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Research Article / Araştırma Makalesi

Forest mapping against rockfalls on a regional scale in Inebolu of Turkey

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Abstract: Determining areas where forest plantations provide protection against rockfall is significant in the prevention of disasters. In this paper, a case study is conducted in the Özlüce Forest District of İnebolu, Turkey. Potential rockfall source areas are firstly calculated and mapped via RollFree, which uses a digital elevation model as the only input. The rockfall travel distance is then identified using an empirical energy line angle to create propagation maps for different scenarios (using a set of four angles: 28°, 32°, 35°, and 38°). By marking the lower boundaries of propagation, the maximum run-out zone of a fallen block is determined as having a very low, low, medium, or high probability of occurrence (marking the lower boundaries of propagation). These propagation maps are then overlapped with a forest stand map to define areas where the forest provides a protective function against rockfall. According to propagation maps that indicate a high probability of occurrence, only 9% of the total forest area is found to be capable of playing a protective role, whereas for those determined as having a low probability of occurrence, 17% of the forest area provides a protective function.

Keywords: Energy line angle, protection forest, rockfall, rockfall propagation map

Kaya yuvarlanmalarından etkilenen orman alanlarının belirlenmesi: İnebolu örneği

Özet: Kaya yuvarlanmalarına karşı potansiyel koruyucu ormanların belirlenmesi, önemli ölçüde koruma sağladıkları için son derece önemlidir. Bu amaç doğrultusunda Özlüce Orman İşletme Şefliği'nde (İnebolu, Türkiye) örnek bir çalışma gerçekleştirilmiştir. İlk olarak potansiyel kaya yuvarlanması kaynak bölgeleri (PKYKB), tek bir girdi olarak Sayısal Yükseklik Modeli (SYM) kullanan RollFree yazılımı ile belirlenerek haritalanmıştır. Daha sonra, çok düşük (düşük yayılım sınırlarını gösteren), düşük, orta ve yüksek şeklinde sınıflandırılan maksimum birikme bölgesi olası sınırlarını elde etmek için farklı senaryolarda, yani dört farklı enerji hattı açısı (28°, 32°, 35° and 38°) için kaya blokları yayılım haritalarının oluşturulmasında ampirik enerji hattı açısı (EHA) yaklaşımı ile düşen kaya bloklarının hareket mesafelerin tespiti ile elde edilmiştir. Kaya yuvarlanmasına karşı koruyucu fonksiyona sahip orman alanlarının belirlenmesi için üretilen kaya yuvarlanması yayılım haritaları meşcere haritası ile çakıştırılmıştır. Yüksek olasılıklı yayılım haritalarına göre toplam ormanlık alanın sadece %9'u kaya yuvarlanmasına karşı koruyucu fonksiyon görürken, çok düşük olasılıklı yayılım haritasına göre ormanlık alanların %17'si koruyucu fonksiyon görmektedir.

Anahtar Kelimeler: Enerji hattı açısı, koruma ormanı, kaya yuvarlanması, kaya yuvarlanması yayılım haritası

1. INTRODUCTION

Rockfalls in mountainous areas are hazardous phenomena capable of damaging property, destroying power lines and infrastructures as well as claiming lives. Despite different definitions of rockfalls in the literature, in general, a rockfall refers to rock fragments falling freely from a cliff (Cruden and Varnes, 1996). The detached rock material descends the slope by falling, bouncing, rolling or sliding (Ritchie, 1963; Dorren et al., 2013). The reasons of rockfall events can be defined as heavy or prolonged rainfall, erosion of surrounding soil/rock, freeze-thaw processes, chemical degradation or weathering, root growth, or root leverage from high winds on trees, and vibrations or disturbance during construction. Despite of factors

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such as the size and shape of the rocks, the coefficients of friction of the rock surfaces and whether or not the rock breaks into smaller pieces, the most important factor controlling rockfall trajectory is the geometry of the slope.

Mountain forests provide protection against geomorphic natural hazards such as rockfalls, snow avalanches, and shallow landslides (Wu et al., 1979; Brang et al., 2001; Roering et al. 2003). The protective function of a forest depends greatly on forest dynamics, which vary with time due to changes in tree size, stand density, tree distribution, and management systems (Wehrli et al., 2006). In Austria and Switzerland, around 50 million Euros have been spent for maintenance to improve the sustainable protective effect of mountain forests (Dorren and Berger, 2006a). Since sustaining the protective function of forests is a key factor for local and regional development, much research has been done covering all aspects, from social to technical, of protection forests (Krauchi et al., 2000; Motta and Heudemand, 2000; Bebi et al., 2001; Vacik and Lexer, 2001; Berger and Rey, 2004; Miura et al., 2015; Rammer et al., 2015).

Forests provide significant protection to low-magnitude high-frequency rockfall events (volume < 5.0 m^3), while they give limited protection against the devastating effects of large magnitude rockfall events (volume > 5.0 m^3) (Berger et al., 2002; Dorren, 2003; Stokes, 2006). In the case of low-magnitude high-frequency rockfalls, forest stands can function as a barrier against the falling rocks. Not only healthy trees, but also felled trees and logs, when they are well positioned on the slopes, can accumulate and act as obstructions to dissipate the energy of the falling rocks. This issue has been intensively researched in recent years (Albisetti et al., 2003; Dorren et al., 2004a; Dorren et al., 2005; Schönenberger et al., 2005; Stokes et al., 2005; Dorren and Berger, 2006b; Aydin et al., 2012).

