



Rockfall characterization and stability assessment of Korbous cliff using GIS

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Abstract

The purpose of this study is to map and geographically locate areas with a high probability of natural events occurring such as “rockfall”. In this context, a multi-method approach is proposed to characterize and evaluate the potential vulnerability of an unstable ground as well as rockfall risk, through morpho-tectonic, geological, and morphometric analysis integrated into a geographic information system (GIS). Several parameters such as slope, lithology, lineaments, morphology, land use, and rainfall have been integrated and indexed in a geographic information system to be able to develop the rockfall risk map that allowed us to detect and geographically delimit the unstable areas in the Korbous cliff. The studied area presents a contrasted territory, from both morphological and geological points of view. The steep slopes’ rockfalls are quite frequent and constitute a potential risk to infrastructure and habitats at the bottom of slopes such as Korbous village, Ain Oktor, and MC 128 road. The proposed rockfall risk map, in this study, would serve as a guide and decision-support tool for the choice of preventive measures for reducing disaster risk (RDR).

Keywords Slope instability · Morphometric · Landslide hazard · Risk · Morpho-tectonic

Abbreviations

RDR	Reducing disaster risk
GIS	Geographic information system
ASTER	Advanced spaceborne thermal emission and reflection radiometer
DEM	Digital elevation model
NIM	National Institute of Meteorology
N	North
N–S	North–South
E–W	East–West
ENE–WSW	East North East–West South West
SSE–NNW	South East–North West

Introduction

Despite the evolution of recognition, the multitude of techniques in addition to the improvement of mitigation measures, land movements that still constitute a source of danger with negative social, economic, and environmental repercussions, can sometimes have catastrophic consequences (Eberhardt et al. 2001).

Several regions in Tunisia’s north-east are facing the “rockfall” hazard, in particular, Korbous cliff which presents a very contrasted territory, from both morphological point of view with its mountains and its coastal exposure (Ben Hammouda et al. 2014; Ben Mammou et al. 2006) and geological point of view with rugged lithological formations characterized by the diversity of their resistance (sand limestone, sandstone, marl) (Ben Salem 1992).

The steep slope rockfalls are quite frequent in the study area; they constitute a potential risk to the infrastructure and habitats at the slope’s bottom as Korbous village, Ain Oktor, and the MC 128 road (Ben Mammou et al. 2006) (Fig. 1).

Several parameters could interfere in the shaping and changing of the rocky clump morphology throughout time (El Aaggad et al. 2015; Hantz 2000), among which, we can mention the following:

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Fig. 1 Big rockfall blocked the road to Korbous

- The geology (Fig. 2) which is expressed on the ground of Korbous cliff by the contrast of competence resulting from the alternation of an unconsolidated geological formation (laminated clays) and a compact one (resistant sandstone) (Ben Salem 1992)
- The morpho-structures with steep slopes governed by the combination and the interaction of neo-tectonic (Fig. 7) and water erosion following a developed river system (Fig. 6), creating a morphometric envelope with an exhibition multi-directional surface and slopes which often exceeds 25° (Fig. 5)

To this end, the GIS method used in this study, for the integration and database examination, aims to evaluate the role of these physical parameters in the morphological change of Korbous cliff and the degree of their influence in triggering the rockfall hazard. The identification and characterization of the risk associated with this sort of movement have been identified through the integration of a high-resolution digital elevation model “DEM,” which provides information and derived maps such as the hill-shade, stream network, convexity profiles, and the different sizes curves maps. The result compilation has helped to define better vulnerable landforms, unstable areas, and those with block detachments (Shantanu and Debi Prasanna 2017).

The Aster data and the 3-dimensional representation of a digital elevation model have served to identify the relief (slope, slope orientation, terrain roughness) and perform the geometrical treatment (the fault planes identification, study of the river system). Both the DEM and the derived maps processing and analysis have authorized the geo-morphological and structural characterization of the study area surface (Achu and Rajesh 2017; Hadji et al. 2018) which covers the entire Korbous massif from the village Mriisa in the south to the village Douala in the north. In this sector, the touristic Korbous village is connected to the rest of the Cap-Bon territory by the unique regional road (MC 128), often marked

by rockslides exposing the population and urban infrastructure to extreme danger.

This road runs along 13 km of the sea border and follows the northern foot cliff culminating at 155 m which presents a succession of steep slopes formed by massive sandstone bars organized in benches carved in sandstone and clays alternations.

To conclude, Korbous village and the MC 128 road are considered to be the most vulnerable mountainous sectors. Several segments of MC 128 road are cut through or along the hill’s feet, destabilizing the area, and can fail in a heavy precipitation event.

For this reason, the morpho-tectonic and morphometric analysis approach integrated into a geographic information system in addition to the stereographic projection were used in this paper, to characterize and evaluate the potential vulnerability of this unstable ground and to zone the rockfall spatial occurrence (Ben Hammouda et al. 2014; Ben Mammou et al. 2006; El Aaggad et al. 2015).

These methods have been chosen for their simplicity, operational rapidity, and their precision, and they could be a solution to predict, characterize, and evaluate the potential vulnerability of any unstable ground.

