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Mass movement inventory map of the Dhar Souk region and its main spatial morphometric characteristics

Carte d'inventaire des mouvements de masse de la région de Dhar Souk et ses principales caractéristiques morphométriques spatiales

Nada Boukhres[1,2], Mathieu Fressard[2], Yannick Thiery[3], Mohamed Mastere[1*], Olivier Maquaire[2], Stephane Costa[2], Brahim Benzougagh[1], Bouchta El Fellah[1]

1. *Department of Geomorphology and Geomatics, Scientific Institute, Mohammed V University in Rabat, Avenue Ibn Batouta, P.O. Box 703, 10106, Rabat, Morocco. mohamed.mastere@is.um5.ac.ma; brahim.benzougagh@is.um5.ac.ma*
2. *Normandie Univ, UNICAEN, CNRS, IDEES, 14000, Caen, France. boukhresnada@gmail.com ; mathieu.fressard@cnrs.fr ; olivier.maquaire@unicaen.fr ; stephane.costa@unicaen.fr*
3. *Bureau de Recherches Géologiques et Minières (BRGM). Y.Thiery@brgm.fr*

Abstract. The Rif region in northern Morocco is characterized by diverse climatic conditions, a unique geology and complex tectonic activity. These features render the region susceptible to mass movements resulting from the continuous expansion of infrastructure on unstable slopes. These events pose a significant risks to local communities and the regional economy. This study addresses the critical knowledge gap of mass movements, especially in the central Rif region, which is still under-documented due to its difficult accessibility. This gap extends across Morocco and hinders risk assessment and susceptibility mapping, two essential elements of the current national policy, supported by the World Bank, for natural disaster management and resilience. In response, this study proposes a medium-scale inventory at 1:50.000 for the Dhar Souk region in the central Rif. Unlike previous studies, this inventory combines high-resolution oblique aerial image interpretations from Google Earth with rigorous field surveys, enabling the identification of both small and large-scale mass movements. Additionally, a typology is developed for each recorded phenomenon, highlighting their specific characteristics. The results are staggering: 746 identified events, including rockfalls, deep-seated landslides, mudflows, debris flows, and shallow landslides along banks and roads. Rockfalls and deep-seated landslides dominate in terms of frequency and area. These results provide valuable insights into the morphometric dominance of certain mass movements in the study area. Notably, the research underlines the added value of a mesoscale approach to risk management. A comparison with regional-scale inventories (1:100.000 and 1:300.000) demonstrates greater precision and a higher number of recorded events at this working scale. In summary, this study's innovative methodology and comprehensive inventory fill a critical gap in assessing mass movement events in the central Rif. The resulting database will be a fundamental resource for future susceptibility mapping, hazard assessment, and risk management, and will significantly enhance the region's preparedness and resilience to mass movement-related disasters.

Keywords: Mass movement events; Spatial analysis; Susceptibility mapping; Unstable slopes; Rif (north Morroco)

Résumé. Le territoire Rifain, localisé dans le nord du Maroc, se distingue par sa diversité climatique, sa géologie unique et son activité tectonique complexe. Ces caractéristiques rendent ce territoire sujette à des mouvements de masse résultant de l'expansion constante des infrastructures sur des pentes instables. Ces événements représentent un risque important pour les communautés locales et l'économie régionale. Cette étude aborde le manque critique de connaissances sur les mouvements de masse, en particulier dans la région centrale du Rif, qui est encore sous-documentée en raison de son accessibilité difficile. Cette lacune s'étend à l'ensemble du Maroc et entrave l'évaluation des risques ainsi qu'à la cartographie de la susceptibilité, deux éléments essentiels de la politique nationale actuelle, laquelle est soutenue par la Banque mondiale, pour la gestion et la résilience face aux risques naturels. En réponse à cette situation, cette étude propose un inventaire à moyenne échelle au 1:50,000 pour la région de Dhar Souk dans le récif central. Contrairement aux études précédentes, cet inventaire combine des interprétations d'images aériennes obliques à haute résolution de Google Earth avec des enquêtes de terrain rigoureuses, ce qui permet d'identifier les mouvements de masse de petite et de grande ampleur. En outre, une typologie est élaborée pour chaque phénomène enregistré, mettant en évidence ses caractéristiques particulières. Les résultats obtenus sont stupéfiants : 746 événements identifiés, dont des éboulements, des glissements de terrain profonds, des coulées de boue, des coulées de débris et des glissements de terrain peu profonds le long des berges et des routes. Les éboulements et les glissements de terrain profonds dominent en termes de fréquence et de superficie. Ces résultats fournissent des indications précieuses sur la dominance morphométrique de certains mouvements de masse dans la région. La recherche souligne notamment la valeur ajoutée d'une approche à méso-échelle pour la gestion des risques. Une comparaison avec les inventaires à l'échelle régionale (1:100.000 et 1:300,000) démontre une plus grande précision et un plus grand nombre d'événements enregistrés à cette échelle de travail. En résumé, la méthodologie innovante et l'inventaire complet de cette étude comblent une lacune critique dans l'évaluation des mouvements de masse dans le Rif central. La base de données qui en résulte sera une ressource fondamentale pour la cartographie de susceptibilité, de l'aléa et des risques futurs et améliorera considérablement la préparation et la résilience de la région aux catastrophes liées aux mouvements de masse.

Mots clés : Mouvements de masse ; Analyse spatiale ; Cartographie de la susceptibilité ; Pentes instables; Rif (nord Maroc)

INTRODUCTION

Mass movements are geomorphologic phenomena that can potentially damage surrounding assets and populations. They include a wide range of different destructive phenomena of various types, such as rockfalls, rotational or translational landslides, mudflows, and debris flows (Froude & Petley 2018, Varnes 1978, Hungr *et al.* 2014). In both the scientific and operational context for risk prevention approaches, knowledge of their spatial and temporal distribution is crucial for understanding their predisposing and triggering factors.

The inventory of landslides is the first important step in building knowledge about the location, typology, volume, activity and date of occurrence of a phenomenon (if available) (Fell *et al.* 2008). These elements allow us to characterize the phenomena, their frequency and magnitude (Corominas *et al.* 2014). The inventory is also the most important basis for assigning mass movements to the control factors predisposition and triggering and, thus, for creating susceptibility and hazard maps (Thiery *et al.* 2020). Inventories can be carried out at a wide range of scales, from regional inventories at very small scales up to 1:100.000, often based on information about events or analyzing directly available documents such as geological maps and aerial photographs (Fell *et al.* 2008a). This type of inventory is only informative and remains imprecise in terms of spatial boundaries and typology of phenomena (Guzzetti *et al.* 2012). Inventories can be more local and carried out at a mesoscale ranging from 1:100.000 to 1:25.000 and therefore has a higher operational advisory value (Cascini 2008, Guzzetti *et al.* 2012), characterized by greater spatial and temporal precision, allowing a more accurate analysis of the processes and typology of phenomena. In addition, inventories are often based on a combination of the estimation of aerial photographs and topographic maps associated with field inspections to validate the observations. Other mapping approaches, at a larger scale of 25.000 to 5.000 or even at a local scale of less than 5.000, are often based on field observations and analysis of very high-resolution imagery using drones and LiDAR; lidar can be used as a complement for legal zoning in cases of identified risk (Cascini 2008, Ghosh *et al.* 2011). Although various approaches have been used to assess susceptibility to mass movements in the Rif region, a systematic, comprehensive inventory of these events is urgently needed to improve preparedness and risk management.

The Moroccan Rif is a mountainous region heavily affected by mass movements. Since the 1960s, numerous inventories have been carried out at different scales, covering various parts of the area and focusing on the western part of the Rif. Avenard (1965) addressed mass movements in the pre-Rif region at different scales (i.e., 1:50.000, 1:100.000, 1:200.000, and 1:500.000). Millies-Lacroix (1968) proposed a predictive map of mass movements for the entire Rif chain at a scale of 1:100.000. Maurer (1968) conducted a geomorphological study on the dynamic processes of the Rifan chain, along with three inventories produced in the Rif, including another map covering the entire Moroccan Rif at a scale of 1:300.000. Mass movements on this regional-scale map hold a "respectable" share, as the phenomena can only be represented as symbols, roughly localized (Mastere 2011). Subsequently, inventory maps were completed and created by El Kharrim (2002) and Sossey Alaoui (2005) in the western Rif, for the Tétouan region and the Tanger Peninsula, respectively. Chacuki (1991), Fares (1994), and Margaa (1994) adopted the methods of ZERMOS cartography (Zones Exposed to Ground and Subsurface Movement-Related Risks) in the Chefchaouen (western Rif), Taounate, and Al Hoceima (central and oriental Rif) regions, respectively, defining direct qualitative approaches and relying on expert knowledge to analyze these phenomena. Mastere (2011) compiled various types of mass movements in an inventory for the Chefchaouen province at 1:100.000 (western Rif). Finally, another revealing study was carried out in the western Rif to map and characterize various ground movements on both sides of the northern limestone ridge in the provinces of Tétouan and Chefchaouen in the north of Morocco the western Rif (Bounab 2022).

