Natural Hazards (2024) 120:14553–14570
https://doi.org/10.1007/s11069-024-06821-9

ORIGINAL PAPER

# Rock-fall runout simulation using a QGIS plugin along north–west coast of Malta (Mediterranean Sea)

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Received: 13 April 2024 / Accepted: 12 July 2024 / Published online: 19 July 2024


**Abstract**

Coastal instability in the form of rock fall is widespread along the northern coasts of Malta and is strictly connected to structural controls, such as lithology and tectonics. The local geological and geomorphological setting combined with extreme weather events, whose spatial and temporal occurrence is enhanced by ongoing climate and land use change, determines rock-fall hazard along the north–west coast of Malta, a hotspot for Mediterranean tourism. The present research portrays the results of a pilot study aimed at analyzing rock-fall runout probability along this stretch of coast. Cliffs and downslope terrains were the object of detailed field surveys. This included the detection of persistent joints in the source areas and the identification of slope-forming materials like debris and boulders present along the downslope terrains. The outcomes of the field surveys and GIS-based processing of topographic information were used for identification of the input parameters for rock-fall runout simulation. The latter was performed using a QGIS based plugin (QPROTO) that allows to determine expected runout extents and assess the rock-fall susceptibility. The result is the characterization and mapping of rock-fall runout probability zones along six investigated sites. The outputs of the research and the replicability of the method can be of interest for authorities aiming at defining risk management actions and undertaking mitigation measures compliant with sustainable development of coastal areas.

**Keywords** Rock fall · Runout simulation · QPROTO · GIS · Malta

## 1 Introduction

Climate-related coastal risks affect both coastal ecosystems and human settlements leading to considerable impacts on socio-economic assets (Magadza 2000; McLean et al. 2001; Senapati and Gupta 2014; Gallina et al. 2020; Masson-Delmotte et al. 2021). Coastal areas are prone to both marine and terrestrial processes including storm-surges, coastal erosion, inundation, slope instability and, on a longer-term, sea level rise (Neumann et al. 2015; Ranasinghe 2016; Vousdoukas et al. 2018, 2020; de Campos et al. 2020; Arabadzhyan et al. 2021; Hauer et al. 2021). Extreme events coupled with rising sea levels increase the risk due to storm surges and coastal inundation (McInnes et al. 2003; Hallegatte et al. 2011;

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Muis et al. 2016; Vousdoukas et al. 2017; Rizzo et al. 2022; Scardino et al. 2022; Vandelli et al. 2022; Hermans et al. 2023). Among these broader coastal risk issues, rock falls have a major impact on rocky coasts acting with high-energy (Carrión-Mero et al. 2021; Cinosi et al. 2023; Neziri and Bytyqi 2024) and having the potential to damage sizable swaths of coastal areas. Rock falls include a single or a group of rock blocks rapidly descending down a steep slope (Volkwein et al. 2011; Hungr et al. 2014). The exact trajectory of any rock block is extremely difficult to anticipate, making it a sensitive undertaking to evaluate the risk of rock fall (Jaboyedoff and Labiouse 2011). Predicting rock-fall runout, and therefore identifying the areas that could potentially be affected, is still challenging. The accuracy of runout distance estimations requires measurements based on observational data, whose reliability depends on the volume and frequency of rock falls (Jaboyedoff and Labiouse 2011), thus leading to better understanding of their behavior and associated risks. In this context, definition of the runout distance and propagation area is vital in any hazard assessment.

Diverse geological, climatic, and topographic factors play a role in the distribution of rock-fall hazard zones at global and regional scales. The importance for understanding and assessing potential threats due to rock falls has been highlighted in numerous papers (Papini et al. 2005; Poisel et al. 2020; Tiranti et al. 2023) which give a broader understanding of rock-fall risk. Rigorous 3D analytical models considering the inertia of rock blocks have been illustrated by Guzzetti (2002), and Crosta and Agliardi (2004) at a global scale. At a regional scale, several insights related to rock-fall dynamics have been reported by Dorren et al. (2006), highlighting the importance of understanding the spatial evolution of such events which can be examined by using numerous techniques. However, simpler models ignore the impact of block shape and size, therefore reducing the volume of blocks to a dimensionless point within a 2D or 3D framework (Piacentini and Soldati 2008; Castelli et al. 2021). On a local scale, even more simplified techniques are used for preliminary research and territorial planning (Corominas et al. 2014; Ferlisi et al. 2019; Nappo et al. 2019; Scavia et al. 2020) that use general parameters without including detailed geotechnical information on the rock mass. In order to cope with limited data availability and scientific uncertainties, a runout model is required to be both straightforward and trustworthy. Amongst a wide variety of methods, the energy angle method (EAM) is the one which is most frequently used (Castelli et al. 2021; Hantz et al. 2021). EAM was initially proposed by Paronuzzi (1987), built on the Fahrböschung strategy introduced by Heim (1932). During the last few decades, a number of simulation software, including those built in GIS environment, have incorporated EAM. This method is applied to understand the spatial distribution of rock-fall susceptibility in order to estimate potential runout distances, and identify areas at risk. One example of a computer tool that incorporates EAM is the CONEFALL tool developed by Jaboyedoff and Labiouse (2011). This tool utilizes GIS data, including Digital Terrain Models (DTMs) and grid files of rock-fall sources, to estimate the potential rock-fall propagation area by applying the EAM principles. Cone method (CM) is the most common term for the 3D manifestation of the EAM. Furthermore, Rock-fall tool (QPROTO) (https://plugins.qgis.org/plugins/qproto/), an open-source cross-platform plugin, is a QGIS tool based on the cone method (Jaboyedoff and Labiouse 2011) developed by Politecnico di Torino and Arpa Piemonte, with reference to parameters that reflect block-ground interaction (Scavia et al. 2020).