To mitigate the ground movement risk in this study area, a risk map was elaborated using the GIS method, which can be able to update the Spatiotemporal evolution of these phenomena and help the authorities in regional planning.

Study area

The study was carried out on the western side of Korbous cliff, located to the northwestern coast of the Cap Bon peninsula, on the right bank of Tunis Gulf with longitude $10^\circ 34' 07''$ East and latitude $36^\circ 48' 59''$ North (Fig. 2).

This structure attached to the governorate of Nabeul is located 60 km far from the capital Tunis.

The Korbous climate is largely influenced by its geographical location and its relief, characterized by high precipitation and a relatively moderate temperature.

Data and methods

This study aims to the digital mapping of the rockfall risk on Korbous cliff in the northeast of Tunisia. According to detailed morphometric features, lithological studies, and morphological analysis, the rockfall risk of the studied area was evaluated (El Aaggad et al. 2015).

The adopted approach used to achieve the goal of this study is carried out using the methodological flowchart below based on data processing and results’ analysis in a GIS environment (Fig. 3). For the realization of this work,

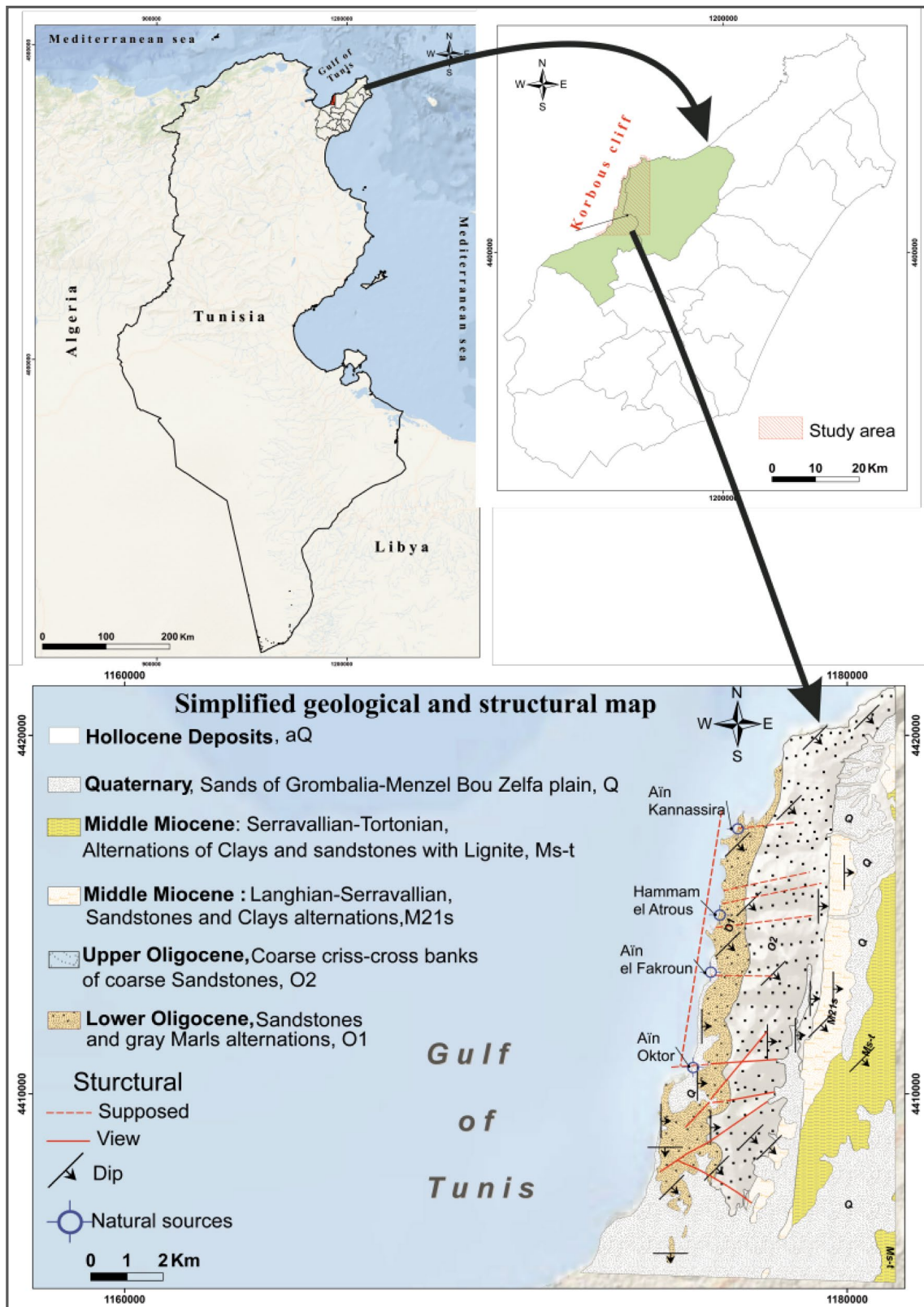


Fig. 2 Geographical position of Korbous cliff

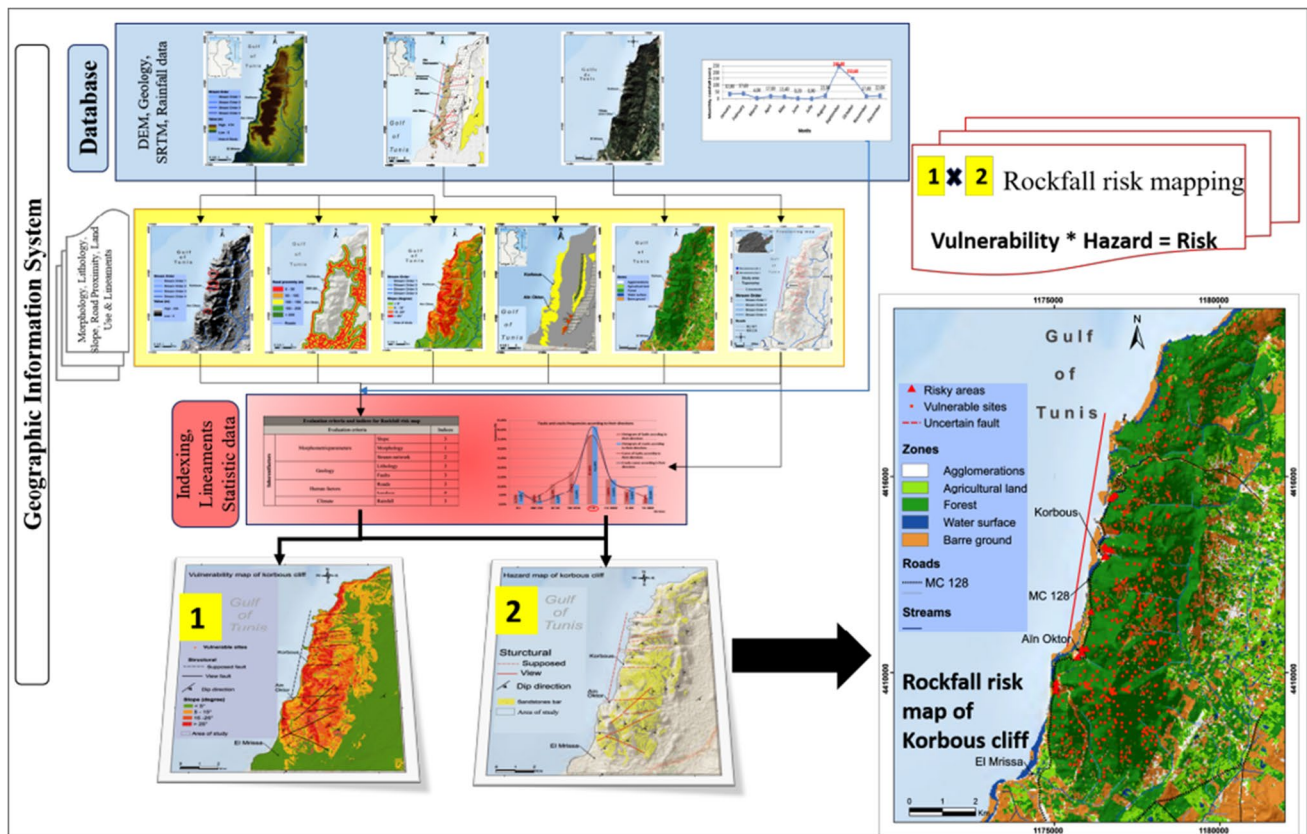


Fig. 3 Flowchart of the adopted methodology

