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Using GIS-based multi-criteria decision support system for developing storm damage risk map

CBS tabanlı çok kriterli karar destek sistemi kullanılarak fırtına risk haritasının geliştirilmesi

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Abstract

Winter storm damages have crucial effect on different tree species and cause significant losses in many regions in Turkey. In a winter storm, trees can break or be thrown if stem and root plates overturn. The most important factors affecting the severity of damage caused by storms on forest trees are tree species, tree age (stage), crown closure, topographic features (elevation, slope), and climate parameters (wind, precipitation). Coniferous species are more susceptible to storms than deciduous species. The storm damage impact on trees increases with tree age and the density of the stand. Although the storm damage is lower at low altitudes (<150 m), the damage increases up to a certain altitude (1000 m) and decreases again at higher elevations. The highest risk of storm damage is in the middle (20-30%) slope groups, while the damage is lower in the low and steep slope groups. Wind speed and direction are climate parameters affecting forest tree storm damage. Pre-storm precipitation causes the soil to loosen and especially contributes to the formation of storm overturns. In order to prevent or minimize storm damage, it is of great importance to develop storm damage maps based on the factors that impact the storm damage. In this study, a storm damage risk map was produced using a GIS-based multi-criteria (Analytical Hierarchy Process-AHP) decision support system considering, tree species, tree age, crown closure, elevation, slope, wind speed and direction, and precipitation. The study implemented in Karadag Forest Enterprise Chief in Karacabey province of Bursa. The results indicated that the most effective risk factor was wind speed and wind direction, followed by the slope.

Key words: Winter storm damage, storm risk map, GIS, AHP.

Özet

Ağaç türleri üzerinde etkili olan fırtına zararları, Türkiye'nin birçok bölgesinde önemli kayıplara neden olmaktadır. Fırtınada, gövde ve kök devrilmesi durumunda ağaçlar kırılabilmekte veya devrilebilmektedir. Fırtınaların orman ağaçlarına verdiği zararın şiddetini etkileyen en önemli faktörler; ağaç türü, ağaç yaşı (çağı), kapalılık, topografik özellikler (yükseklik, eğim) ve iklim parametreleridir (rüzgâr, yağış). İğne yapraklı türler, yaprak döken türlere göre fırtınalara daha duyarlıdır. Ağaçların üzerindeki fırtına hasarı etkisi, ağaç yaşı ve meşcere yoğunluğu ile artış göstermektedir. Alçak rakımlarda (<150 m) fırtına hasarı düşük görünürken, belirli bir yüksekliğe (1000 m) kadar hasar artmakta, daha yüksek rakımlarda ise tekrar azalmaktadır. Fırtına hasarı riski orta eğim (%20-30) gruplarında çok yüksek, düşük ve dik eğim gruplarında ise hasar daha düşüktür. Rüzgâr hızı ve yönü, orman ağaçlarında fırtına hasarını etkileyen en önemli iklim parametreleridir. Fırtına öncesi yağışlar toprağın gevşemesine neden olup, özellikle fırtına devriklerinin oluşmasına neden olmaktadır. Fırtına hasarını önlemek veya en aza indirmek için, fırtına hasarına etkisi olan faktörleri dikkate alarak, fırtına riski haritaları geliştirmek büyük önem taşımaktadır. Bu çalışmada, ağaç türleri, ağaç yaşı, kapalılık, yükseklik, eğim, rüzgâr hızı/yönü ve yağış dikkate alınarak, CBS tabanlı çok kriterli (Analitik Hiyerarşi Süreci-AHP) bir karar destek sistemi ile fırtına risk haritası üretilmiştir. Çalışma, Bursa ili Karacabey ilçesinde bulunan Karadağ Orman İşletme Şefliğinde uygulanmıştır. Sonuçlar, en etkili fırtına risk faktörünün rüzgâr hızı ve yönü olduğunu ve bunu eğimin takip ettiğini göstermiştir.