This paper deals with the analysis of rock falls that characterize the north–west coast of Malta. Rock falls occur along steep cliffs that limit plateaus made up of resistant limestones. These plateaus often show structural discontinuities due to tectonic and stratigraphic factors, resulting in lateral spreads and block slides. Rock spreading enlarges structural discontinuities or produce long and deep cracks that can isolate large limestone slabs prone to fall or topple from the cliffs (Devoto et al. 2012; Soldati et al. 2019).

In detail, the research deals with rock-fall susceptibility assessment, which serves as a crucial component to build a comprehensive approach to risk management. The study represents an application of the QGIS predictive rock-fall QPROTO tool (Castelli et al. 2021), in order to simulate rock-fall runout probability along six sites in the north–west coast of Malta. QPROTO is a user-friendly and non-commercial tool. Its application led to detailed propagation analysis and to the estimation of the rock-fall probability within the detected invasion zones.

Rock falls may affect infrastructures leading to socio-economic losses (Mignelli et al. 2014; Cloutier et al. 2015; Antronico et al. 2017; Donnini et al. 2017). Therefore, in order to cope with hazardous situations, it is immensely important to implement the use of simulation tools which can determine runout distance and kinetic energy (Volkwein et al. 2011) involved in the process in order to detect rock-fall prone areas.

Taking into consideration the general lack of comprehensive coastal safety management plans with reference to rock-fall occurrence along the Mediterranean rocky coasts, this study intends to provide authorities with a useful insight and replicable means for undertaking effective hazard assessments aiming at a sustainable management of rocky coastal areas.

## 2 Study area

The study area is located in Malta, which is the largest and most populated island within the Maltese archipelago. The latter lies in the central Mediterranean Sea (Fig. 1), ca. 100 km south of Sicily and 290 km east of Tunisia (Said and Schembri 2010). The Maltese Islands are situated on the Malta-Hyblean platform, an extensive submerged shelf bridge at the convergence zone of the African and Eurasian tectonic plates, which is controlled by two faults. The Great Fault is oriented WSW–ENE, contrary to the Maghlaq Fault which is aligned NW–SE marking Malta's primary tectonic discontinuity (Pedley et al. 1978; Alexander 1988; Galea 2019; Gauci and Schembri 2019). Tectonic activity, geomorphological processes, and sea level changes have all collectively shaped the coastline of these islands (Biolchi et al. 2016b). The Great Fault actually splits the Island of Malta into two structural regions. North of the Great Fault, four horsts alternate three graben features and correspond to prominent ridges and well-shaped valleys, respectively (Devoto et al. 2012). These structural landforms are approximately WSW–ENE oriented.

This study focuses on the north–west coast of Malta, from Paradise Bay to Gnejna Bay (Fig. 1). The investigated area hosts six well-known tourist spots, namely Paradise Bay, Anchor Bay, Golden Bay, Ghajn Tuffieha Bay, Il-Qarraba promontory and Gnejna Bay (Fig. 2). These are attractive destinations for the presence of pocket beaches (Zammit Pace et al. 2019), a natural park characterized by rich variety of geoheritage sites (Coratza et al. 2011; Cappadonia et al. 2018; Selmi et al. 2019), an amusement park and for the possibility to carry out a variety of leisure activities. These areas can be hazardous for various users and the numerous tourists who visit the area due to widespread coastal instability processes (Devoto et al. 2013; Soldati et al. 2019; Mantovani et al. 2022).

The rocks outcropping in the study sites were formed between Miocene and Upper Oligocene belonging to a marine sedimentary succession of five lithostratigraphic units, comprising Tertiary limestones, clays and marls overlaid by thin surficial deposits (Pedley et al.