two phases were followed. The first one consists to the use of Aster data to prepare a digital elevation model and a geographic information system which is adopted for the evaluation of linear, surface, and relief aspects; in addition to Satellite Imagery Sentinel 2 with a spatial resolution of 10 m for the establishment of land use map, at the end, the precipitation values were collected from the National Institute of Meteorology surface, and the 1/25,000 geological map was used to elaborate the lithological map. The second phase corresponds to the use of the thematic layers namely, slope, relative relief, land use, drainage density, road proximity, curvature, precipitation, and lithology which were integrated into a database for the assignment of weights to elaborate vulnerability and hazard maps used in the establishment of the rockfall risk map of Korbous cliff (Amaya et al. 2014; Feizizadeh et al. 2011).

Geological and morpho-structural overview

The Korbous cliff is a very steep slope with many steep embankments occupied by prominent sandstone bars forming continuous topographic landmarks and arranged

parallel to the rocky coast along the western edge of the northern Cap Bon Peninsula border.

At the top, the sedimentary series is consisted of massive sandstone and silty clay alternations; towards the summit, the hard sandstone bars abound and become thicker (2–3 m), forming fairly upright slopes (70 to 90°).

From a lithological point of view, the whole series is arranged in the Oligo-Miocene and corresponds to the stacking of terrigenous detrital sandstone-carbonate formations at the base Fm “Korbous” and “El Haouaria” surface (Ben Salem 1992; Hooyberghs 1977), Fm “Oued el Hammam,” “Aïn grab” and “Mahmoud” at the top surface (Hooyberghs and El Ghali 1990).