Anahtar kelimeler: Fırtına zararı, fırtına riski haritası, CBS, AHP.

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1. Introduction

Storm damages are common occurrences in many countries worldwide, including Turkey. Storm damages result in significant amounts in timber volume losses. Failure to remove the products quickly in the area damaged by the storm and strong wind causes quality loss and insect damage to the product. In addition, erosion occurs due to the delay of afforestation in the area where there is no soil and root connection due to storm damage. As a result of strong winds or storms, the root systems of the trees partially or entirely come to the surface of the soil, then cracks, breaks, and bending occur in the tree trunks. Tree species, tree age, crown closure, topographic characteristics, and climate parameters are the most important factors affecting the severity of the damage caused by storms on forest trees. Coniferous species are more susceptible to storms than deciduous species. The resistance to storm damage is higher than coniferous mixed stands such as pine-spruce. Oak is the most resistant tree against storm damage (Taş, 2017).

The danger of storm damage increases with tree age and is more severe in stands over 50 years old. Also, older trees with root rot and other stem defects are more susceptible to storm damage (Moore, 2000). Since trees growing in closed and dense stands have limited space for crown and roots to develop, storm resistance is weaker than trees growing in sparse stands (Mitchell, 2000 Schmoeckel and Kottmeler (2008) stated that storm damage is lower at low altitudes (<150 m), the damage is seen up to a certain height (1000 m), and trees are more resistant to storms at higher altitudes because they grow under continuous storms and other environmental effects. Schütz et al. (2006) reported an inverse correlation between the increase in ground slope and storm damage. Similarly, storm damage was very low in very steep lands.

Wind direction and speed are the most vital climatic parameters affecting storm damage to forest trees. Loosening of the soil in areas that received continuous and heavy rainfall before the storm makes an outstanding contribution to the formation of storm overturns (Çanakçıoğlu, 1993). With the melting of the snow, the wet soil also contributes to the overturned formations. It is crucial to map the areas at risk of storms in the fight against storm damage, which is one of the leading abiotic damages affecting forests. GIS techniques, which are an effective tool in studies of different disciplines, can be used in storm damage risk analysis by integrating with empirical models (Lekes and Dandul, 2000). GIS-based mathematical models are frequently preferred for the most realistic solution to complex problems that require the evaluation of many different factors. Especially, multi-criteria decision analysis systems (Analytic Hierarchy Process-AHP, Regression Models and Fuzzy Logic) can be integrated with GIS and used effectively in producing risk maps. Within the scope of this study, it is aimed to develop the risk map of storm damages by using the AHP method integrated with GIS. Tree species, tree age, cover, elevation, slope, wind speed/direction, and precipitation were considered storm risk factors.

2. Material and methods

2.1. Study area

The study area is within the borders of Bursa Forestry Regional Directorate, Karacabey Forestry Enterprise Directorate, and Karadag Forestry Enterprise Chief (FEC). In the study area, whose total forest area is approximately 9176 hectares, the average altitude from the sea is 360 m. The dominant tree species in the floodplain forest are Stone pine, Linden, Black pine, Beech, Chestnut, Brutian pine, Maquis, Oak, and Maritime pine.

Figure 1. Study area.

2.2. GIS Database

A GIS database was generated in the "ArcGIS 10.5" software environment to produce the numerical data layers of the variables determined as the storm damage risk factors. Using the digital stand map of the Karadag FEC, data layers such as tree species, tree age, and crown closure of the forest area that are the subject of the study were produced. DEM was developed by using the contours of the study area, and the height values were divided into height classes at 200 m intervals. Then, the aspect and land slope layers were developed using DEM, and the slope values were divided into slope classes with 10% intervals. Wind and precipitation data of the study area were adapted from

Karacabey Meteorology Station data. An aspect map-based wind data layer was developed from these data, especially considering the direction of the maximum wind speeds. Average rainfall was estimated using land elevation values.