When examining the scientific research carried out in various regions of the Rif, it becomes clear that certain areas of the Rif, especially the western Rif, are better covered by cartographic work than other parts of the central and eastern Rif, which have not been sufficiently explored due to their inaccessibility and considerable remoteness. The only regional inventories in the study area are available at a scale of 1:100.000 for the province of Taounate (Abidi *et al.* 2019, Ozer *et al.* 2019, Sahrane *et al.* 2022, Sahrane *et al.* 2023). A summarized inventory for the entire Moroccan Rif was compiled at a scale of 1:300.000. It found 4.177 phenomena over an area of 1,065 km^2, corresponding to only 3 % of the study area, about 37.000 km^2 (Mastere *et al.* 2020).

All these inventories of mass movements in certain regions of the Rif chain were carried out at a scale of 1:100.000 or more, but without proposing a typology of these phenomena. As a result, knowledge remains fragmented without the entire area being surveyed. There is still a lack of knowledge about the types and locations, which makes it difficult to reduce the scale of a risk management approach through susceptibility mapping and hazard mapping, as recommended by the current national policy on natural hazards and supported by the World Bank. To compensate for this lack of information, a national strategy for assessing natural hazards, including landslides, has been in place since 2020 (Boukhres *et al.* 2022). This strategy aims to improve knowledge while strengthening risk prevention. In addition, it includes systematic mesoscale landslide inventories to improve reliable knowledge for improving disaster management capacities and preparedness at institutional and community levels, and knowledge to prepare the state and the population for successful disaster management.

This article presents the inventory of mass movements carried out at a meso-scale of 1:50.000 in the area of Dhar Souk in the central Rif. The originality of this study lies in this inventory and in the definition of the different types of mass movements in the study area, which have never before been carried out at this working scale and specifically for this study area. The study aims to complement the existing small-scale inventory with a medium-scale analysis based on the combination of several essential data sources for the precise mapping of mass movements, such as (i) Google Earth Pro (GEP) and (ii) field studies, GEP provides a very high-resolution aerial image of the study area, which facilitates the identification of phenomena compared to satellite images such as Landsat 8 and Sentinels, etc., which do not provide sufficient resolution. On the other hand, (ii) field surveys represent a crucial step in this study, which initially aims to confirm the actual presence of sites previously identified from the images provided by GEP. In addition, they allow the discovery of new locations that remain invisible as small-scale phenomena on satellite images. Then, in this study, the local typology will be presented successively, followed by an analysis of the spatial distribution and the main morphometric characteristics. The results will help fill a cartographic gap in this region and represent a first step towards susceptibility mapping.

MATERIALS AND METHODS

Study area and mass movements inventory

The “Dhar Souk” area extends over 636 km² at the intersection of three administrative provinces: Taza, Taounate and Al Hoceima (Fig.1). It is part of the outer area, which corresponds to an extensive structural area pushed by the allochthonous flysch layers and the inner area. Its complex internal structure reflects a paleogeographic arrangement corresponding to the African margin of the Tethyan Ocean (Durand-Delga *et al.* 1962, Lespinasse 1975). The Outer Rif consists of rooted and detached units, which are, from inside to outside, the Intra-Rifain Zone, the Meso-Rifain Zone and the Pre-Rifain Zone (Suter 1980). In addition, the study area is framed by two intramontane basins: Dhar Souk and Beni Oulid, the extent of which is due to the pressure play of the great Nekor accident (Asebriy *et al.* 1993, Morel 1989).

These mountainous landscapes are characterized by a complex topography between 322 and 1846 meters above sea level (Fig. 1-2) with different landforms:

- Numerous ridges in high mountain ranges.
- Escarpment of carbonate rock (massive micritic limestone from the Jurassic-Lias) at <1000 m altitude.
- Sofs in Dhar Souk village is a local geomorphologic term for the rock alignments formed by the predominant Messinian sandstones at 600 m altitude.
- Highly gullied Tortonian-Messinian marl formations (badlands) on the NE-NW slopes (Intratif-Mesorif) and other marl formations of different ages on the SE-SW slopes (Prerif) of the study area (Fig. 1-2).
- Valleys, especially that of the Ouergha (Fig. 1-2), the widest and most extensive valley filled with Quaternary alluvium, or the other, narrower valleys enclosed between mountain massifs, plateaus and hills and crossed by tributaries of the Ouergha flowing over impermeable soils (marl and clay).
- Plains used for agriculture (grain, cannabis).
- Hills with forests and natural vegetation (olive trees, oaks, matorrals, etc.).

The region is characterized by a typically semi-arid continental climate with cool, wet winters accompanied by periods of intense, sudden rainfall of up to 1385 mm/year, sometimes with snowfall. Summers are less humid, hot and dry.

The area of Dhar Souk, located in the external domain of the Rif mountain chain, has geomorphologic and structural features consistent with the Rif region’s characteristic features. Consequently, it is subject to a high frequency of mass movements across its slopes. Still, these phenomena do not differ significantly from the events classified as a significant risk by the Moroccan authorities responsible for managing this natural hazard. However, very few studies have been carried out to address this issue and establish an inventory of the different phenomena observed in the study area at a medium or finer level, broadly or in detail.

The triggering of these phenomena in the study area results from the interaction of several natural and anthropogenic factors to which the entire Rif area is exposed. The natural factors include: (i) the climatic instability linked to the geographical location of the Rif, which is simultaneously exposed to Mediterranean influences in the north and Atlantic influences in the west. This constellation leads to irregular and often torrential rainfall and prolonged periods of drought; (ii) geological instability and particular tectonic events in the Rif region. The Rif area is characterized by a variety of different geological formations and structures that have been shaped by significant tectonic activity. This activity has played a fundamental role in forming the Rif mountain range by creating superimposed geological plates that have slid over each other. These layers are bounded by major tectonic contact zones, including the Nekor Fault, which crosses the central Rif Mountains, including the study area, and the Jebha Fault, which crosses the western Rif Mountains. The anthropogenic factors such as (iii) construction works and (iiii) deforestation, two of which are particularly dominant and frequent in the study area, play an important role in the mass movements: First, (iii) the construction and infrastructure works such as: Building houses on unstable slopes, especially on marl and clay soils, increases susceptibility to landslides and mudflows. Similarly, building houses near rocky cliffs increases the risk of rockfalls and stone block falls. Road construction works, including roads and tracks on steep and unstable slopes, disrupt the natural water drainage, leading to landslides and rockfalls. In addition, the extraction of construction materials such as sand, marl, stones and blocks significantly disturbs the slopes’ balance and weakens the soil’s stability. Secondly, (iiii) deforestation leads to soil instability and exposes slopes to erosion.Consequently, the risk of landslides increases considerably.

The combination of these natural and anthropogenic factors make the Rif region inherently unstable, exposed to a significant risk of mass movements that can devastate and threaten the region’s inhabitants and associated infrastructure. This situation requires special attention in terms of risk management and territorial planning to minimize the potential damage to the local population and their property and increase resilience to these natural hazards. It is, therefore, essential to carry out in-depth studies on this phenomenon, starting with precisely identifying these events, to conduct an inventory listing these various events, and establishing a database at different levels of investigation.

The morpho-structural characteristics of the study area led to a great variety of deep and superficial mass movements with very different surfaces and volumes. The spatial distribution and spread of these phenomena can have economic consequences for the local population, which is dependent on agriculture (Mastere *et al.* 2013, El Fellah & Mastere 2015).

The inventory was carried out using a visual geomorphological interpretation of satellite images available on Google Earth Pro, providing multitemporal coverage for the study area in 2001, 2013, 2016, 2018, 2019, 2020, 2021 and 2022.