These essentially sandy series are affected by multi-directional faults varying from North-East to East-West; the most important one is the North 10 direction which corresponds to a large vertical fracture affecting the western flank of Korbous cliff limiting the golf of Tunis to the West-East. This fault delineates a fault system with a direction close to East-West and the most important one which passes by Ain Oktor cutting the Korbous rock massif in a series of parallel corridors characterized by the presence of detached blocks whose borders correspond

to natural discontinuities of stratigraphic and/or tectonic origins, cutting this massif into blocks mosaic with various shapes and volumes.

Geology and formations are part of the parameters previously cited, and they are expressed on the cliff by the contrast of competence resulting from the alternation of an unconsolidated soft and erodible geological formation (laminated clays) and the compact one (resistant sandstone) with high intensity of fracturing (Figs. 2 and 4)

Results

Slope

The majority of landslides occurrence depends on its slope angle derived from a digital elevation model and reclassified into four different classes: flat slope ($<5^\circ$), gentle slope ($5\text{--}15^\circ$), moderate slope ($15\text{--}25^\circ$), and very high slope ($>25^\circ$) surface (Achu and Rajesh 2017) as shown on Fig. 5 on which it is noticed that the prominent classes are the very low slopes, and the very high slopes which are hekkled and aligned in a North-South direction parallel to the direction of the constituent sandstone layers forming the cliff on which it develops the collapse phenomenon of detached elements which are cantilevered.

Morphology

Morphologically, a large extent of the cliff surface eastern part shows terrain with concave curvature; those are more or less stable via the land movement phenomenon (Achu and Rajesh 2017). The convexed one dominates the medium and steep slope relief part, and they are supposed to be unstable areas because of their role in triggering the rockfall phenomena.

In addition to that, the Korbous cliff is presented in a N–S direction parallel to the constituent layers which are sheared by the dominant E–W direction creating relatively tilted blocks at the crossing of the structural direction and the tectonic one.

The tilted blocks are shown on the morphological map (Fig. 6) by the shaded corners where we have collected the maximum of the detached blocks according to the principal compression dihedron.

Fracturing

Morpho-structures with steep slopes forming the Korbous cliff are the result of the interaction between neo-tectonic and water erosion that follows a well-developed drainage network flowing to the sea through the MC 128 road.

In this study, the fracturing factor is among the influencing factors (Fig. 7) that plays a very decisive role in

Fig. 4 Lithology

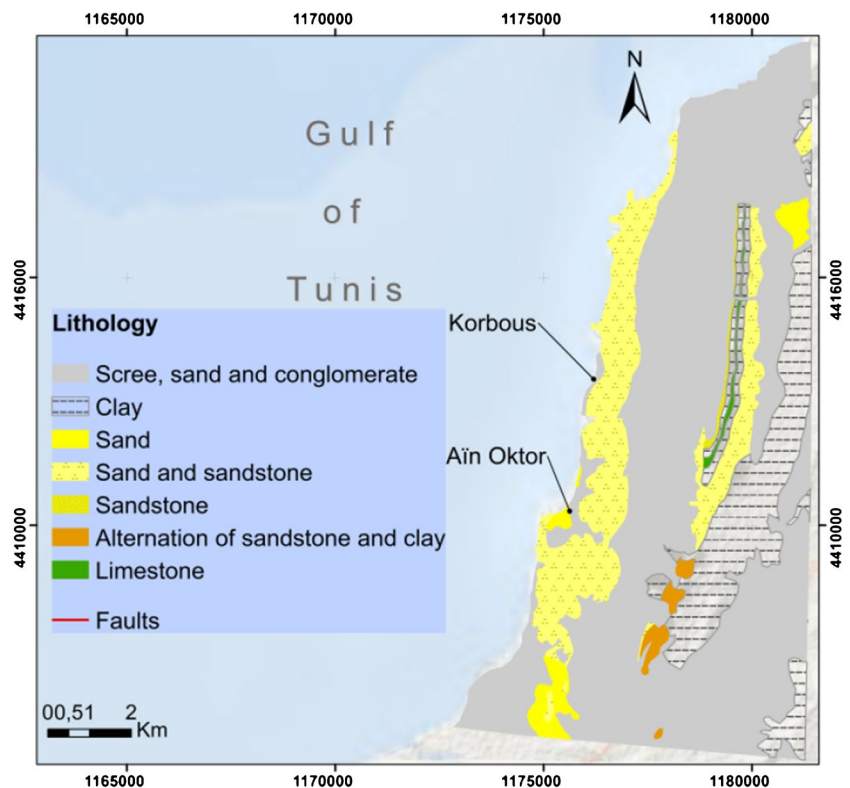
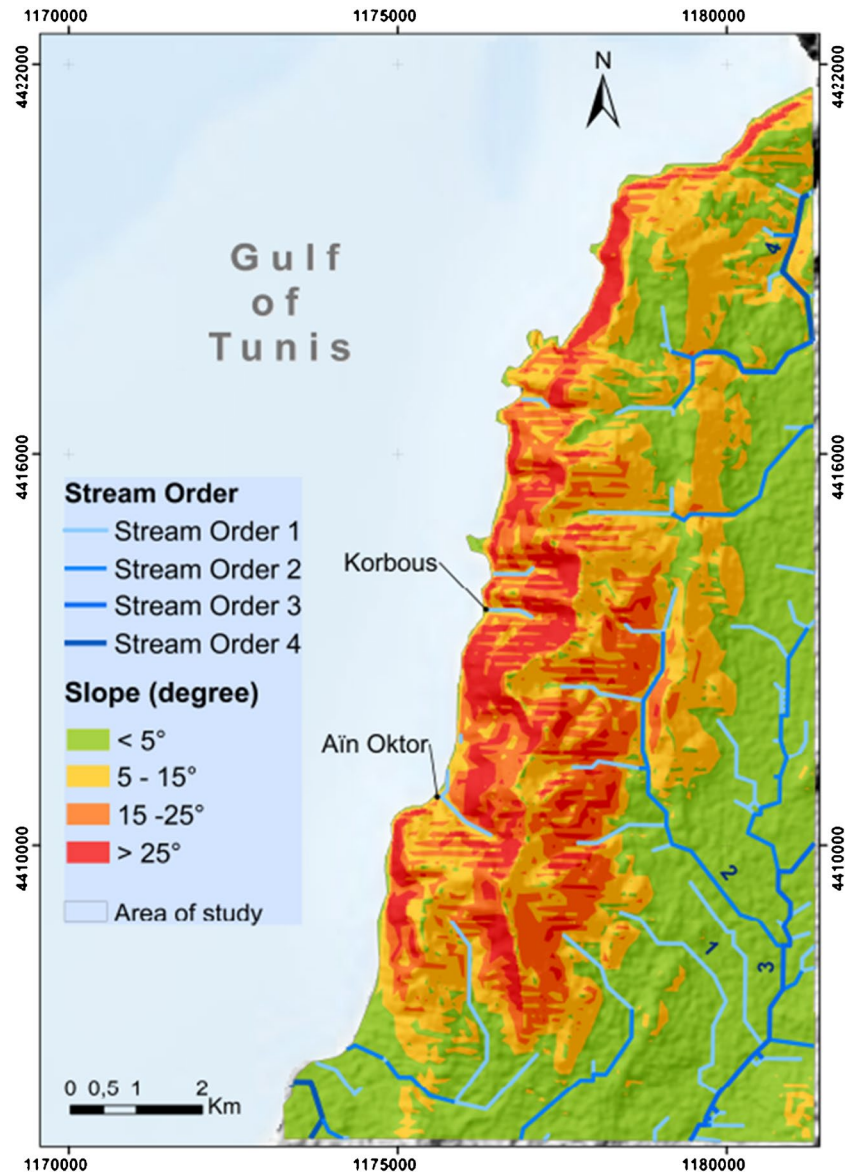