2.3. AHP Application

In the AHP methodology, each set of components that comprise the hierarchical structure defines a different hierarchy level (Saaty, 1977).There is the main purpose at the top level of the structure; below it, the criteria and sub-criteria to achieve the goal, and the alternatives at the bottom. This study evaluated tree species, tree age, crown closure, elevation, slope, wind speed/direction, and precipitation as the main criteria. Within the scope of the study, storm risk was divided into five alternative risk groups (very low, low, moderate, high, and very high) to determine the storm risk levels of forested areas. In pairwise comparisons, the relative importance scale is used to numerically express the importance of the criteria. In this study, 1-9 relative importance scales were preferred, which are widely used and give good results (Table 1). The AHP structure developed in the study is shown in Table 2.

Table 1. The relative importance values.

Importance Scale	
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

Table 2. AHP model.

Main Criteria						
Tree Species	Tree age	Crown closure	Elevation (m)	Slope (%)	Wind Direction (m)	Precipitation (mm)
Subcriteria						
Stone pine	Newly Planted	Bare-land	0 - 200	0 - 10	Flat	250 - 300
Linden	Young	Sparse	200 - 400	10 - 20	N	300 - 350
Black pine	Mature	Moderate	400 - 600	20 - 30	NE	350 - 400
Beech		Dense	600 -800	30 - 40	E	400 - 450
Beech-Linden			> 800	40 - 50	SE	> 450
Chestnut				50 - 60	S	
Brutian pine				60 - 70	SW	
Maquis				70 - 80	W	
Oak				80 - 90	NW	
Oak-Linden				> 90	N	
Oak-Beech						
Oak-Chestnut						
Maritime pine						
Alternatives						
Very Low Risk	Low Risk	Moderate Risk	High Risk	Very High Risk		

Pairwise comparisons are conducted by considering the viewpoints of an expert or individuals knowledgeable about the study subject. When multiple decision makers are involved, there are certain drawbacks to reaching a single decision that incorporates all preferences, primarily in terms of consistency. To ensure greater consistency, the study's results regarding the impact of criteria on storm risk were used to make pairwise comparisons by a single decision maker. The decision makers' adherence to realistic pairwise comparisons is evaluated by calculating the Consistency Ratio (CR). If the CR value is less than 0.10, it indicates that the decision maker maintains consistency. Lastly, in the Analytic Hierarchy Process (AHP), the relative importance values of the alternatives were determined with a focus on overall purpose. During the decision phase, the relative importance values of the alternatives were compared, and the level of storm risk was determined.

3. Results and conclusions

3.1. Digital maps of risk factors

The tree species data layer determined 13 stand types composed of pure and mixed species (Figure 2). Pure oak stands covered the largest area (39.91%), followed by pure beech stands (19.77%). The tree age data layer is given in Figure 3. The young trees covered the largest areas (69.47%), followed by the newly planted trees (23.66%). A map showing the degree of crown closure of the forest areas in the study area has been developed (Figure 4). Fully enclosed dense stands covered the largest area (74.64%).

DEM of the study area was developed, then DEM-based slope and aspect maps were produced. Figure 5 shows the DEM of the forested regions of the study area. Accordingly, the average altitude in forest areas is 360 m, and varies between 40 m and 815 m. The forest area average slope was 25.45% (Figure 6). Within the scope of climate data, wind and precipitation data layers were produced. Using the aspect data layer, especially the maximum speeds of the winds blowing in the main and intermediate directions were taken into account (Figure 7). The precipitation data of the forested areas were calculated depending on the altitude by using the average precipitation data (Average: 245.15 mm) obtained from the closest meteorology station and DEM. The precipitation data layer is given in Figure 8.