The Mountain Forest Protocol of the Alpine Convention emphasizes the value and importance of protection forests by declaring: "*mountain forests…can provide to a territory often far more extensive than just the mountainous areas the most effective and economical protection appropriate for the landscape against natural hazards…*" (European Communities, 1996). Protection forests can protect particular objects (Schönenberger, 2000) and/or a site (Dorren et al., 2004b). The first task in front of the foresters or forest landowners is to define the sites of the potential protection forests. This task will then be the basis for the quantification of the protection potential, which will require silvicultural interventions together with quantifying the protection potential of the given stand and establishing management policies for such forests (Motta and Heudemand, 2000; Brang, 2001; Berger and Rey, 2004; Dorren et al., 2004b; Brauner et al., 2005; Frehner et al., 2005; Brang et al., 2006; Gauquelin and Courbaud, 2006; Stoffel et al., 2006; Kajdiz et al., 2015; Rammer et al., 2015).

The main aim of rockfall hazard analysis is the identification of the exposed area located below rock cliffs. For this reason, the accurate determination of the maximum rockfall travel distances (i.e., maximum run-out zone) is essential because the element at risk could be located just below the rock cliffs (Copons et al., 2009). The rockfall travel distance is corresponding to the point resulting of the graphical intersection between the horizontal plan and a virtual line (the energy line) starting at the release point and having a specific slope angle (°) (Larcher et al. 2012). In other words, the maximum run-out zone or the lower boundary of the fallen rocks can be investigated by identifying the farthermost areas where boulders from previous rockfalls have fallen (Copons and Vilaplana, 2008; Wieczorek et al., 2008). Accordingly, several software programs have been developed to analyze rockfall events (Guzzetti et al., 2002; Dorren and Seijmonsberger, 2003; Crosta et al., 2004; Jabeyadoff and Labiouse, 2011; Dorren, 2016). These models are mainly categorized as: i) empirical models, ii) process-based models and iii) geographic information system (GIS)-based models (Dorren, 2003).

Currently, empirical models are proving to be quite useful tools for preliminary assessment to define the sites of the potential rockfall protection forests. In addition, they can be visualized in a GIS environment (Meissl, 1998). The energy line angle (ELA) approach, which can be integrated into GIS (Toe and Berger, 2015), is one of the widely used empirical models. (Wehrli et al., 2006; Berger and Dorren, 2007; Michoud et al., 2012; Wei et al., 2014). The ELA, proposed by Heim in 1932, can be calculated 1) using the geometric angle which is calculated using the horizontal projection of the direct slope line between the release point and stopping one, or 2) using the travel angle which is calculated from the length of the horizontal projection of the line corresponding to the water flow direction along the slope (Larcher et al. 2012). The advantage of such models is that they don't required any meteorological and geological data in order for identifying potential release zones and propagation zones (Berger et al., 2012). Moreover, on a regional scale, rockfall assessment via the ELA model provides experts and land-use managers with valuable information such as the locations of potential rockfall source areas (PRSAs) and run-out or propagation zones with an acceptable level of accuracy. Overlapping the hazard maps (i.e., outputs of the ELA model) onto the forest map will then spatially determine the forest areas that have the potential capability of protection against rockfalls (Berger et al., 2012; Berger et al., 2013; Toe and Berger, 2015).

The present study aimed: 1) to identify rockfall source areas via the digital elevation model (DEM) approach proposed by Dorren and Seijmonsbergen (2003) and Larcher et al. (2012), 2) to define rockfall travel distance by using the empirical ELA, which has been evaluated previously by many researchers (Heim, 1932; Hsü, 1975; Lied, 1977; Bigot et al., 2009; Copons et al., 2009; Jabayedoff and Labouise, 2011) and 3) to map the forests having a potential rockfall protection function based on the rockfall travel distance determined for the desired scenarios. For the first two aims, RollFree (Toe and Berger, 2015) software was used. This paper presents some basic information on the methodology of defining rockfall source areas and on the ELA approach, followed by a case application in the Özlüce Forest District of İnebolu, Turkey.

2. MATERIAL AND METHODS

2.1 Study Area and Data Description

The Özlüce Forest District (İnebolu, Kastamonu Province), located in the Central Black Sea Region of Turkey, was selected as the study area because rockfall events are common in this district (Figure / Şekil 1). The north, west, east, and south coordinates of the study area in the UTM ED1950-Zone 36 coordinate system are 4650221, 543303, 557533, and 4634101, respectively. In the present study, the DEM with a resolution of 10 m was generated from a digital 1/25000-scale topographical map (Figure / Şekil 2a). Elevations in the area range from 9 m (a.s.l.) to 1376 m (a.s.l.). The topography has recently changed due to the construction of a road and new settlements along the coastline in the area, so these sections were excluded from the analysis. Furthermore, a land use/forest stand map was obtained for the overlapping analysis in order to identify the forests having a protective function (Figure / Şekil 2b). The study area covers 14469.80 ha, with the land use classified as forest (10417.50 ha total area) and non-forest (4052.30 ha total area).