Fig. 5 Slope



landslide occurrence, in addition to the slope (Fig. 5) and lithological factors (Fig. 4).

To reinforce the founded results, a statistical study of all the fractures was made and illustrated on a modal-type histogram showing a dominant direction which is E–W (Fig. 7).

Two micro-tectonic observations among several were stereographically projected, showing as results that all the lineaments/fractures are organized as families with different directions showing the dominance of the E–W one, which confirms the fracturing histogram result.

The impact of the E–W direction is shown by 9 out of 10 blocks having one side of this direction (stereogram and rose diagram Fig. 7) while the other side is scattered

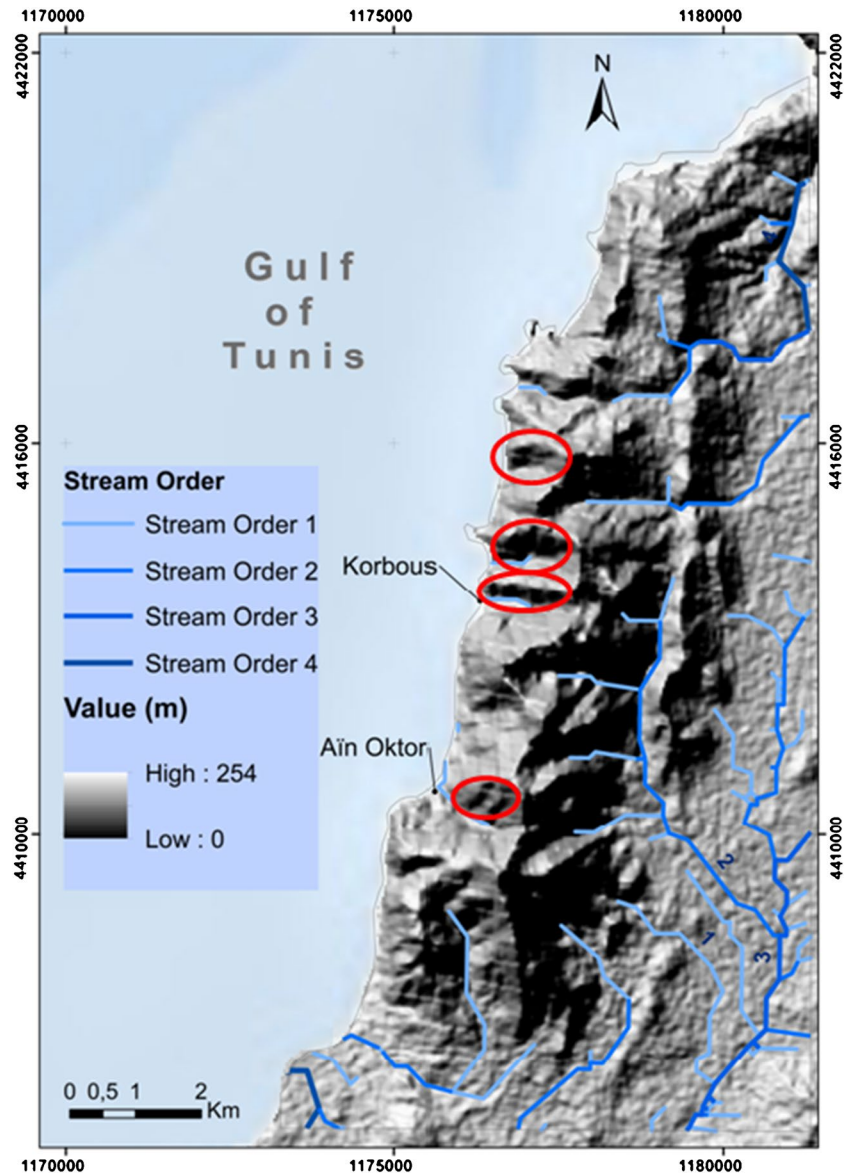
in the rest of directions, within particular ENE–WSW, and SSE–NNW.