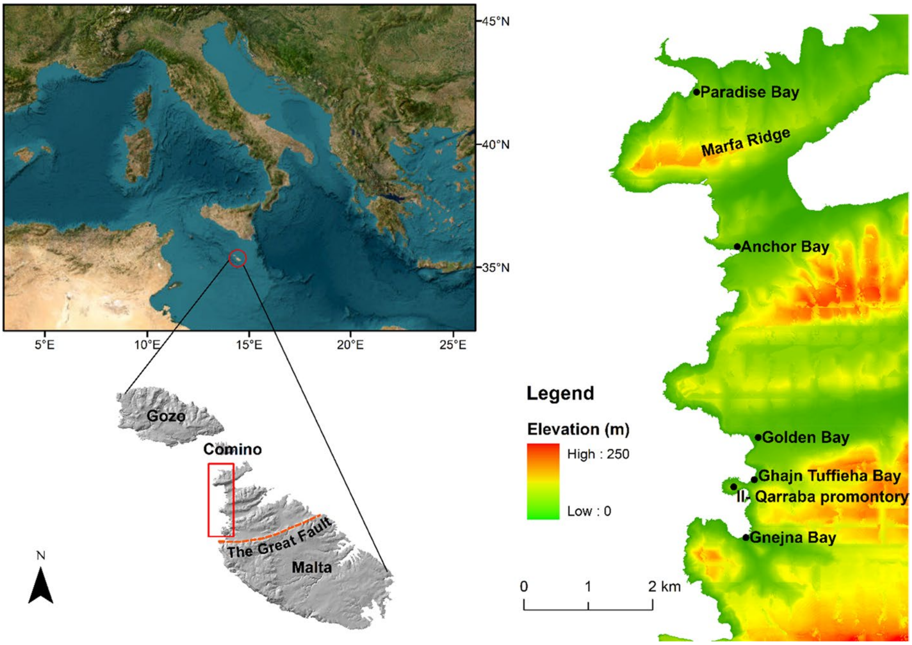


**Fig. 1** Geographic setting of the study area and location of the investigated sites along the north–west coast of Malta. The satellite image is derived from ArcGIS Online World Imagery (map data: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

1978, 2002; Scerri 2019). These units include, from the bottom to the top, Lower Coralline Limestone Formation, Globigerina Limestone Formation, Blue Clay Formation, Greensand and Upper Coralline Limestone (UCL) Formation (Baldassini and Di Stefano 2016).

Slope instability processes like rock falls are diffused along the north–west coast of Malta due to the presence of large rock spreads (Soldati et al. 2019). The latter result from the overposition of two geological formations showing a different mechanical behaviour like the Blue Clay and UCL (Devoto et al. 2012). According to Soldati et al. (2019), rock falls are common in the investigated area and represent 11% of total area affected by landslides. These rapid landslides mainly affect the edge of UCL plateaus, which are characterized by persistent discontinuities. Tens of these discontinuities are originated and widened by lateral spreading, and were recently inventoried and mapped using the outputs of UAV-DP technique (Devoto et al. 2020). These discontinuities often occur in clusters, as in the caprock of Il-Qarraba, isolating large blocks and making them prone to be detached. Inventories of gravity-induced discontinuities that characterize karst plateaus of north–west and north–east coasts of Malta were produced by Devoto et al. (2020, 2021). Furthermore, the combination of gravity-induced joints and other types of discontinuities can separate large blocks that can fall or topple from the structural cliff that limits the plateaus. Most of these rock falls are therefore originating as collateral landslides of lateral spreads and block slides (cf. Pasuto et al. 2022).

Rock falls also occur from Lower Coralline and Globigerina limestone steep cliffs such as in Gnejna Bay, but they are rare compared to events that affect UCL plateaus. Large


**Fig. 2** The investigated sites along north–west coast of Malta. **a** Paradise Bay, **b** Anchor Bay, **c** Golden Bay, **d** Ghajn Tuffieha Bay, **e** Il-Qarraba promontory (photo by Col. M. Marchetti), **f** Gnejna Bay

blocks either rest close to the scarp face from which they have been detached or extend to sea level and shield the coast from further erosion.

There have been incidents where people were injured as a result of rock falls or difficult terrain accessibility due to the occurrence of rock blocks at the base of the cliffs (Main et al. 2022). Such rock falls also affected the Il-Qarraba caprock on 26th November 2011 and northern cliff of Anchor Bay during the Helios storm event on 9th February 2023 (Fig. 3).

## 3 Materials and methods

The rock-fall susceptibility analysis based on runout probability was performed considering a methodological approach as shown in Fig. 4. The research benefited from the use of high-resolution topographic data consisting of a LiDAR-derived Digital Terrain Model (DTM) with 1 m resolution (ERDF 156 Data 2013).