2.2 Identification of the potential rockfall source areas (PRSAs)

The PRSAs can be mapped via field surveys, aerial photographs, reports of past events, or delineation of slope thresholds, depending on the resolution of DEM (Larcher et al., 2012). For larger areas or at regional scales, slope threshold values were often applied, depending on the DEM (Clouet et al., 2012; Dorren et al., 2013; Toe and Berger, 2015). The slope threshold value (α) for the given DEM resolution (RES) was calculated using the following formula:

$$\alpha = 55 * RES^{-0.075} \quad (1)$$

The cells with equal or higher slope values than slope threshold value "α" were identified as PRSAs. The slope threshold values for selected DEM resolutions are given in Table / Tablo 1. RollFree software automatically calculated the threshold values and created the PRSA map. In this study, a DEM with a resolution of 10 m was used as input.

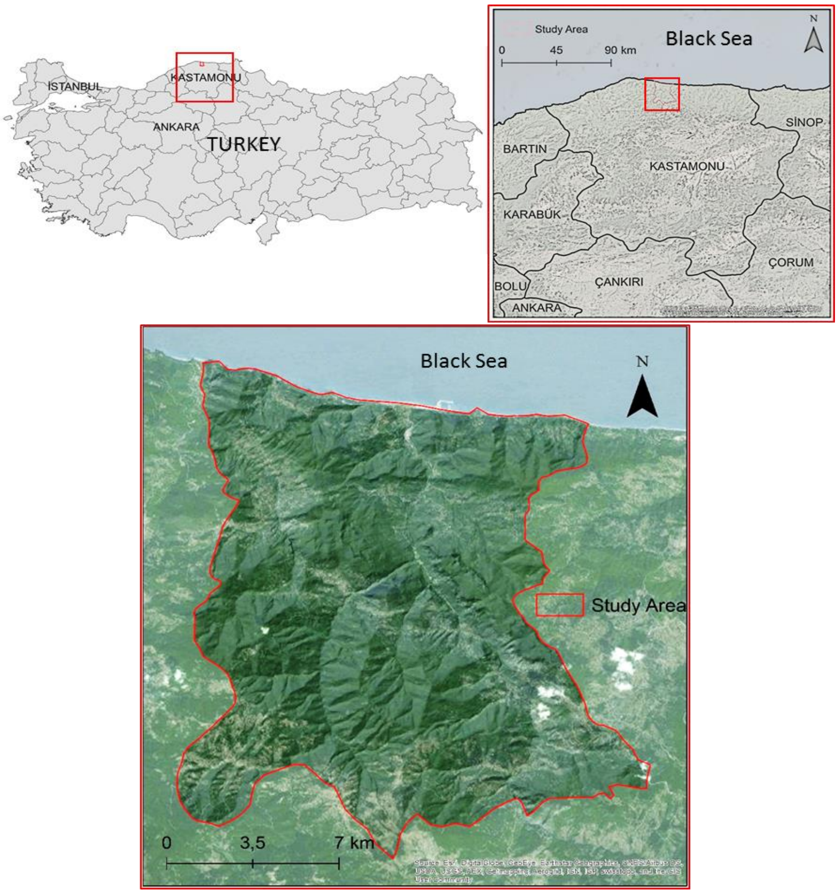
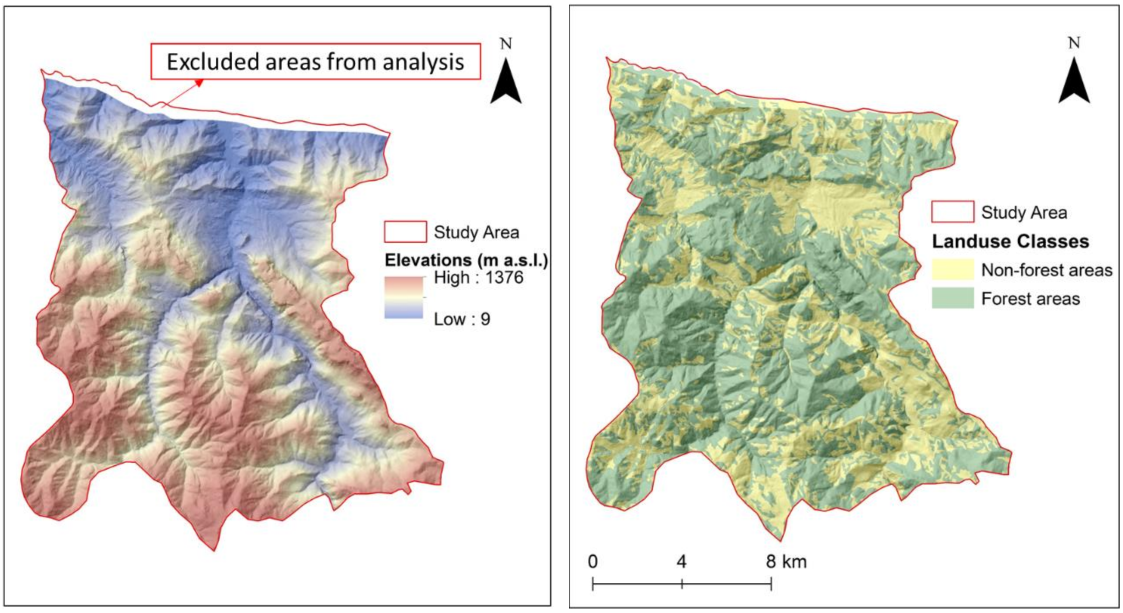