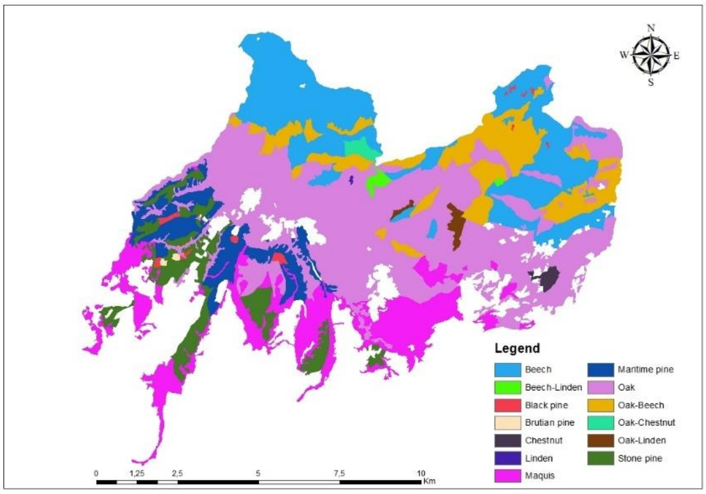

Figure 2. Species map.

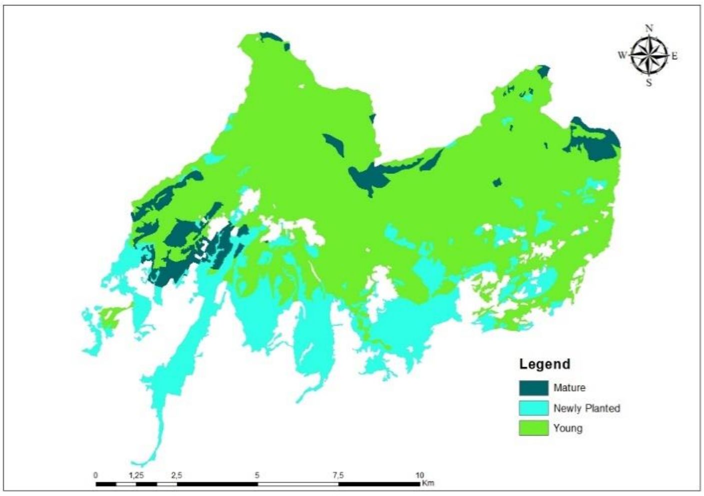

Figure 3. Tree stages map.

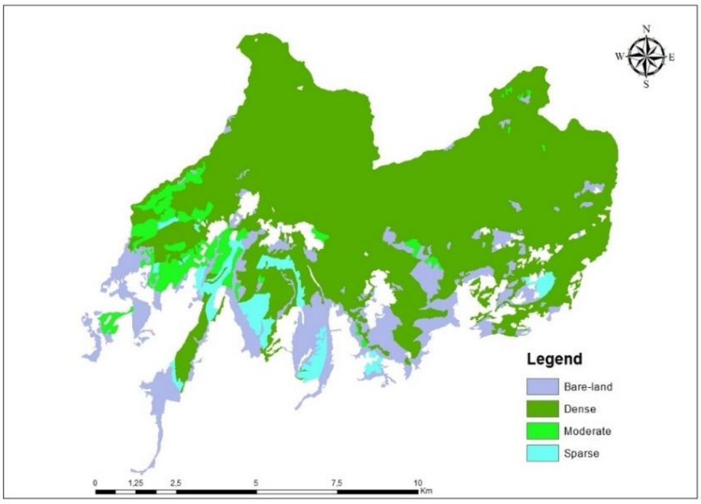

Figure 4. Crown closure map.