Rainfall

Due to its geographical position, the north of Tunisia is characterized by a predominantly Mediterranean climate (semi-arid), especially influenced by cold and humid winds coming from the west in winter.

According to the National Meteorological Institute, our study area which shows an irregular diversity due to its relief (the relief configuration helps to determine the spatial distribution of precipitation), is characterized by hot, dry summer and mild and relatively rainy winter (certain

Fig. 6 Location of the unstable areas in the study area



exceptional meteorological events make it possible to become aware of the natural elements sporadic violence).

With its irregularity and torrential character, rainfall is one of the factors that play a very important role in triggering landslides in unstable sector surfaces (Hadji et al. 2018). The precipitation data of 2018 were collected and analyzed for this study (Fig. 8).

The result of the interaction between the topographic factor (slope) and the precipitation in September and October 2018 (Fig. 8) shows a very strong relationship between these events and the manifestation of landslide phenomena of sandstone blocks which mostly overlook the cliff clays, as well as the collapse phenomena, noticed along the roadside in November 2018 (Fig. 9) (El Mekki et al. 2017).

Indexing of vulnerability classes

Several spatial analysis techniques have been applied for the evaluation of risky areas in Korbous cliffs, and among these techniques are weighting, superposition, and combination which are very important operations for the final implementation of the rockfall risk map of our study area.

Each layer of spatial data corresponding to the factors selected (the most relevant factors having an influence on the vulnerability to landslides of Korbous cliff; among which are relief morphometry (slopes, curvature, and stream network), lithology, fracturing affecting the geological layers, precipitation, and land use) and pre-processed in a geographic information system is assigned