A detailed analysis of the landforms on the basis of topographical maps at a scale of 1:25,000 supplemented the interpretations. Particular attention was paid to identifying morphological indices that provide information on the phenomena’s typology and state of activity (McCalpin 1984, Varnes 1984, Guzzetti *et al.* 2006, Hungr *et al.* 2014), the presence or absence of scars, fractures and cracks, vegetation, mounds and the type of materials. Whenever possible, the year or period of triggering was also indicated. Following the inventory with photo interpretation, several field inspections were conducted to clarify interpretations worthy of discussion regarding typology, activity indices and the limits of certain phenomena. Each phenomenon was assigned a score from 1 to 3, indicating the degree of certainty in observing and identifying the type of phenomenon. In some cases, on-site surveys were not possible due to accessibility issues, which

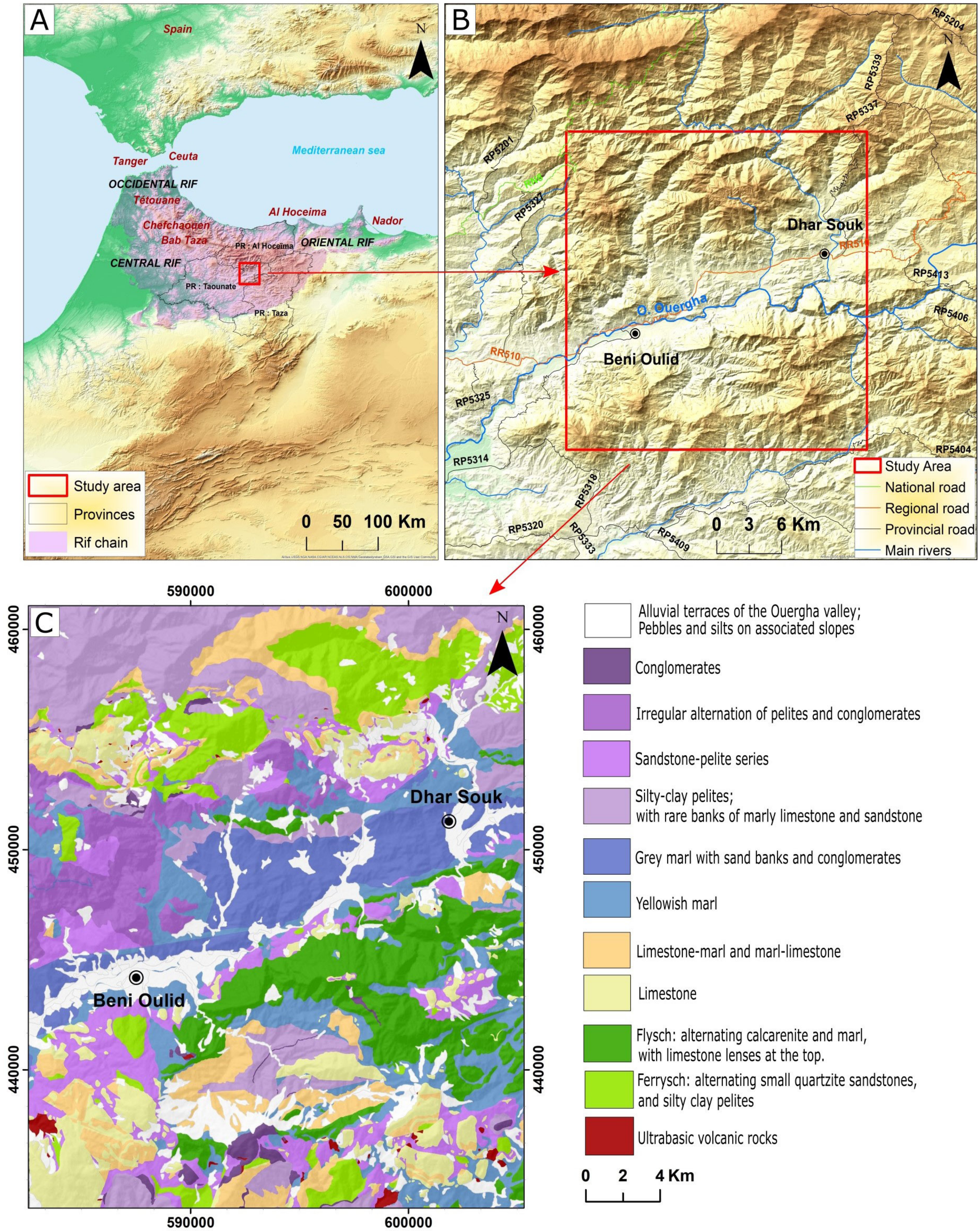

Figure 1. Geographical location of the study area. A: General location of the study area on the scale of the Rifan range in Morocco, B: Study area (Dhar Souk at 1:50.000), C: Simplified lithological map of the Dhar Souk region (adapted from Saadi et al.1979).

Figure 1. Situation géographique de la zone d'étude. A : Localisation générale de la zone d'étude à l'échelle de la chaîne du Rifaine au Maroc, B : Zone d'étude (Dhar Souk au 1:50,000), C : Carte lithologique simplifiée de la région de Dhar Souk (adaptée de Saadi et al. 1979).

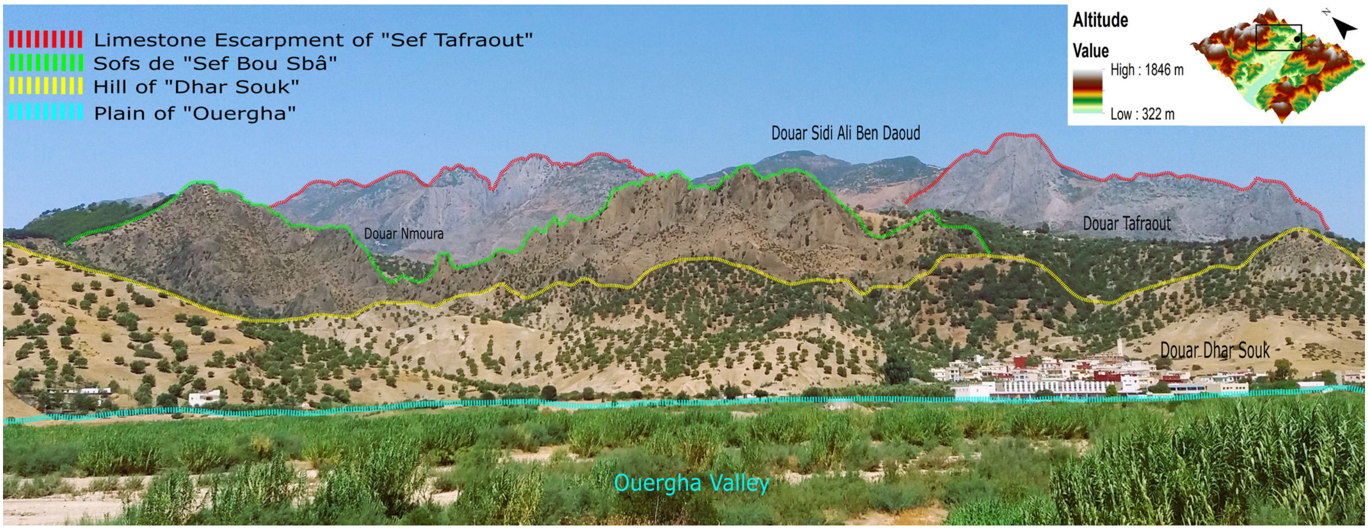

Figure 2. Panoramic view of the village of Dhar Souk, highlighting the various landforms observed. The white frame in the upper right corner of the figure corresponds to a digital elevation model (DEM) of the study area.

Figure 2. Vue panoramique du village de Dhar Souk, mettant en évidence les différentes formes de relief observées. Le cadre blanc dans le coin supérieur à droite de la figure correspond à un modèle numérique de terrain (MNT) de la zone d'étude.

limited the reliability of some observations. In addition, various elements relating to vulnerable persons were included in the inventory.

The identified phenomena were mapped in polygon format in the GIS software (with ArcGIS 10.8) using the Merchich (Grad) North Morocco projection (EPSG: 102191). The trigger and run-out zones were mapped independently. Each polygon is linked to an attribute database describing all the features shown.

Morphometric indices

Based on the mapped polygons, different morphometric indices were calculated, in GIS with ArcGis 10.8, to characterize the morphological signature of the phenomenon. The selected indices are standard values and provide a good description of the different types of phenomena (Schmaltz *et al.* 2016): Total length, the width of the trigger and run-out zones, area, elevation (of the highest point of the trigger zone and the lowest point of the run-out zone), elevation difference and mean slope (Fig. 3). The elevation values were extracted from the digital SRTM terrain model with a resolution of 30 m.