Firstly, detailed field surveys were carried out at the above-mentioned selected sites of the north–west coast of Malta, in order to incorporate and verify a set of data collected through desk activities that involved analysis of existing maps, reports, and papers regarding past landslide events. The second step included processing of GIS based topographic information in order to identify a set of rock-fall source points along the edge of the plateau in the test sites and defining various input parameters. This was followed by the third step

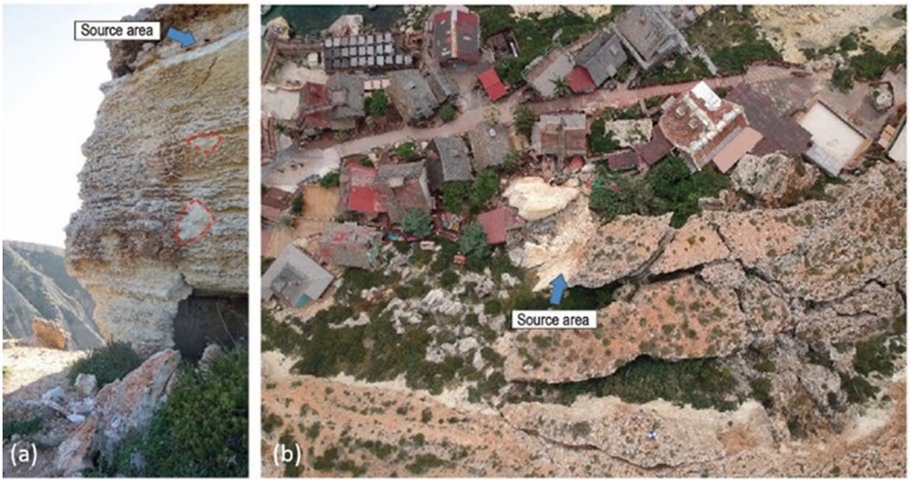


**Fig. 3** Examples of rock-fall events along the north–west coast of Malta. **a** Rock fall occurred on 26th November 2011 on the cliff of Il-Qarraba caprock (red dotted lines indicate the impacts of the detached rock mass); **b** Rock fall occurred on 9th February 2023 in the north side of Anchor Bay

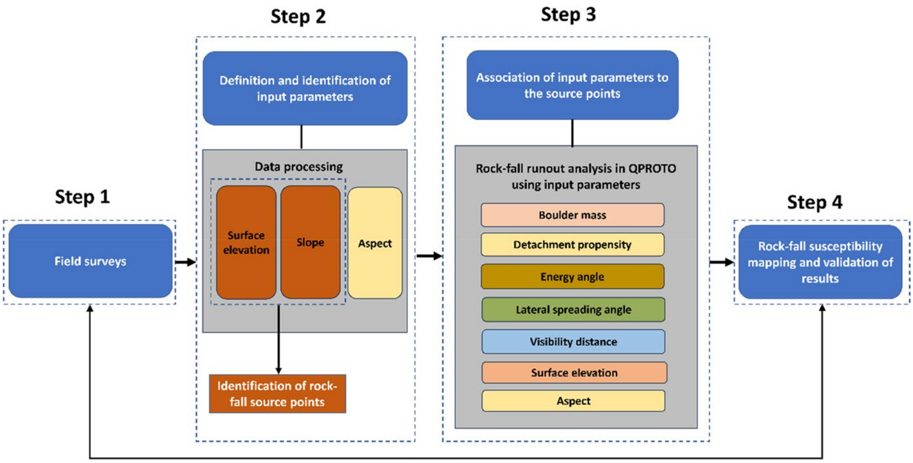


**Fig. 4** Flow chart of the methodological approach applied for the analysis of rock-fall susceptibility along the north–west coast of Malta

in which association of the input parameters to each source point and analysis of rock-fall prone areas were carried out using QPROTO tool in a GIS environment (https://plugins.qgis.org/plugins/qproto/ accessed on November 2023) utilizing a cone method modelling approach in order to provide rock-fall runout probability simulations. Finally, in the fourth step, the modelling outputs were mapped and validated through in-situ surveys in order to compare the localization of rock-fall accumulation zones (invasion zones) observed on the field with those generated by the model. In the following sub-sections, a detailed description of each step of analysis is provided.

### 3.1 Field surveys (step 1)

Field surveys included identification of the cliffs which could host potential rock-fall source points and boulder accumulation zones beneath these cliffs.

In particular, the field surveys led to integration and validation of the outcomes of preliminary desk activities that included: (i) analysis of existing maps, reports and papers; (ii) analysis and interpretation of multi-temporal Google Earth Images.

### 3.2 Definition and identification of input parameters (step 2)

The detection of the potential release areas (source points) was carried out in a GIS environment taking advantage of topographic features like elevation and slope. Then, the source points were refined with reference to the information gathered from field surveys. In order to detect the rock-fall source points along the edge of the plateaus, a slope angle-based approach that takes into consideration slope inclination of 45° was adopted (Castelli et al. 2021). The calculation is based on the processing of the DTM of the investigated area.