Figure 1. The location map of the study area
Şekil 1. Çalışma alanı konum haritası



(a) (b)

Figure 2. (a) DEM map and (b) land use map
Şekil 2. (a) SYM haritası ve (b) arazi kullanım haritası

Table 1. Threshold values for determining the PRSA based on DEM resolutions (Larcher et al., 2012)
Tablo 1. SYM çözünürlükleri tabanlı PKYKB belirlemedeki eşik değerleri (Larcher et al., 2012)

DEM resolution (m)	Slope threshold value(°)
1	55.0
5	48.7
10	46.3
25	43.2

2.3 Energy line model and run-out distances

The energy line model concept, based on the ELA, was first proposed by Heim (1932) to investigate rockfall hazards. The ELA principle can be used to model the run-out distance of many types of moving masses by joining the top of the source cliff to the toe of the stopping point for a given block using a straight line with a given angle (Figure / Şekil 3). The ELA approach requires only the DEM, without any meteorological or geological data, as input to determine the PRSA and propagation area (Berger et al., 2012). In practice, this is one important advantage of the approach for the end-users. Studies in the literature show the wide range of ELA variations for the run-out zone and include those of Moser (1986), Meissl (1998), Corominas et al. (2003), Copons et al. (2009) and Dorren et al. (2013) among others. For hazard mapping purposes, the geometrical ELA matrix (Table / Tablo 2) is possibly more user-friendly. The potential rockfall propagation area is firstly estimated in the model using a DEM and a raster map containing PRSAs. Then, from each grid representing PRSA, potential propagation directions are detected by using D8 algorithm (Jones, 2002). All grids with a height below the height of PRSA are selected as potential propagation direction. For each propagation direction, all grids located in a cone in accordance with energy line condition are mapped (Toe and Berger, 2015). In this study, rockfall run-out zones were mapped by using a set of four angles (28°, 32°, 35° and 38°) in order to indicate the very low (showing the approximate lowest boundaries of propagation), low, medium, and high probability of a maximum run-out zone for a fallen block.

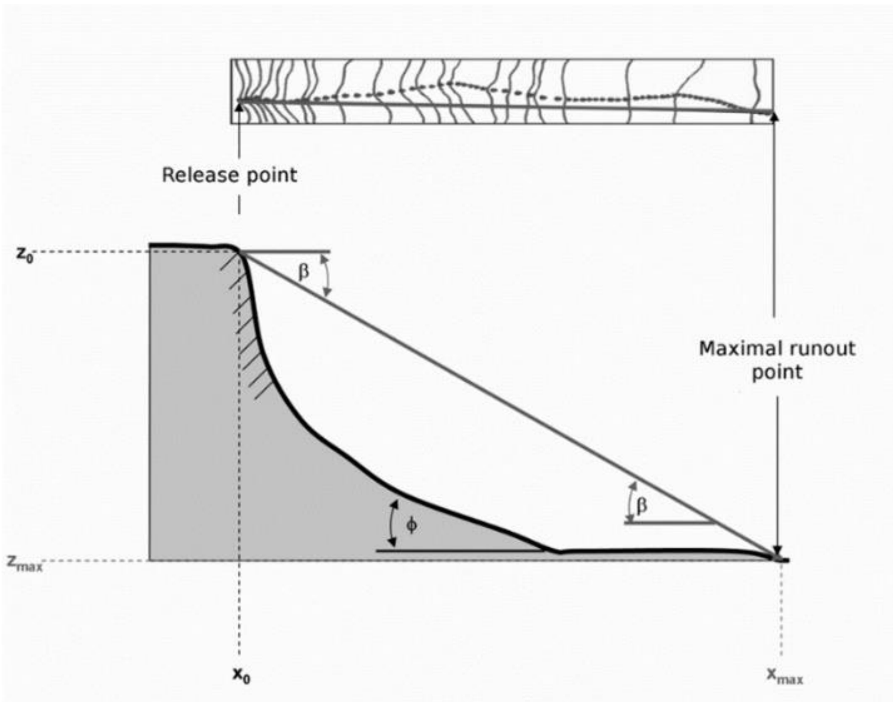


Figure 3. Energy line angle principle
Şekil 3. Enerji hattı açısı prensibi

Table 2. The geometrical ELA matrix (Larcher et al., 2012)
Tablo 2. Geometrik ELA matrisi (Larcher et al., 2012)

Geometrical ELA thresholds	Probability of rockfall propagation
≥ 38°	High
35° ≤ <38°	Medium
32° ≤ <35°	Low
28° ≤ <32°	Very low but not nil