Spatial distribution of phenomena

A density analysis is used to obtain an overview of the spatial distribution of mass movements (Guzzetti *et al.* 2003, Reichenbach *et al.* 2004), and is a precursor to susceptibility and hazard mapping (Soeters & van Westen 1996, Reichenbach *et al.* 2018). We have used a special form of density map, the isopleth map. An automatic density calculation is performed with empirically defined sliding circle windows. The resulting values are interpolated, and then density classes are defined. The size of the cells and the sliding window represent the density values obtained, which are analyzed using the Kernel Density tool available in ArcGIS. After a sensitivity analysis of the size of the circular sliding window, a value of 2000 meters were used. This corresponds to the proposed default value. This is an optimized adjustment based on the size of the study area and the density of the point seed entered. The mapping was carried out independently for each type of mass movement.

RESULTS

Typology of mass movements

The inventory included 746 events, which are categorized into six types: (1) rockfalls, (2) mudflows, (3) debris flows, (4) deep-seated landslides (i.e., deep-seated rotational landslides, boulder slides, and complex landslides), (5) bank shallow landslides, and (6) road shallow landslides (Tab. 1), (Fig. 4-5-6).

Mass movements can be classified according to their displacement rate by dividing them into two categories: slow movements, such as landslides, and fast, sudden movements, such as flows and rockfalls.

Rockfall corresponds to a phenomenon of detachment of rock blocks or stones from a steep slope, where the detachment occurs along a surface with minimal or negligible shear displacement (Cruden and Varnes 1996). These phenomena are frequently encountered in the study area (Fig. 5) and they are primarily associated with the geological nature of slopes, which constitutes a fundamental predisposing factor controlling their occurrence. The majority of the documented rockfalls occur on slopes predominantly composed of resistant and fractured rocks, such as the massive micritic limestones of the Lias, which are overlain by often impermeable soft formations (marls and clays). Superficial flows, arising from fractures within rock formations, consequently facilitate the dispersal, deposition, and accumulation of materials at the base of steep rock cliffs or downstream in valley bottoms. The materials resulting from rockfalls often exhibit a distribution in heterogeneous clusters (Fig. 4-A-B). In mountainous areas, it is common for this type of phenomenon to occur on a daily basis. The risks posed by Rockfalls are particularly significant due to their sudden nature, where rockfalls can block transportation routes.

Landslides are slow, deep-seated displacements of a slope (Fig. 4-C) that occur several hundred meters below the earth's surface. In the study area, they are more common than rockfalls (Fig. 5).

Flows (mudflows and debris flows) are characterized by the rapid and sudden movement of a mass of fragmented

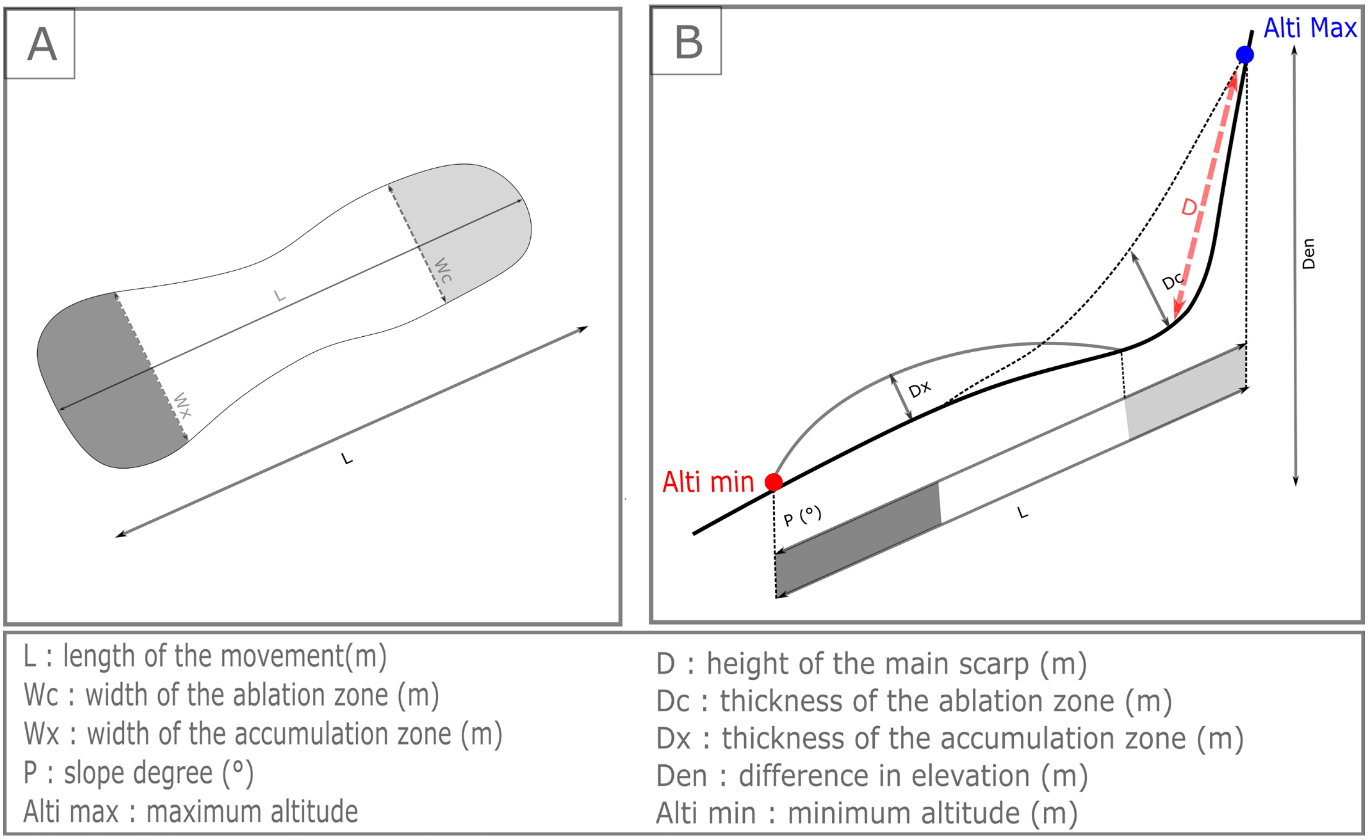

Figure 3. Schematic representation of morphometric indices used for the mass movement analysis. A: planar view, B: profile view.
Figure 3. Représentation schématique des indices morphométriques utilisés pour l'analyse des mouvements de masse. A :vue plane, B : vue de profil.

and heterogeneous material with significant water content and varying viscosity (Varnes 1978, Hungr 2014). In the Rif, flows are characterized by steep slopes at the source zones of the material and an accumulation or deposition zone downstream. These phenomena can correspond to slope failure in waterlogged terrain and occur during extreme drought with heavy rainfall (Maurer 1986). They are evenly distributed in the study area, often at intermediate elevations (Boukhres *et al.* 2022), along convex and concave slopes in water concentration zones (Fig. 4-D). They are also less frequent in the study area than rockfalls and deep-seated landslides (Fig. 5).

Superficial landslides (bank shallow landslides (Fig. 4-E) and road shallow landslides (Fig. 4-F) are abrupt movements that originate from the upper part and lead to the displacement (separation) of the entire debris cover from the surface (Maurer 1986). They are less frequent compared to other types in the study area.

Statistically, and based on the results obtained for the intact phenomena, landslides are the most frequent, accounting for 25% of the events (i.e., 186 events). Rockfalls are also well represented, with 158 events (21%). Mudflows account for 16% of the total (122 events), and debris flows 13% (95 events). Finally, bank shallow landslides account for 13% (93 events) and road shallow landslides for 12% (92 events). In terms of area, landslides and rockfalls are the most important phenomena, accounting for 4.2 and 4.1 % of the total area of the study area (16.4 and 15.1 hectares). The other phenomena occupy less than 0.5% of the study area (less than 3 hectares). At this point, it should be noted that the area of the phenomena (including rockfall) includes both ablation and accumulation zones and that the calculated area is planimetric.

Spatial distribution of mass movements

The results are presented in the form of six maps showing the density of the recorded mass movements and the location of their centroids for better readability on a regional scale (Fig. 7). The spatial distribution of rockfalls forms five clusters in the central parts of the main massifs surrounding the Ouergha valley. They are homogeneously and continuously distributed along the upper slopes at high altitudes. These slopes are characterized by resistant, fractured rocks, mainly different types of limestone (Liassic and Jurassic) overlying soft, often impermeable formations (marl and clay).