The procedure for rock-fall runout simulation applied in this research is based on propagation analysis performed with the Predictive Rock fall Tool (QPROTO) plugin. In order to perform rock-fall runout analyses with QPROTO, a set of data (input parameters) pertaining to the slope conditions and the anticipated rock-fall scenario must be associated with each source point having an inclination of 45° (Castelli et al. 2021). Detailed information about the input parameters used in the present study to perform the propagation analysis is listed in Table 1 and described in Sect. 3.3.

### 3.3 Association of the input parameters to the source points (Step 3)

In this phase, all the attributes required by QPROTO (cf. Table 1) were linked to each source point present along all the cliffs of the six test sites. Elevation and aspect were extracted from the DTM. Block mass of 2000 kg and block volume of 1 $m^3$ were considered as representative of the phenomenon with respect to the investigated area. Such consideration was made based on (i) the UCL densities observed at a coastal boulder deposit located at Marfa Ridge by Biolchi et al. (2016a), (ii) the average size of blocks located at the foot of the cliff and (iii) expert knowledge. Each source point's detachment propensity (DI) was set to 1 and visibility distance was set to 800 m (Castelli et al. 2021). DI indicates that the probability of occurrence of each computed parameter is the same at any point inside propagation area. Since the investigated area is devoid of forest, the energy line angle $\varphi_p$ was considered 34° based on the function of slope inclination and block volume for a non-forested slope (Castelli et al. 2021). A constant value for lateral angle $\alpha = \pm 12°$ was assumed (Castelli et al. 2021) which best simulated the observed runout area. The intensity of the phenomenon under consideration within the runout area (kinetic energy) is calculated using an energy balance equation following the QPROTO plugin (https://plugins.qgis.org/plugins/qproto/) in QGIS environment (http://qgis.org). Figure 5 elucidates the process of model computation for rock-fall susceptibility analysis and mapping using QPROTO with reference to the Anchor Bay study site.

**Table 1** List of attributes used to perform a propagation analysis using the QPROTO plugin (modified after Castelli et al. 2021 and Milan et al. 2023)

| Input parameters | Description | Input values |
|---|---|---|
| ID | Source point identification number | Progressive number |
| Elevation (m) | Source point height (a.s.l.) | From the DTM analyses |
| Aspect (°) | Slope dip direction at source point | From the DTM analyses |
| Detachment propensity (-) | Source point propensity to originate rock falls | 1 |
| Boulder mass (kg) | Boulder mass used for computation of kinetic energy of rock blocks | 2000 |
| Visibility distance (m) | Maximum runout distance to which the analysis can be extended | 800 |
| Energy line angle (°) | Energy line angle of cone with apex at source point | 34 |
| Lateral spreading angle (°) | Lateral angle of cone with apex at source point | 12 |

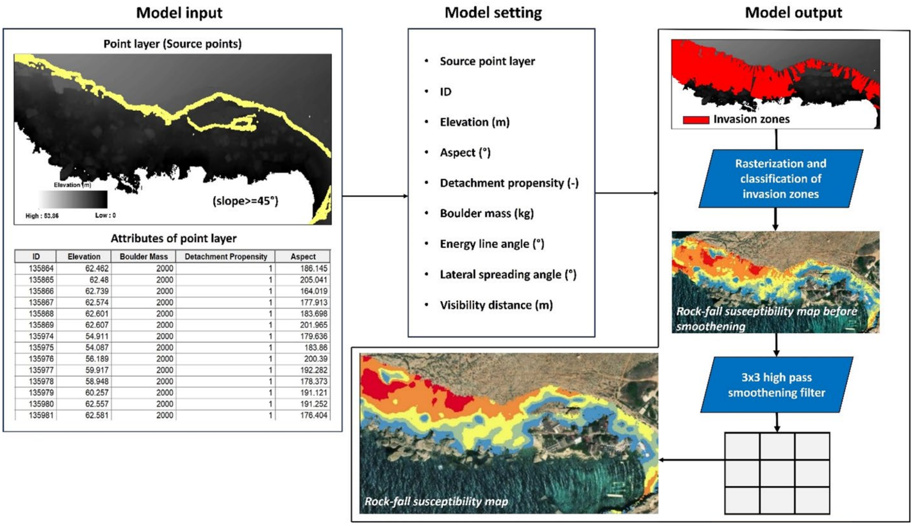


**Fig. 5** Workflow of model computation for rock-fall susceptibility analysis and mapping using QPROTO

### 3.4 Rock-fall susceptibility mapping and validation of results (Step 4)

The results obtained from the QPROTO simulations were rasterized considering the mean kinetic energy field in ArcGIS 10.3 software. Additionally, a smoothed filter with kernel size (3 × 3 pixel) was considered in order to get enhanced area of runout probability. This allowed smoothening of the pixels making the data easier to be interpreted and visualized (Fig. 5). Specifically, the values of mean kinetic energy (kJ) obtained from the QPROTO analysis were classified into five classes in order to depict the runout probability. To this aim, the geometrical interval classification method was applied. Based on the classified rock fall invasion zones, rock-fall runout probability maps were prepared and validated through field surveys in order to compare the representation of invasion zones observed in the ground with the ones generated and mapped by the model and GIS tools respectively.