3. RESULTS AND DISCUSSION

In the present study, a methodology for the determination of forest areas, which can potentially serve a protective function against rockfalls, was presented, along with a case application in the Özlüce Forest District (İnebolu, Turkey). The methodology employed includes three main steps: i) the mapping of potential rockfall source areas via slope threshold values, ii) the calculation of rockfall run-out zones (i.e. propagation maps) for different ELA values (28°, 32°, 35° and 38°) in order to indicate the very low, low, medium and high probability of a maximum run-out zone for a fallen block and iii) the overlapping of the generated rockfall propagation maps with the forest stands map in order to determine the forests with a potential protective function against rockfalls. The PRSAs calculated by RollFree depending on the DEM with resolution of 10 m are shown in Figure / Şekil 4. According to analysis results calculated with RollFree, in total, 320.72 ha (i.e., 32072 grids) were mapped as PRSAs in the Özlüce Forest District. The PRSAs were mostly found on continuously steep, evenly distributed slopes throughout the study area. When the PRSAs were overlapped with the forest stands map, 91.55% of the PRSAs (corresponding to 293.62 ha) were found to be located within the forested areas (i.e., all coppices and high forests regardless of stand types), with the remainder (corresponding to 27.10 ha) located over non-forested areas (Figure / Şekil 4).

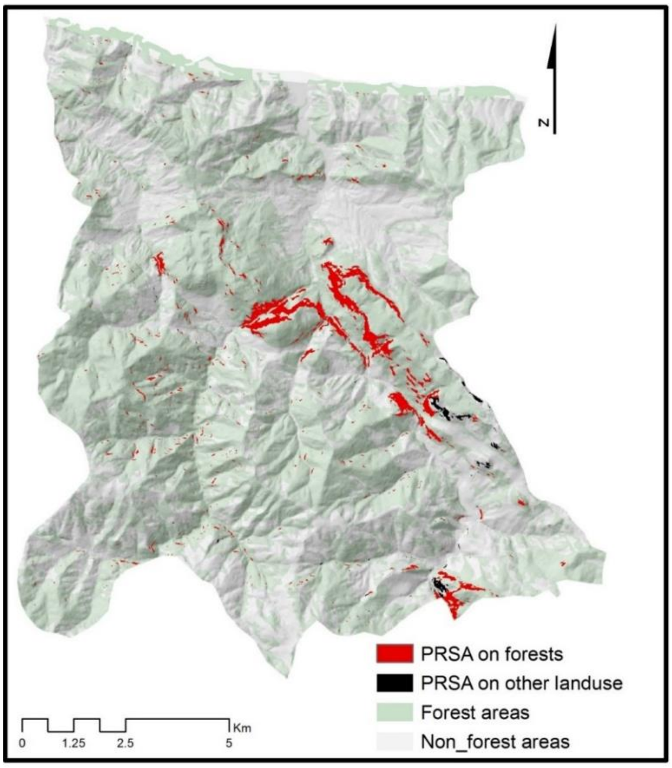


Figure 4. Mapped PRSAs
Şekil 4. Haritalanmış PKYKB'ler

In application, rockfall run-out zones are calculated for describing low and high probability by using a set of two angles (32° and 38°) (Tacnet, 2012) or for describing low, medium and high probability by using a three-angle set (32°, 35° and 38°) (Toe and Berger, 2015). The output map calculated with the 32° angle represents the most probable maximum run-out zones without taking into consideration the protective effect of forests. However, the output map calculated with the angle of 38° represents the probable run-out zone by considering the optimal role of a forest with an ideal protective function. In other words, this output map displays the potential maximum efficiency that forests can provide (Berger et al., 2012; Toe and Berger, 2015).