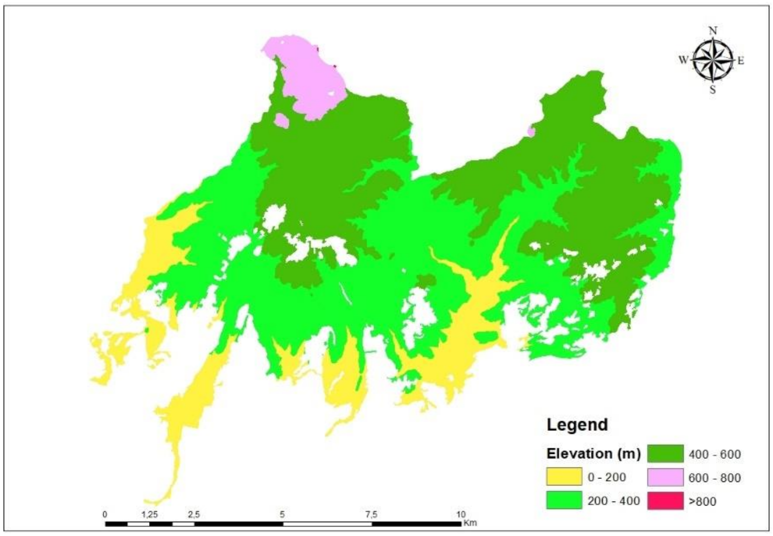

Figure 5. Elevation map.

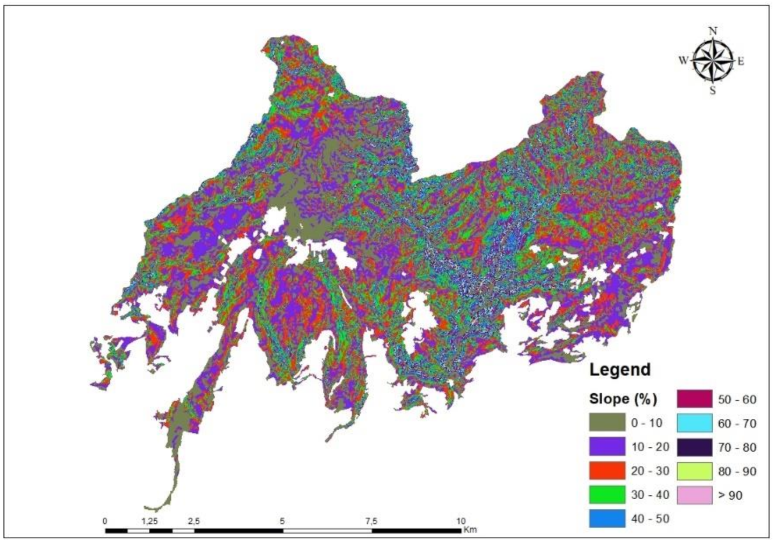

Figure 6. Slope map.

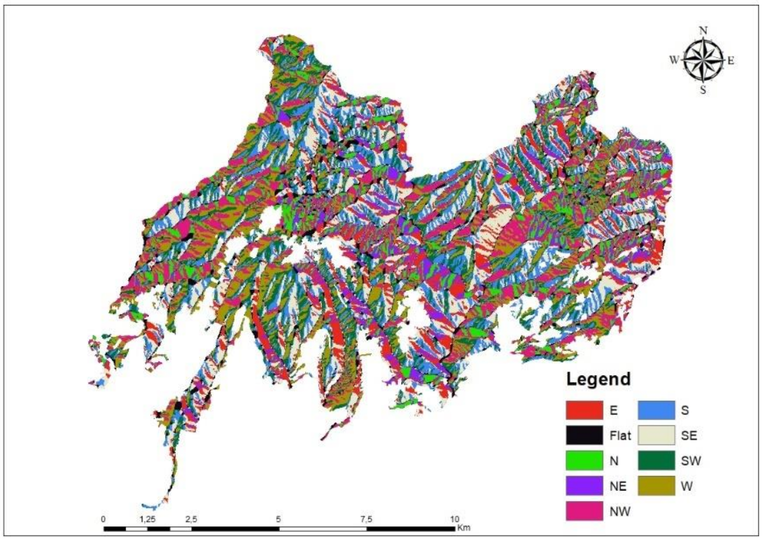

Figure 7. Wind direction map.