## 4 Results and discussion

The outcomes of the analysis of the six investigated sites of north–west coast of Malta are represented as follows: (i) GIS-based maps that show the spatial distribution of rock-fall runout probability zones, (ii) areal extent and relative percentage under different runout probability zones.

The spatial interpretation of rock-fall runout probability zones (cf. Section 3.4) is representative of the expected rock-fall invasion areas. The classification of runout zones has enabled the delimitation of the investigated territory and calculation of the areal extents with different runout probability levels (susceptibility classes). The areal extents are expressed in square metres and percentages of the total investigated surface under different probability zones (Table 2). Spatial distribution of rock-fall runout probability for the six test sites is presented as maps in Fig. 6. The runout zones of the cliffs were generated

**Table 2** Areal extent and percentage of surface area under rock-fall runout probability zones estimated for the investigated sites

| Test site | Very low ($m^2$) | Surface (%) | Low ($m^2$) | Surface (%) | Medium ($m^2$) | Surface (%) | High ($m^2$) | Surface (%) | Very high ($m^2$) | Surface (%) | Total runout area ($m^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Paradise Bay | 6158 | 28.0 | 2538 | 11.5 | 4770 | 21.7 | 5615 | 25.5 | 2912 | 13.3 | 21,991 |
| Anchor Bay | 6163 | 18.8 | 5839 | 17.8 | 7775 | 23.7 | 9142 | 27.9 | 3884 | 11.8 | 32,801 |
| Golden Bay | 5196 | 19.1 | 4069 | 14.9 | 8244 | 30.2 | 7493 | 27.5 | 2273 | 8.3 | 27,273 |
| Ghajn Tuffieha Bay | 6024 | 26.5 | 3638 | 16.0 | 6441 | 28.3 | 5700 | 25.1 | 927 | 4.1 | 22,729 |
| Il-Qarraba promontory | 2906 | 17.1 | 3554 | 20.9 | 4257 | 25.0 | 4398 | 25.9 | 1887 | 11.1 | 17,001 |
| Gnejna Bay | 16,067 | 21.0 | 12,706 | 16.6 | 21,466 | 28.0 | 22,466 | 29.3 | 3954 | 5.1 | 76,657 |

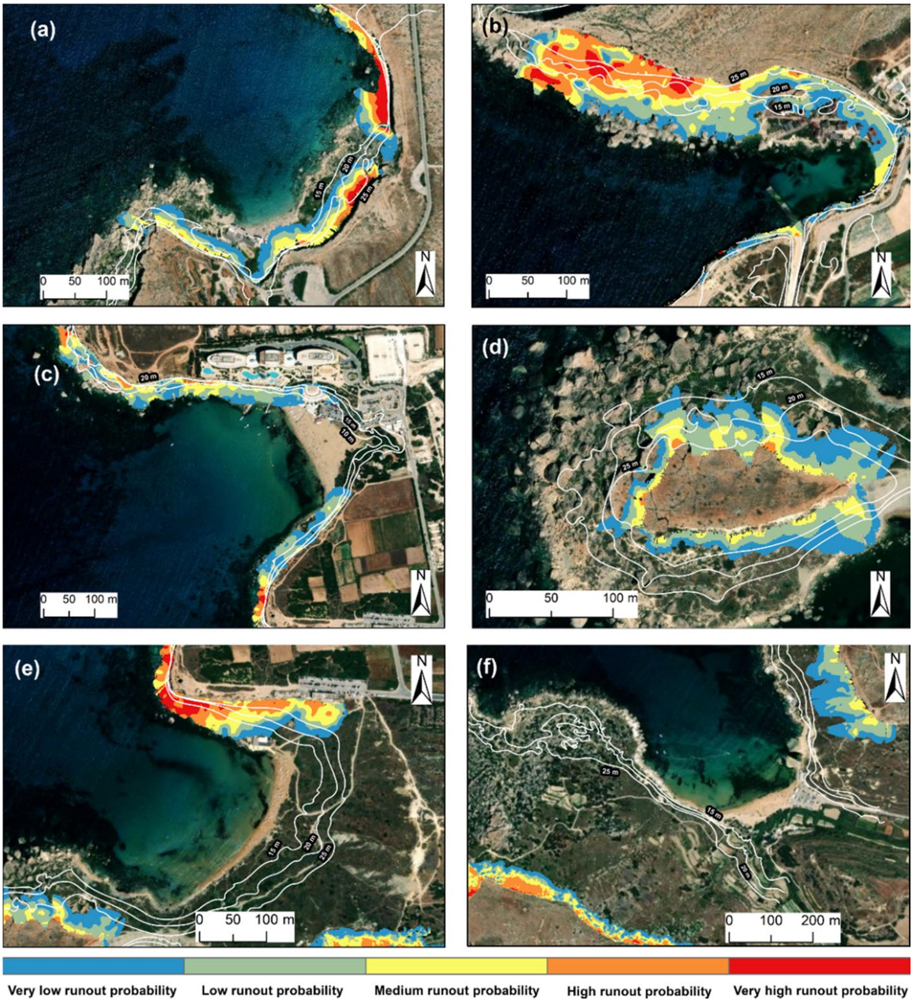


**Fig. 6** Rock-fall runout probability zonation in the investigated sites: **a** Paradise Bay, **b** Anchor Bay, **c** Golden Bay, **d** Il- Qarraba promontory, **e** Ghajn Tuffieha Bay and **f** Gnejna Bay