Deep-seated landslides are evenly distributed across the study area. They are found at the base and in the middle of slopes at low altitudes (90% of landslides are triggered at altitudes between 320 m and 1000 m and only 10% between 1000 m and 1846 m). They mainly occur in soft geological formations of different ages: black clay-silt-pelite, black pelite and grey marl.

Mudflows are mainly located in the central part of the study area, on the right bank of the Ouergha valley. They are found in significant concentration on Flysch outcrops (Miocene), at a moderate level on black clay-silt Pelites (Barremian), and occur sparsely on mixed formations located at the transition between limestone beds and marly limestone (Upper Jurassic), particularly on steep slopes. Triggering areas are preferentially located at the summit escarpments, and tend to propagate long distances downstream to the slope breaks at the bottom of the slopes.

Debris flows are concentrated in two main areas to the east and west of the study area. These debris flows occur at the boundary between resistant and soft formations when

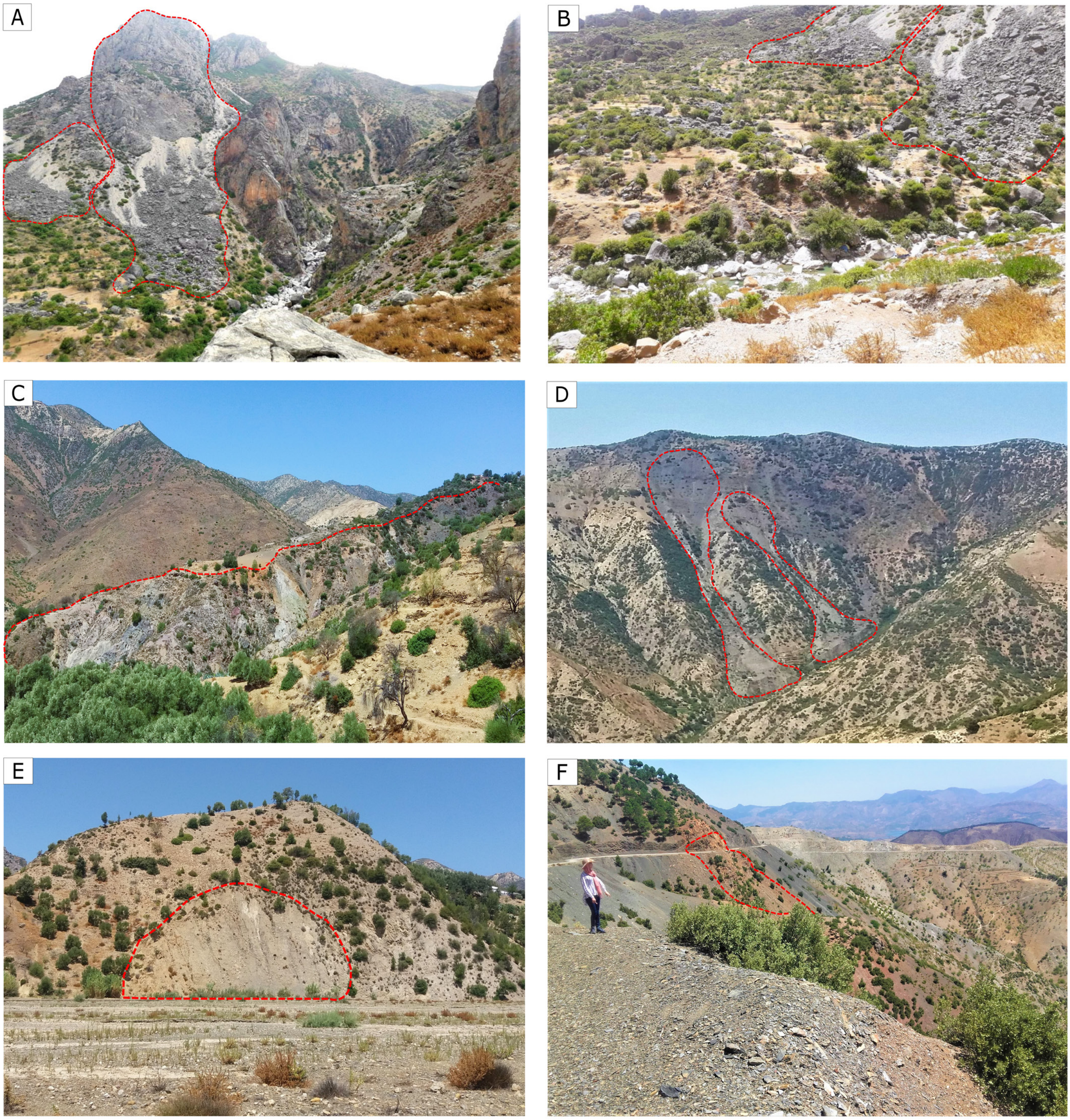

Figure 4. Some examples of inventoried mass movements. A: rockfalls; B: accumulation zone of the rockfall (A); C: deep-seated landslides of the slope; D: mudflows; E: bank shallow landslides; F: road shallow landslides. Pictures are taken in the field of the study area.
Figure 4. Quelques exemples de mouvements de masse inventoriés. A : éboulements ; B : zone d'accumulation de l'éboulement (A) ; C : glissement profond du versant ; D : coulées de boue ; E : glissement peu profond des berges ; F : glissement peu profond de la route. Les photos sont prises sur le terrain de la zone d'étude.

the main prominent scarp of the triggering zone consists of solid material (limestone and calcarenite) covered and/or overlain by softer material (marl) or debris. Specifically, they occur on slopes characterized by the following lithological composition: (i) an irregular alternation of pelites, highly quartzose arenites and conglomerates with megacreccias containing some decimeter-sized limestone clasts (Miocene), (ii) flysch (Miocene), (iii) marl-limestone layers (Barremian), (iii) thick-bedded limestone and/or marly limestone (Upper Jurassic) and (iii) Ferrysch formations (Malm). Their dispersal areas often extend to the downstream watercourse and offer the potential for the remobilization of material during flood events.

Bank shallow landslides are the result of fluvial erosion processes, often characterized by torrential flows that lead to the erosion of soils near the banks and the reshaping of the material flowing through. This erosive effect favours the development of landslides, which occur in conjunction with

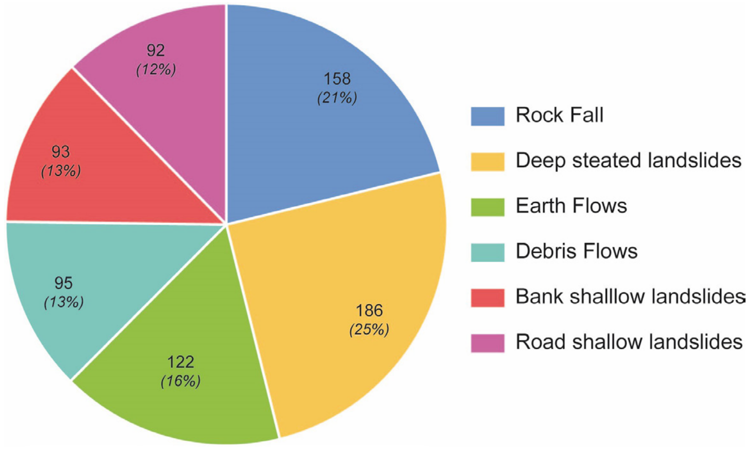

Figure 5. Distribution of the mass movements types over the Dhar Souk area.
Figure 5. Distribution des types de mouvements de masse dans la zone de Dhar Souk.