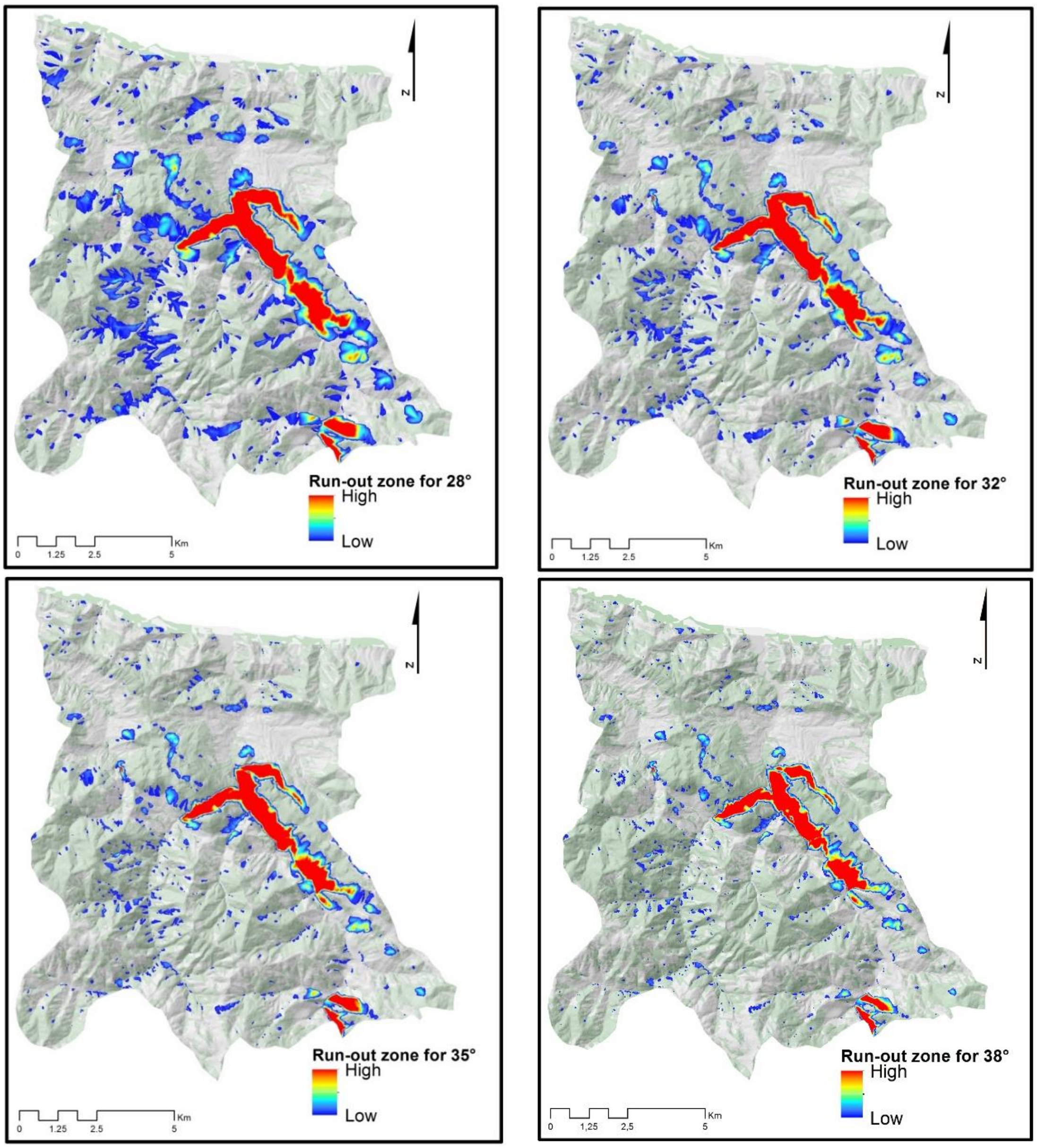


Figure 5. Run-out zones modelled for different ELAs (“Low” and “High” refer to passage frequency)
Şekil 5. Farklı EHA değerleri için (“Düşük” ve “Yüksek” geçiş sıklığı) modellenmiş birikme bölgeleri

The output map calculated with an angle of 35° represents the situation between the output maps calculated with angles of 32° and 38°. In the present study, the run-out zone for each ELA was calculated separately and mapped for angles of 28°, 32°, 35° and 38° (Figure / Şekil 5). Here, 28 of ELA was additionally used to determine the approximate lowest boundaries of propagation of blocks. According to the results, the total area susceptible to rockfalls was determined as 2351.0 ha. Of the total area affected by rockfalls, 1724.84 ha were located within the forest area with the remainder (626.16 ha) located within other land-use areas. The various ELA values are given in Table / Tablo 3, where it can be seen, for example, that the ELA of 28°, the forests in the propagation zone were found as 17% of the total forest area in the district, and the propagation zone as 16% of the total district area.

Table 3. Some outputs related to different ELA values
Tablo 3. Farklı EHA değerleriyle ilgili bazı çıktılar

ELA	Forest area (a) (ha)	Non-forest (b) areas (ha)	Total (c) (ha)	c/d*	a/e**
28°	1724.84	626.16	2351.00	0.16	0.17
32°	1392.15	418.51	1810.66	0.13	0.13
35°	1115.83	265.99	1381.82	0.10	0.11
38°	902.68	158.88	1061.56	0.07	0.09

*d: Total area of Özlüce Forest District
**e: Total forest area of Özlüce Forest District

In the assessment of the probability of rockfall propagation, the analysis with the ELA of 38° covered the area closest to the rockfall source area. This zone was defined as having a high probability of propagation, and forests in this zone were thus deemed valuable for serving a protective function (Tacnet, 2012). High ELA angles are a subset of the lower ones; therefore, for defining and calculating the medium, low and very low probability of rockfall propagation areas, the area of consecutive probabilities is extracted (i.e., for defining a medium probability, the area ELA of 35° is extracted from the ELA of 38°). In the high probability of propagation zone, an area of 902.68 ha is covered by forests, with 158.88 ha classified for other land uses, and a total area of 1061.56 ha was assessed as being exposed to the hazards of rockfalls (Table / Tablo 4). The spatial distribution of high, medium, low and very low probability of rockfall propagation is shown in Figure / Şekil 6 and the spatial distribution of potential protection forests in Figure / Şekil 7.