as consistent areas of rock-fall invasion and were represented in the form of maps. Furthermore, areal extent of rock-fall runout probability zones and percentage of surface area under these zones for each investigated site are reported in Table 2 and outlined in Fig. 7.

In detail, Gnejna Bay shows the maximum percentage area under high runout probability level (29.3%). This corresponds to high kinetic energy within this zone, followed by Anchor Bay (27.9%) and Golden Bay (27.5%). However, Il-Qarraba promontory, Paradise Bay and Ghajn Tuffieha Bay have 25.9%, 25.5% and 25.1% area under high runout probability level respectively. According to Jaboyedoff et al. (2005), the higher the intensity of an event and its mean probability, the higher is the degree of danger for exposed elements. It is worth noting that the coastal sectors in the north–west of Anchor Bay, north–east of Paradise Bay, north of both Golden Bay and Ghajn Tuffieha Bay and south–west of Gnejna Bay have very high and high rock-fall runout probability levels (Fig. 6).

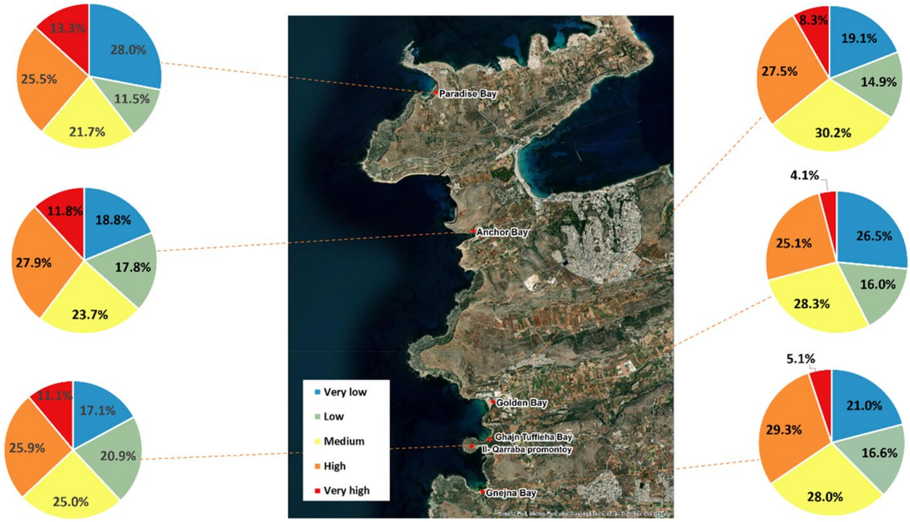


**Fig. 7** Graphical representation of percentage area under different runout probability zones for the investigated sites located along the north–west coast of Malta

This is due to the presence of steep slopes beneath the cliffs and the occurrence of numerous persistent discontinuities, which are located along the external sectors of Upper Coralline Limestone plateaus (Devoto et al. 2020) resulting in high fragmentation of the rock masses, a common physical process during rock-fall (Jaboyedoff et al. 2005; Matas et al. 2020). Persistence of these joints and their high values of apertures (Devoto et al. 2020) have a significant impact on the fragmentation characteristics during detachment and fall of the outer portion of limestone plateaus when rock spreading and block sliding occur. The inner sector of the bays shows medium to low rock-fall runout probability zones, being located farther away from the cliff and the rock-fall source areas. Furthermore, there is a low rock-fall runout probability around the Il-Qarraba caprock. This is due to the presence of gentle Blue Clay slopes and hummocky terrains related to earth slides around Il-Qarraba caprock (Devoto et al. 2012).

It is important to highlight that runout zones (i.e., propagation areas) of the investigated sites are strictly connected to the outcomes of empirical cone method analyses carried out in an open source QGIS environment using QPROTO plugin. The obtained results are consistent with real cases and literature data. In fact, the modelled rock-fall propagation areas are congruent with the observations made during field surveys and with the outcomes of the analysis of available materials (maps, reports and papers) on past rock-fall events. Such simulation outcomes are aimed at achieving accurate and reliable results (Milan et al. 2023) in the form of rock-fall runout probability maps. One great advantage of the application of such an approach is that it could be applied to different study areas (Miele et al. 2021; Torsello et al. 2022) in order to assess runout zones in similar rock-fall prone locations. This is due to the wide variety of input parameters which is another advantage for easy computation of rock-fall runout probability. Moreover, resolution of the DTM significantly impacts the correct identification of source areas (Losasso et al. 2017) and the simulation of the runout probability zones. High resolution DTM enables precise detection of source areas and detailed representation of propagation zones leading to implementation of improved risk management strategies. However, such high-resolution data requires more computational time and high performing computers.