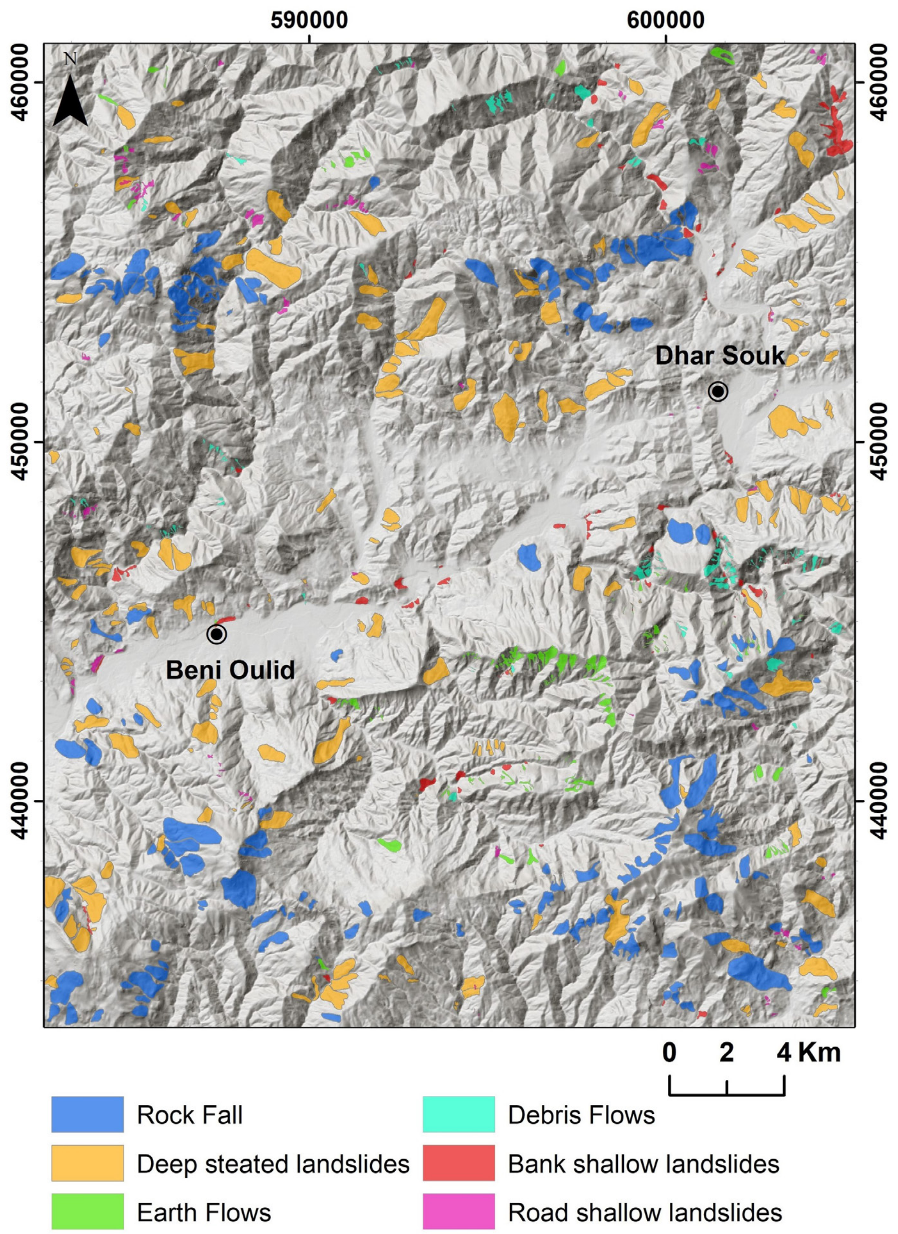

Figure 6. Inventory map of mass movements in the Dhar Souk region.
Figure 6. Carte d'inventaire des mouvements de masse de la région de Dhar Souk.

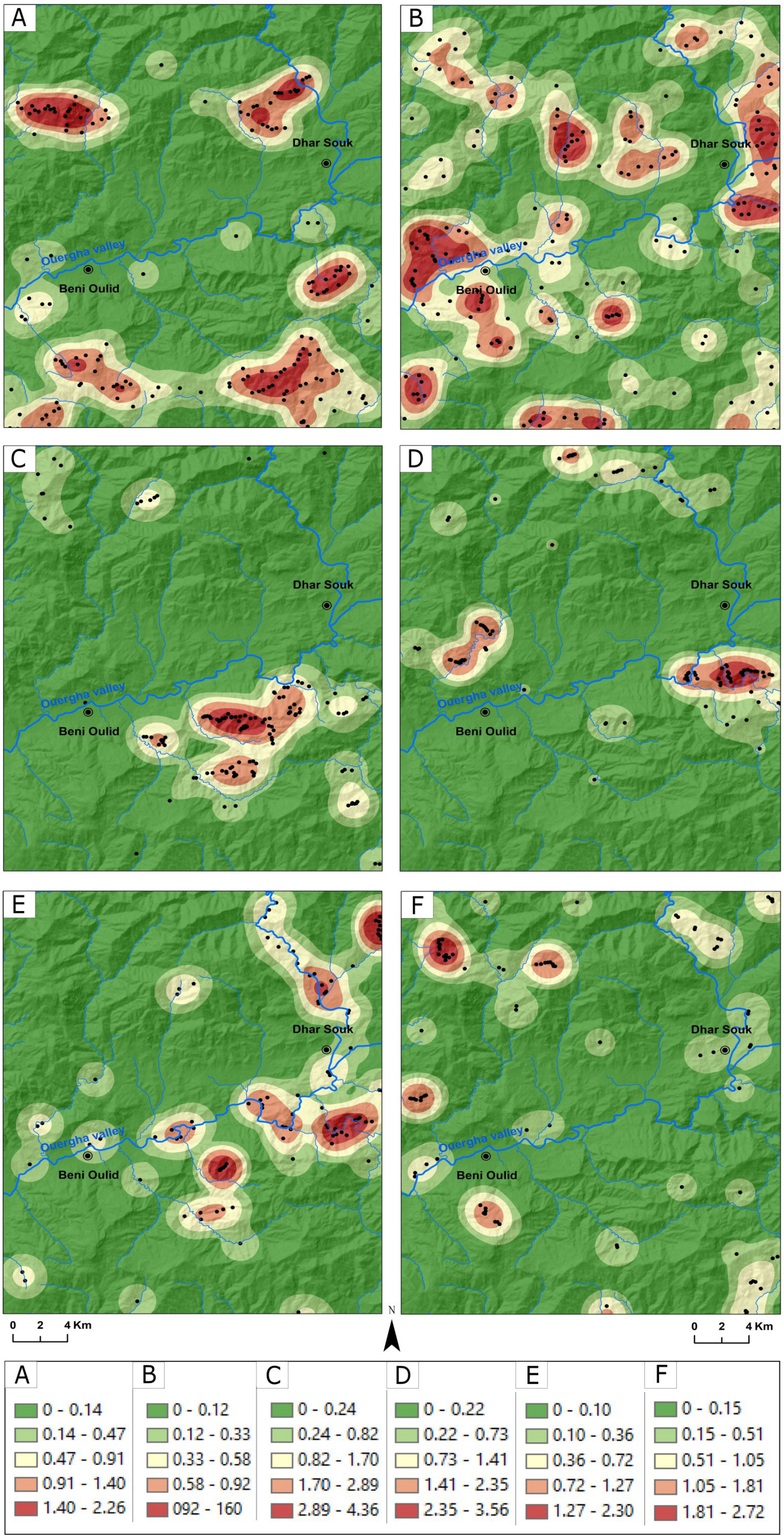

Figure 7. Density map of mass movements (number of mass movements per km²). The black dots correspond to the inventoried phenomena. A: density of rockfalls, B: density of deep-seated landslides, C: density of mudflows, D: density of debris flows, E: density of bank shallow landslides, F: density of road shallow landslides.

Figure 7 : Carte de densité des mouvements de masse (nombre de mouvements de masse par km²). Les points noirs correspondent aux phénomènes inventoriés. A : densité des éboulements, B : densité des glissements profonds, C : densité des coulées de boue, D : densité des laves torrentielles, E : densité des glissements superficiels de berge, F : densité des glissements superficiels de route.

the undercutting of the banks. They appear on steep slopes with concave and convex shapes, on soft formations, as well as on alluvial deposits composed of fine elements, silt and clay. These phenomena are found along the watercourses of the Oued Ouergha and its tributaries in loose formations (marl and clay) on highly incised slopes.

Road shallow landslides are often triggered by road construction work. They occur near roads (regional road RR510, provincial roads RP5337 and RP5404 and tracks), either uphill (road embankments) or downhill (cut slopes). These activities disrupt the natural balance of the slopes by filling or removing a considerable amount of soil, weakening the stability of impermeable soils (marl and clay) and disrupting surface flows. These changes can lead to water accumulation in impermeable soils, favouring the development of landslides.

Morphometry of mass movements

Table 1and Figure 8 show a selection of three parameters used to analyze the morphometry of mass movements. The area indicates the intensity of the observed phenomena and allows a first hierarchical classification of the typology according to this criterion. Rockfalls and deep-seated landslides generally are characterized by a much larger surface area than other phenomena (16.4 and 14.5 ha on average, respectively). Flows (mudflows and debris flows), bank shallow and road shallow landslides are characterized by smaller average surface areas, between 1.6 and 2.4 ha. The maximum values also reveal an overall ratio of 1 to 10 between rockfalls and deep-seated landslides compared to the other types of processes.