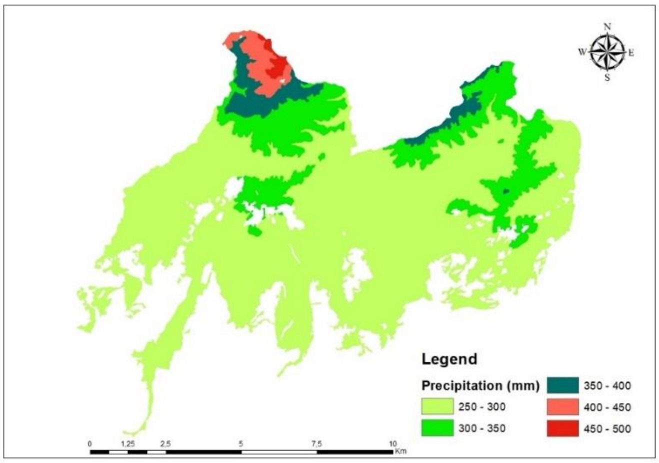

Figure 8. Precipitation map.

3.2. AHP results

After the data layers representing the storm damage risk factors were classified in the GIS environment, weighted importance degrees were assigned for each sub-criterion with a single decision-maker approach in line with the information obtained from the literature. The weighted values of the subcriteria are indicated in Table 3. The pure Stone pine, followed by the Maritime pine forest, had the highest weighted values (highest risk), while the Oak forest had the lowest weighted values (lowest risk). The mature stages had the highest weighted values, while newly planted trees had the lowest values. The forests with dense crown closure had the highest weighted values, followed by moderate crown closure. The weighted values increased as the elevation increased in the area. On the other hand, weighted values increased up to 40% slope, and then values were lower for the steep grounds. It was found that weighted values were higher in the northeast, followed by the north. Regarding the precipitation factor, weighted values increased as the precipitation amount increased.

Upon conducting the consistency analysis, the corresponding criteria were assigned weighted average values using the "Spatial Analyst" extension of ArcGIS 10.5. Subsequently, the "extAhp 2.0" plug-in was employed to combine these weighted averages and calculate the AHP scores. Based on the assigned weighted average values for the storm damage risk map criteria, it was found that the most influential criterion was wind speed/direction, followed by slope and tree species. Tree ages and crown closure had a similar effect on storm damage risk, while elevation and precipitation had the lowest effect on storm damage risk (Table 4).

Table 4. The weighted values of the risk factors

Risk factors	Values
Species	0.1466
Tree Age	0.0881
Crown Closure	0.0881
Elevation	0.0521
Slope	0.2289
Wind	0.3440
Precipitation	0.0521

According to Figure 9, which illustrates the distribution of the storm damage risk map, the results show that approximately 46.86% of the forests in the study area were classified within the moderate-risk zone, while approximately 31.09% were within the high-risk zone. Moreover, about 11% of the forests were categorized as high and very high storm damage risk areas.

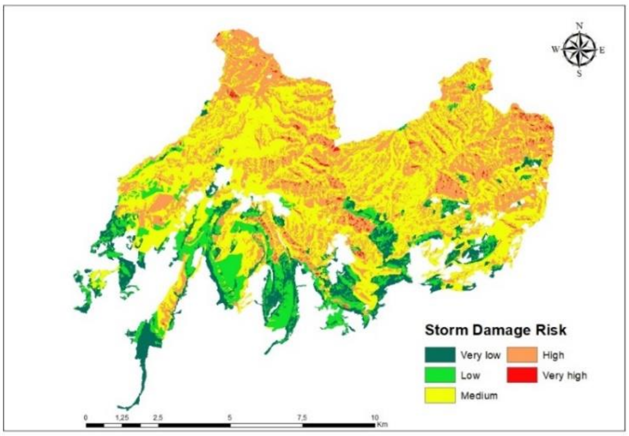

Figure 9. Storm damage risk map.

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