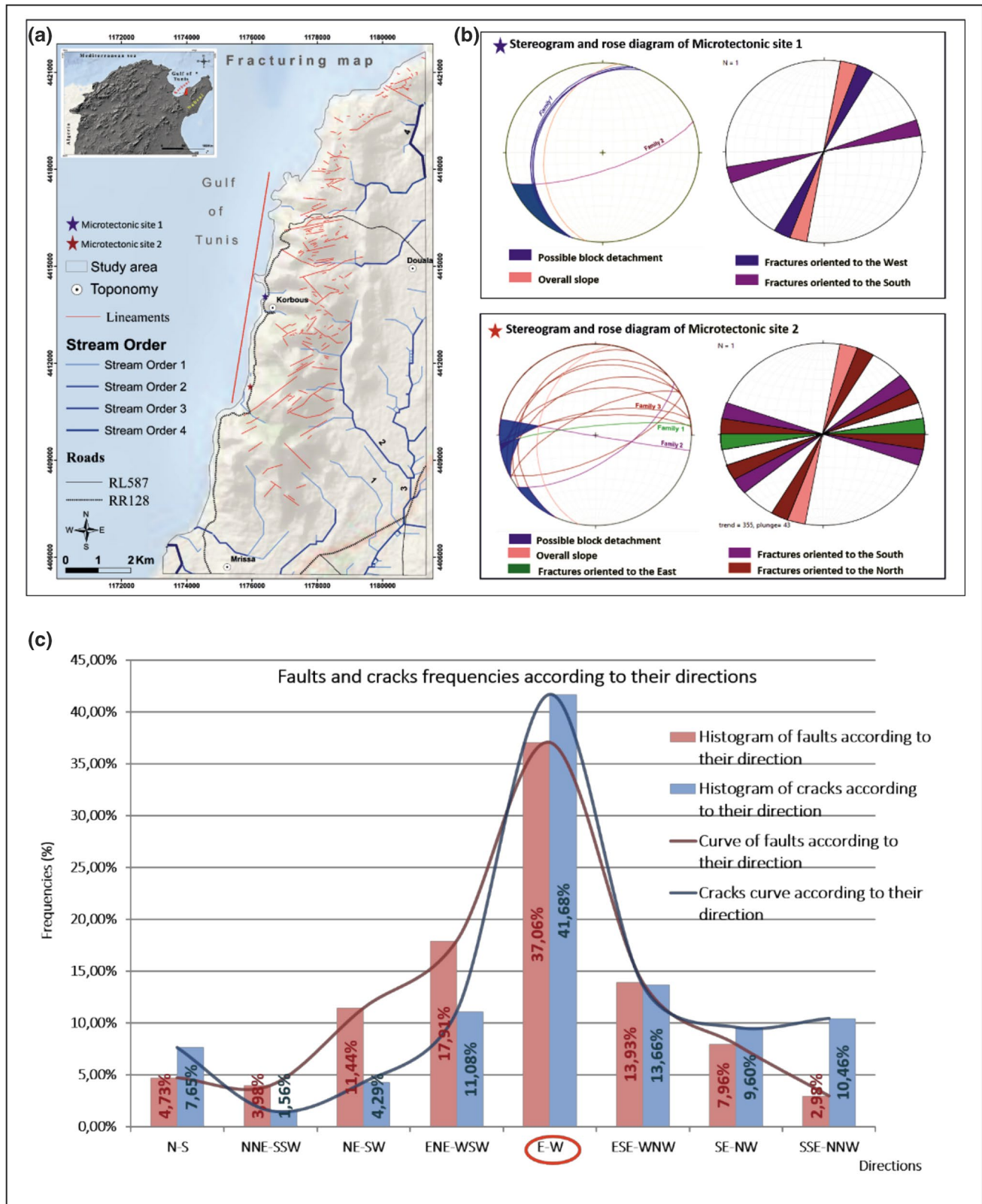


Fig. 7 Lineaments

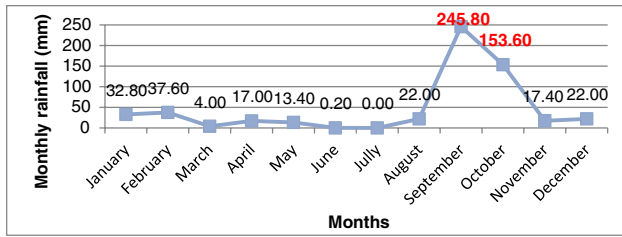


Fig. 8 Monthly rainfall in Nabeul 2018

a weight, to take into account the objective of mapping the Korbous cliff rockfall risk map carried out using a simple approach of combining the factors involved in the phenomena (Tables 1 and 2) (Amaya et al. 2014; Feizizadeh et al. 2011).

The different combinations of elementary thematic maps cited below and obtained by digital processing of all the spatial reference data lead to the creation of the resulting

Table 2 Indexing of inherent factors

Evaluation criteria and indices for a rockfall risk map			
Evaluation criteria		Indices	
Inherent factors	Morphometric parameters	Slope	3
		Morphology	1
		Stream network	2
Geology		Lithology	3
		Faults	3
		Human factors	Roads
Climate		Land use	2
		Rainfall	3

rockfall risk map which corresponds to a be-dimensional matrix obtained from the product of two parameters Eq. (1) (Metzger and D'Ercole 2011).

$$\text{Hazard} \times \text{vulnerability} = \text{Risk} \tag{1}$$

Table 1 Indexing of vulnerability classes

Factor					Index
Inherent factors	Slope morphometry				
	Slope type	Slope angle (degree)	Type of failure	Slope condition	
	Flat	<5	Slides with creep	Unfavorable	1
	Gentle	5–15	Slides with creep	Unfavorable	1
	Moderate	15–25	Creep	Favorable	2
	Very high	>25	Falls and topless	Very favorable	3
	Lithology				
	Scree, sand, and conglomerate				3
	Clay				1
	Sand				1
	Sand and sandstone				2
	Sandstone				3
	Alteration of sandstone and clay				2
	Limestone				3
	Fracturing conditions				
	Parallel faults				1
	Certain faults				2
	Intersecting faults				3
	Curve				
	Flat				2
	Convex				1
	Concave				3
	Land use classes				
	Agglomerations				3
	Agricultural land				1
	Forest				1
	Water surface				1
	Bare ground				2

Discussion

The main classes of issues retained for the rockfall risk map development are the agglomerations of Korbous and Ain Oktor villages, the Korbous forest, and the main road MC128 that links the villages together and which is considered to be the most vulnerable area to slope instability in mountainous regions. Several segments of the road network are found in particular in mountainous regions in the study area; they are severely cut through or along the hill's feet, destabilizing the area, and can fail in a heavy precipitation event.

Many ground movements (landslides, rockfall, and collapses) that have occurred in the past and occur to the present day in the study area are close to the MC 128 road, Korbous, and Ain Oktor villages.

The conjunction of the various factors depending on each other and their compilations in a geographic information system has enabled us to better define the vulnerable reliefs to the terrain instability hazard and to geographically limit the tilting and dihedral landslide zones which are manifested

by rockfalls in addition to landslides in sandstones overcoming soft levels affected by erosion (Fig. 9) (Shantanu and Debi Prasanna 2017). These hazards were mapped along the Korbous cliff and classified in terms of how threatening and dangerous they could be. This work was imperative to help plan and choose the necessary actions to stabilize the cliff and secure the road and the cities.