In addition to the surface area, the length of the slope movements can also be used to document the dispersal potential. A total of three groups can be distinguished. As with the surface area, rockfalls and deep-seated landslides are characterized by long lengths, on average about 600 meters, with standard deviations between 330 and 360 meters. Lengths of around 300 meters represent mudflows and debris flows. Bank shallow and road shallow landslides have shorter lengths, on average between 170 and 190 meters.

The slope is more an indicator of the morphological context in which the phenomena are triggered and spread. The two types of flows have the steepest gradients, averaging 37° and 30°, respectively. Rockfalls are characterized by modest average slope values for this phenomenon (25°), as both triggering and propagation zones are considered. Bank sallow and road shallow landslides are characterized by similar values between 24° and 26°. Finally, deep-seated landslides usually start in less steep areas with an average value of around 20°.

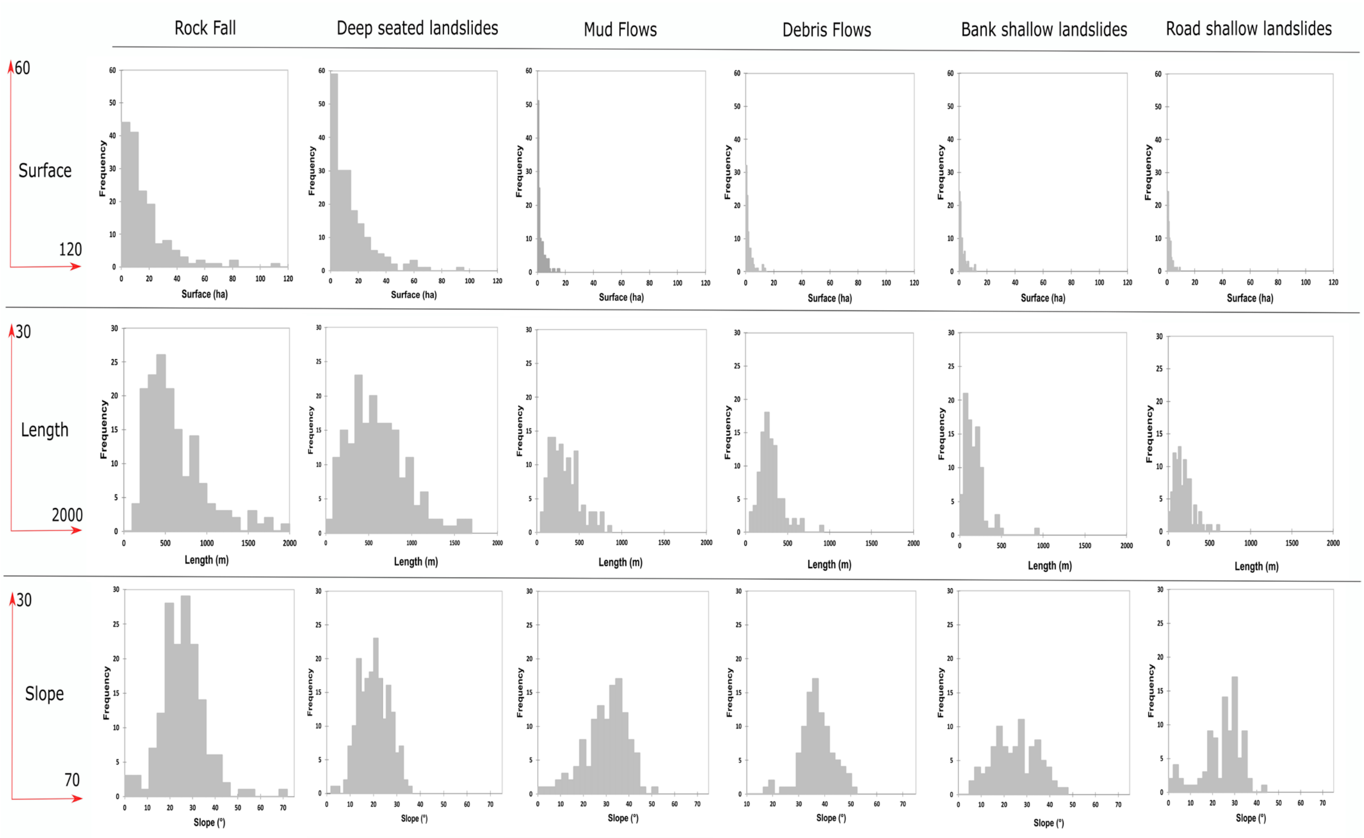

Figure 8. Histograms show the distribution of the inventoried mass movements' most important morphometric features (surface area, length, slope). The diagrams were created with XLSats.

Figure 8. Les histogrammes montrent la distribution des caractéristiques morphométriques les plus importantes des mouvements de masse inventoriés (surface, longueur, pente). Les diagrammes ont été créés avec XLStats.

Table 1. Summary statistics for the main morphometric parameters investigated.
Tableau 1. Statistiques récapitulatives des principaux paramètres morphométriques étudiés.

Variable	Type	Min	Max	Mean	St. dev.
Surface (ha)	Rock Fall	0.8	113.5	16.4	17.1
	Deep-seated landslides	0.1	94.7	14.5	15.1
	Mudflows	0.1	15.7	2.4	3
	Debris Flows	0.1	13.9	2.1	2.6
	Bank shallow landslides	0.1	11.5	2.4	2.6
	Road shallow landslides	0.02	9.2	1.6	1.6
Length (m)	Rock Fall	153	1957.2	619.5	353.8
	Deep-seated landslides	62.7	1671.9	609.1	338
	Mudflows	58.5	878.5	333.4	173.8
	Debris Flows	66.3	928.8	296.9	139.5
	Bank shallow landslides	19.1	941.1	173.7	130
	Road shallow landslides	19.8	614.6	183.2	112.3
Slope (°)	Rock Fall	2.9	70.8	25.8	9.7
	Deep-seated landslides	2.4	35.5	20.3	6.3
	Mudflows	2.3	51.6	29.9	9.3
	Debris Flows	17.7	51.3	36.9	6.3
	Bank shallow landslides	6	46.9	24.8	9.7
	Road shallow landslides	0.7	43.6	24.3	9.1

DISCUSSION

Dhar Souk mass movements in the context of the Moroccan Rif

The comparison of the 1:50.000 inventory (of this study) with the 1:100.000 inventory of the province of Taounate (Sahrane *et al.* 2022) and the 1:300.000 inventory of the entire Moroccan Rif (Mastere *et al.* 2020) shows a good agreement in the distribution of the slope movements recorded by the different authors (Fig. 9). Indeed, the entire study area is affected to varying degrees by mass movements concentrated in favoured sectors along the main mountain massifs surrounding the Ouergha valley and closely related by their typology to the slope and nature of the affected areas. Not surprisingly, the number of phenomena found correlates with the scale of this work. The inventory was conducted at a scale of 1:50.000 with field checks, identifying more phenomena (746 of all types, including 371 landslides of all kinds: 186 deep-seated landslides, 93 shallow landslides and 92 shallow roadside landslides) than the inventory by Mastere *et al.* (2020), which identified a total of 65 phenomena with three types of mass movements (37 landslides, 15 debris flows and 13 rockfalls). The same applies to the 1:100.000 scale inventory by Sahrane *et al.* (2022), who identified 128 phenomena of two types: deep-seated and shallow landslides.

Inventory quality and data acquisition prospects

The question of spatial and temporal completeness is a central issue in the inventory of mass movements (Glade & Crozier 2012, Broeckx *et al.* 2018). The problem of subjectivity and the difficulties in assessing quality have also been widely addressed in the literature (Van Westen 1993, Guzzetti *et al.* 2000, Van Westen *et al.* 2006, Fressard *et al.* 2014). The inventory produced in this study was compiled using freely available data, including satellite imagery available on Google Earth Pro, topographic maps, and subsequently verified in the field. However, the satellite coverage of the study area is not complete. Significant gaps exist between 2001 and 2013, between 2013 and 2016, and between 2016 and 2018. Therefore, it is difficult to determine the exact date of occurrence of most phenomena, especially since a large part was already visible in the 2013 images.