Furthermore, since deviations of rock blocks from the predefined path cannot be taken into consideration (Losasso et al. 2017), such kind of application falls short of accurately describing the real trajectory of rocks that fall or topple. For example, slopes that are characterized by strong orientation gradient may lead to deviation of rocks from the original dip direction of the blocks (Castelli et al. 2021) producing unrealistic results. In the current study, this problem was resolved by using a large number of source points which resulted in the generation of wide invasion areas by overlapping differently oriented cones.

The application of the QGIS predictive rock-fall tool used in this study serves as an effective tool for a prompt evaluation of rock-fall runout probability zones leading to easy mapping of such areas in a GIS environment. These maps play a crucial role for land planning purposes since they allow for rapid identification of critical areas within extensive slopes. In practical terms, these slope segments require in-depth assessments, installation of monitoring tools, or consolidation work. Nevertheless, such outputs provide an easy solution for creating useful framework of knowledge and represent adequate response to the growing need for effective tools for the study of coastal instability processes (cf. Piacentini et al. 2015; Mantovani et al. 2016).

## 5 Conclusions

The north–west coast of Malta shows a wide variety of coastal instability processes which determine risk situation for the numerous users and visitors of this sector of the island. Among those, rock falls require special attention by territorial and land planning authorities due to their rapid and often unexpected onset. This aspect plays a crucial role in developing suitable risk management strategies and effective planning of land use in the context of sustainable development.

This study aimed at providing insights on rock-fall hazard issues in Malta by means of a systematic application of the QGIS predictive rock-fall tool for the assessment of potential rock-fall source areas and their propagation at a local scale in six selected sites. Specifically, this study addressed rock-fall susceptibility by simulating runout along cliffs where rock falls are widespread, also as collateral processes linked to the extensive lateral spreads and block slides, that affect limestone plateaus overlapping clayey terrains.

Within the investigated sites, the coastal sectors that showed the most critical conditions in terms of rock-fall runout probability are the north–east cliff of Paradise Bay, the north side of Anchor Bay and the north cliff of Ghajn Tuffieha Bay where high rock-fall runout probability levels were detected, mainly due to presence of steep slopes beneath the cliffs and numerous persistent discontinuities predominant along the edges of the Upper Coralline Limestone plateaus.

A robust and user-friendly tool like QPROTO allowing rapid generation of susceptibility maps facilitates the assessment of risk prone zones and supports cost-effective communication to relevant authorities, which is valuable for land use planning and management. A broad overview of susceptible areas, as that provided in this study, can guide more detailed investigations aimed at planning appropriate interventions and mitigation measures in specific locations for the safeguard of assets and people. The application of the QPROTO tool shows high degree of replicability and can be of great interest for territorial entities dealing with risk assessment and mitigation both in coastal areas and mountain regions, as also reported in literature.

**Acknowledgements** This paper and related research have been conducted during and with the support of the Italian inter-university PhD course in Sustainable Development and Climate Change (SDC). The authors wish to acknowledge the support and encouragement of George Buhagiar and Christopher Gauci at the Ministry for Public Works and Planning, Research and Planning Unit, Malta.

**Author contributions** N.S.: Conceptualization, Methodology, Software, Validation, Data curation, Writing original draft and Visualization. S.D.: Conceptualization, Methodology, Data curation, Visualization, Validation and Review. V.V.: Methodology, Software, Data curation and Review. S.R.: Software, Data curation and Visualization. M.S.: Conceptualization, Methodology, Visualization and Review. A.R.: Methodology, Visualization, Review and Supervision.

**Funding** Open access funding provided by Università degli Studi di Modena e Reggio Emilia within the CRUI-CARE Agreement. The research was carried out in the frame of the project "Training new generations on geomorphology, geohazards and geoheritage through Virtual Reality Technologies" (GeoVT) under the Erasmus + Programme, Key Action 2: Partnerships for Cooperation (Agreement number: 2021-1-SE01-KA220HED-000032142)—Coordinator: Arjen P. Stroeven (Stockholm University); Partner organization leader: Mauro Soldati (University of Modena and Reggio Emilia). The research was also funded by the RETURN Extended Partnership supported under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.3-D.D. 1243 2/8/2022 – European Union Next Generation EU (no. PE00000005, CUP: B53C22004020002).

## Declarations

**Conflict of interest** The authors have no relevant financial or non–financial interests to disclose.



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