Conclusions

Rockfalls are part of the most damaging natural disasters, events of which human societies and environments were victims for decades, while many measures have been taken to control and reduce the impact of this destructive phenomenon.

This study highlighted the interaction importance between the different natural parameters (topography, slope, rainfall, drainage density, lithology, road proximity, and land use and land cover; see Figs. 2, 4, 5, 6, 7, 8, and 9) and their roles in risk triggering in Korbous cliff.

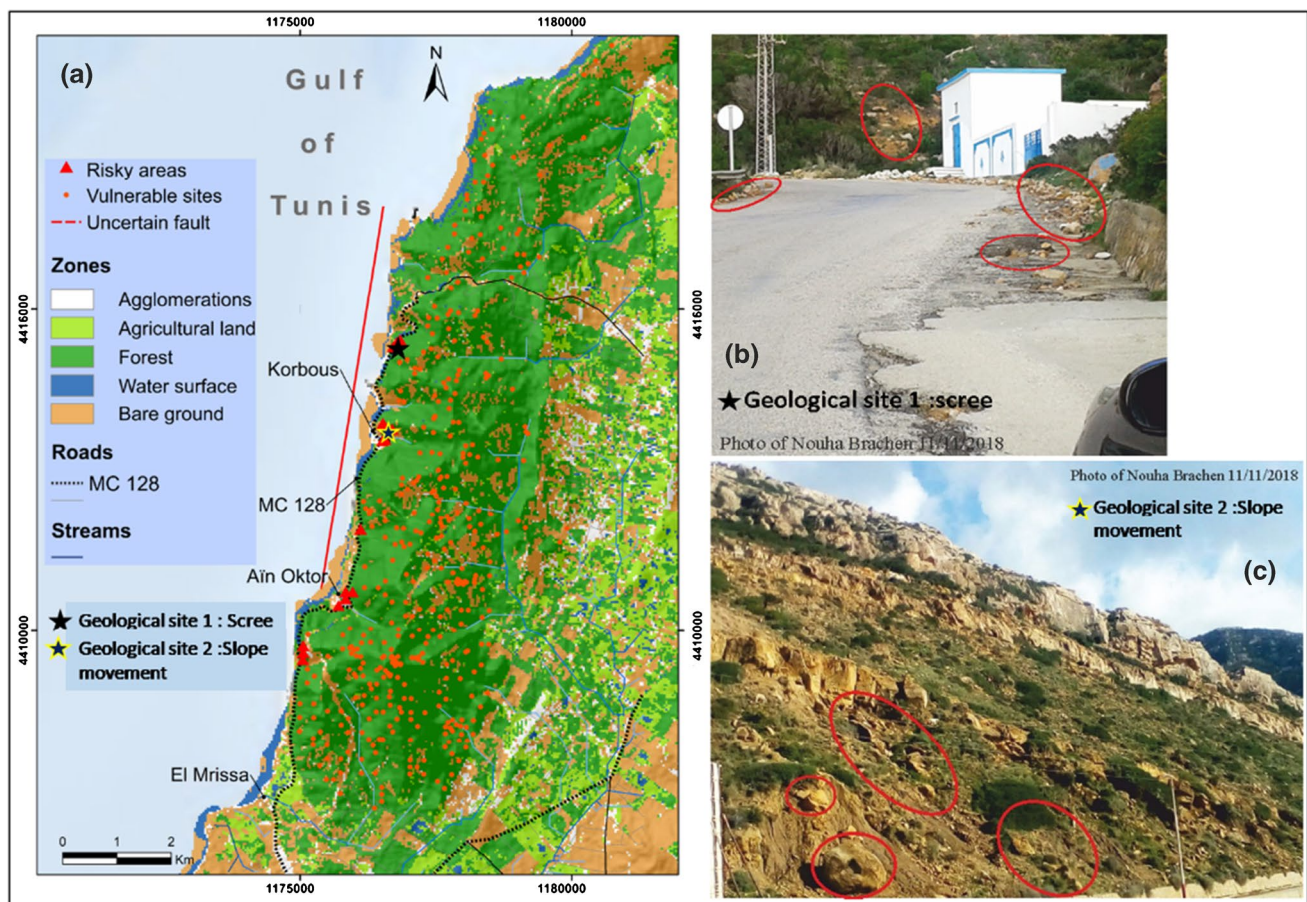


Fig. 9 a Korbous cliff rockfall risk map; b scree and crumbled bloc on MC 128 Road; c slope movements

The various combinations of indexed morphometric maps in a GIS environment and the product of the rockfall hazard map with the vulnerability one allowed the establishment of the Korbous rockfall risk map.

By examining this resulting map, we can deduce that the highly unstable regions are the agglomerations (Korbous and Ain Oktor villages) built along the MC 128 road which is characterized by several areas touched by the rockfall phenomenon.

This result has been validated by the field survey and the micro-tectonic approach used to determine the geometry and geomorphological location of potentially unstable blocks.

Indeed, the established maps in this study could constitute a basic document for any development facilitating rockfall risk management in any studied area.

Declarations

Conflict of interest The authors declare no competing interests.

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