Nevertheless, it is possible to identify the triggering period for some phenomena based on a morphological analysis of the freshness of the forms between the available image series +/- 1 to 5 years, as shown in Figure 10. This type of data could be used to derive temporal probabilities of occurrence in the context of hazard mapping (Guzzetti *et al.* 2006, Coe *et al.* 2004, Frattini *et al.* 2007, Thiery *et al.* 2021). In these mountainous regions, the resolution of the available images is sometimes insufficient to detect with certainty many phenomena, especially smaller ones, and certain specific surface indices that can be used to characterize the state of activity. In this respect, systematic checks in the field are essential to ensure the consistency of the inventories.

This is in line with the conclusions of Jacobs *et al.* (2017) on the quality of inventories, especially in the subtropics and tropics, where there are still considerable uncertainties, mainly due to the lack of spatial data (aerial or satellite images with sufficient spatial and temporal resolution and DEMs). Field investigations can improve the spatial accuracy of reported events by up to 67%.

In this case, the inventory includes 746 events, listing only events whose observation is dependable following a selection process based on the attribute table of an initial inventory containing 892 events (Boukhres *et al.* 2022). This choice has dropped events with uncertainties, notably due to the difficulty of conducting a systematic field survey.

More detailed mapping will be necessary for hazard mapping by enlarging the working scale (1:25.000 or 1:10.000) and conducting systematic field investigations in conjunction with population surveys. In this way, we can inventory small-scale phenomena and determine the typologies, boundaries and activity states of phenomena whose identification is doubtful.

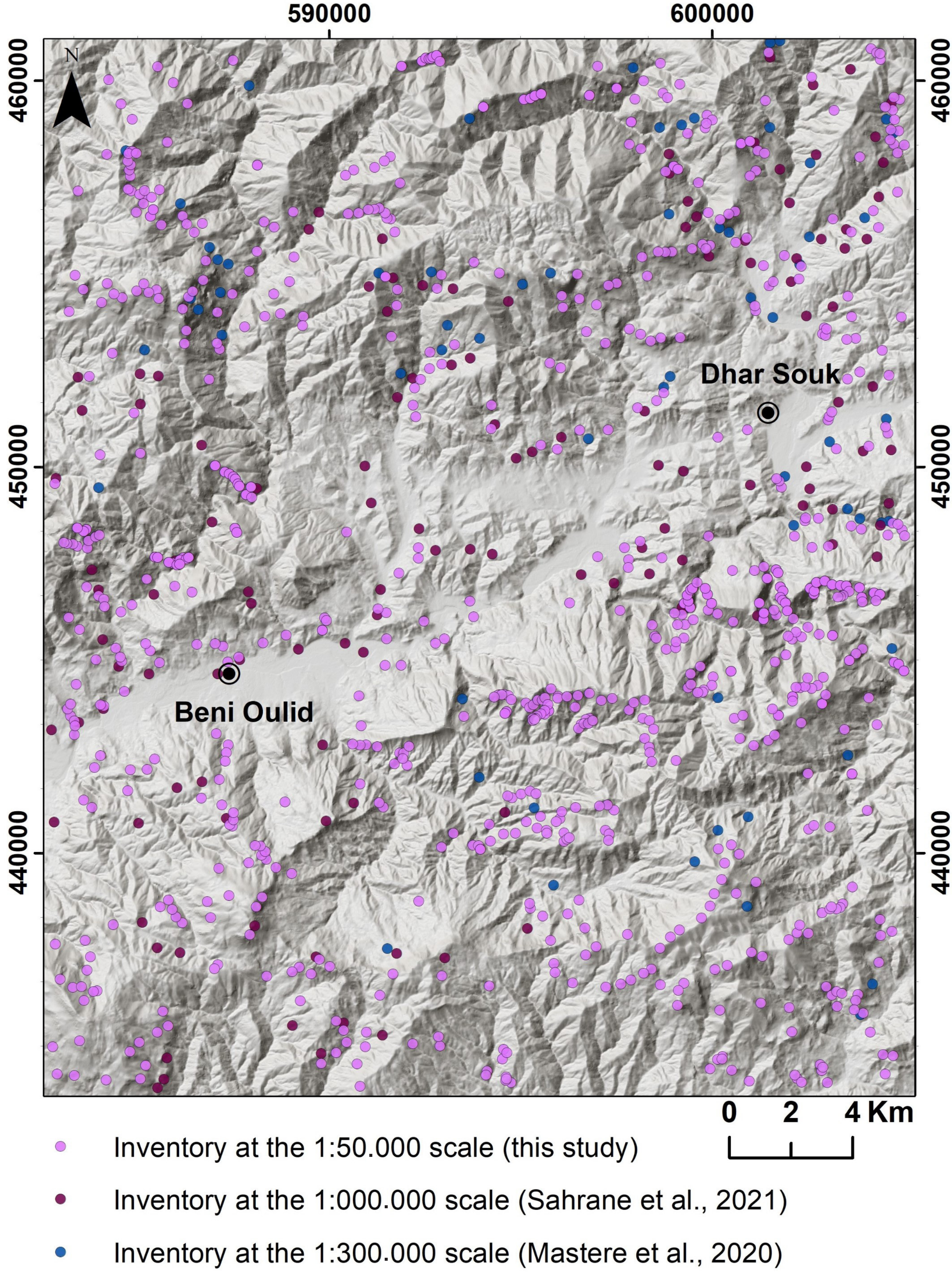

Figure 9. Comparison of the 1:50.000 inventories (this study) with the 1:100.000 inventory of the province of Taounate (Sahrane *et al*. 2022) and the 1:300.000 inventory of the entire Moroccan Rif (Mastere et al. 2020).

Figure 9. Comparaison des inventaires au 1:50,000 (cette étude) avec l'inventaire au 1:100 000 de la province de Taounate (Sahrane et al. 2022) et l'inventaire au 1:300,000 de l'ensemble du Rif marocain (Mastere et al. 2020).

Figure 10. Illustration of the triggering of a debris flow using multitemporal images of Google Earth Pro.
Figure 10. Illustration du déclenchement d'une coulée de débris à l'aide d'images multi-temporelles de Google Earth Pro.

CONCLUSION

The growing social demand for comprehensive natural hazard management plans, especially those related to mass movements, is a challenge faced by many countries, including Morocco. Moroccan authorities recognize various phenomena, such as rockfalls, mudslides, landslides, subsidence, collapses, and avalanches, as significant risks. This vulnerability is particularly pronounced in mountainous regions, notably the Rif mountains, due to their unique geological and climatic conditions.

This research represents a significant step in understanding and addressing mass movement hazards in the Rif region, with a focus on the Dhar Souk area. It presents an inventory that categorizes the different types of mass movements affecting the study area and provides an initial qualitative analysis of their local triggering context. Additionally, the study offers valuable insights into the spatial morphometric characteristics of these phenomena, such as rockfalls, deep-seated landslides, mudflows, debris flows, bank shallow landslides, and road shallow landslides observed in the study area.

The medium-scale inventory conducted at 1:50.000 fills a crucial knowledge gap by documenting 746 confirmed mass movement events affecting the study area. Rockfalls and deep-seated landslides are the most frequent, followed by mudflows and debris flows, while bank shallow and road shallow landslides are less common. Importantly, a statistical analysis reveals the predominance of rockfalls and landslides in terms of size and area extent.The comparison with available regional-scale inventories (i.e., 1:100.000 and 1:300.000) highlights the added value of a mesoscale approach in identifying phenomena from a risk management perspective, including the number of events counted, typology, and precision of boundaries. Despite the valuable contributions of this study, there are limitations, particularly concerning the subjectivity and completeness of the data. For example, the aerial coverage of the study area on Google Earth is not comprehensive, making it challenging to estimate the evolution, number, and timing of mass movements on a temporal scale. Therefore, estimating the evolution, number, and timing of mass movements on a temporal scale remains challenging. It would be necessary to supplement large-scale aerial coverage for missing dates to facilitate the monitoring of the spatiotemporal evolution of the inventoried events and the interpretation and detection of the year of occurrence of a specific phenomenon.

In conclusion, the study's innovative methodology and comprehensive inventory provide a solid foundation for ongoing and future research in the Rif region and similar regions worldwide. These 1:50.000 scale inventories will be crucial in correlating mass movement phenomena with predisposing and triggering factors, contributing to a more thorough susceptibility, hazard, and risk assessment for each identified type. This research facilitates a more comprehensive understanding of mass movement hazards in the Rif region, improving preparedness and resilience. Additionally, the results have broader implications, supporting national and international disaster risk management efforts. Expanding the scale of the study to examine sub-sectors at 1:25.000 or 1:10.000 scales, accompanied by the development of higher spatial resolution data, would enable more precise comparisons and enhance the effectiveness of mitigation strategies for this study area.

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