduce the risk of soil erosion and degradation. Further studies are needed to deepen our understanding of these processes and refine land management recommendations.

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