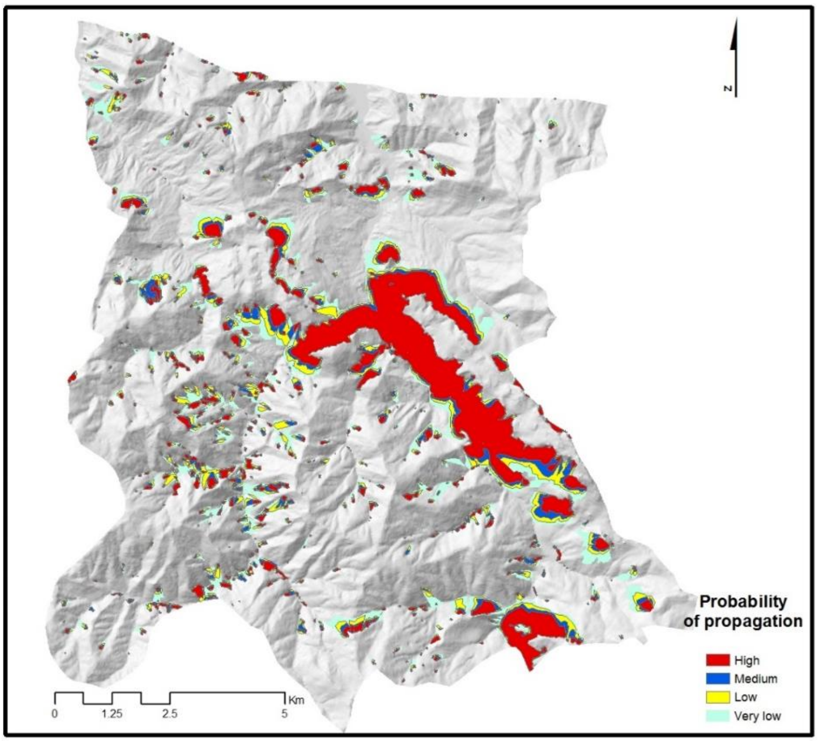


Figure 6. Spatial distribution of probability of rockfall propagation
Şekil 6. Kaya yuvarlanması yayılım olasılığının konumsal dağılımı

Table 4. Probability of propagation
Tablo 4. Yayılım olasılığı

	Forested (ha)	Non-forested (ha)	Total (ha)
High	902.68	158.88	1061.56
Medium	213.15	107.11	320.26
Low	276.32	152.52	428.84
Very low (but not nil)	332.69	207.65	540.34

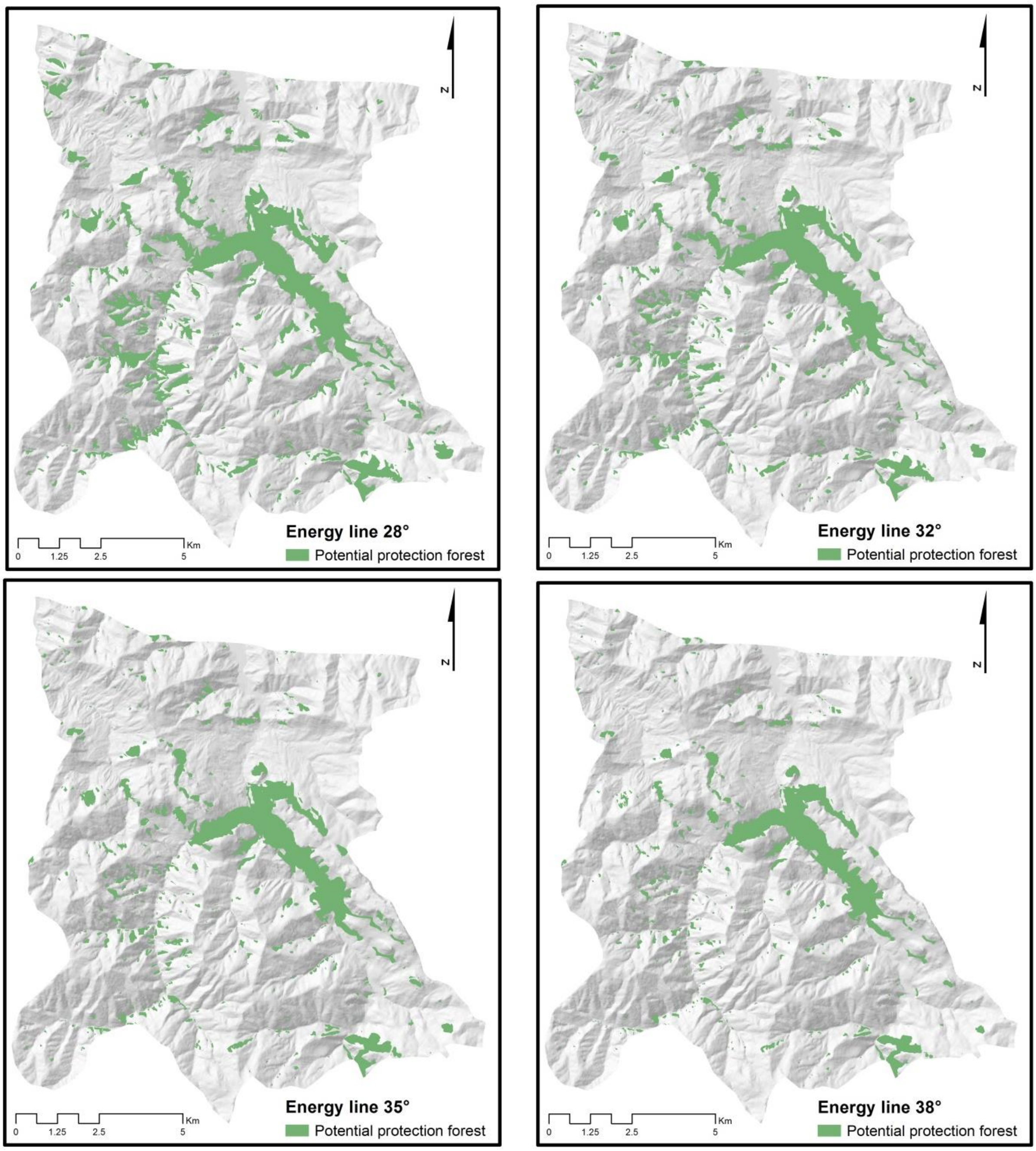


Figure 7. Spatial distribution of forests having potential protective function
Şekil 7. Potansiyel koruma fonksiyonuna sahip ormanların konumsal dağılımları

In the regional scale approaches, the hazard maps are quite coarse due to the data and modeling techniques employed (Toe and Berger, 2015), making verification using past events a demanding task. In the study area, the results obtained were validated with four well-known documented past events. Since their trajectories were fully or partly developed in a forested area, the maximal run-out distances for all past events remained in the ELA of 38°. Figure / Şekil 8 displays the example of Kayaarkasi village, where rockfalls caused considerable tree damage in forest stands (Aydın et al., 2012). RollFree software was able to identify the source area (yellow circles) and maximum run-out point (red circle) in the propagation zone.

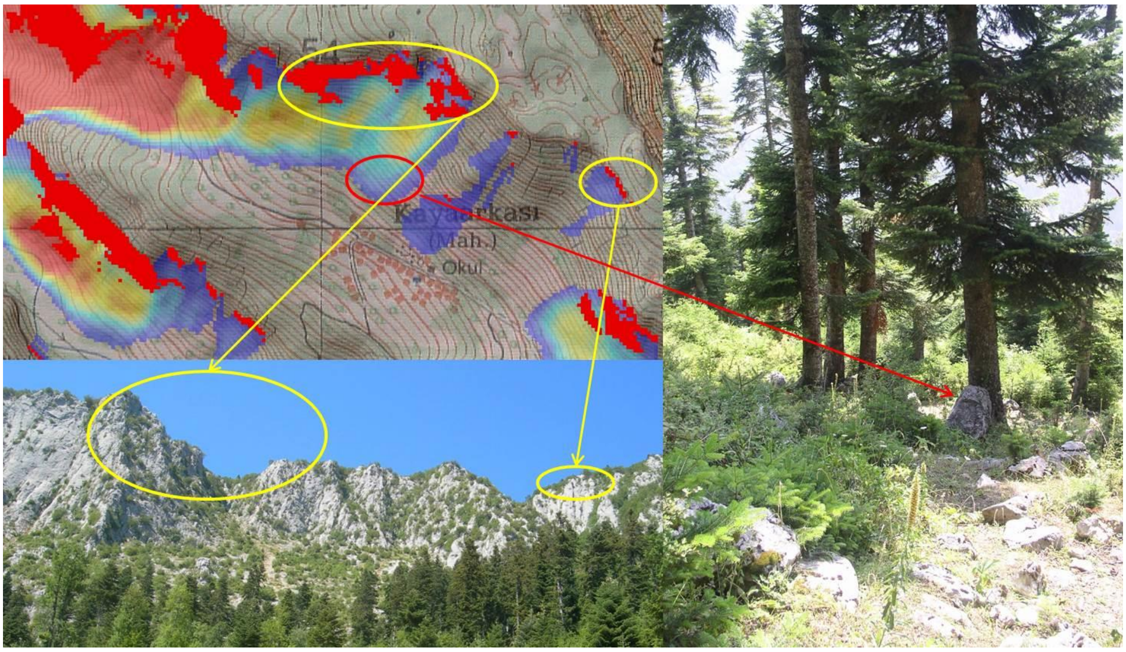


Figure 8. Validation of RollFree results for a past event
Şekil 8. Meydana gelmiş bir olay ile RollFree sonuçlarının doğrulanması

4. CONCLUSIONS

Mountain forests provide significant protection, especially to low-magnitude-high frequency rockfall events. For this reason, the determination and sustainable management of forests having a protective function are important for forest managers and landowners. This is not easy task due to a number of factors including changes in the forest dynamics over time due to changes in tree size, stand density, tree distribution and management systems. It is possible to map forests having a protective function against rockfalls via the ELA approach (Tacnet, 2012; Toe and Berger, 2015).

The methodology in this study was applied to generate resultant maps of forests with potentially protective function at regional scales. Thus, it was not possible to use them for risk evaluation. That’s why these maps have be used carefully (Toe and Berger, 2015). However, this approach can be seen as a first step in the evaluation of rockfall hazards. Furthermore, the ELA approach is quick and uncomplicated due to the use of the DEM as the only input. Of course, the requirements for a more detailed and advanced analysis in the determination of the protective function of a forest should be kept in mind. Another important point is the validation of the obtained results. All outputs of the approach (i.e., potential rockfall source areas, rockfall propagation maps and forest areas determined to have a protective function) should be corroborated by fieldwork (Tacnet, 2012).

The resultant propagation maps for each ELA value were overlapped with the forest stand map and the spatial distribution of forests with a protective function was extracted. These generated maps of forests providing protection against rockfalls will have an important function as basic data for forest managers and can be used in planning rational management strategies and making accurate decisions for suitable silvicultural operations. Determining ELA values both in forested and non-forested areas in Turkey is a demanding task for researchers in order both for effective usage of the method and for producing more accurate final maps.

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