

Landslide Risk Assessment of the Santorini Volcanic Group

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Abstract: The aim of this work is the assessment of landslide risk of the Volcanic Group of Santorini (Greece). The methodology followed was based on the application of multi-criteria analysis (Multicriteria Decision Analysis - MCDA) in a Geographical Information System (GIS) environment (ArcGIS 10.5). The original data was converted to digital form, georeferenced in the national coordinate system GGRS'87, and individual layers were processed through digitization. Furthermore, a geodatabase was created in order to enrich the spatial information with the requisite descriptive information. The above was necessary for further processing and analysis, which include the classification of factor's data, according to the specific requirements of the region. Model Builder, an ArcGIS tool, was used to produce a Model which resulted in individual maps for each thematic layer, in addition to providing local authorities with an easy-to-use adaptable tool for landslide susceptibility mapping. Finally, a ranking method was used to generate criterion values for every factor. Then, each factor was weighted according to the estimated significance for causing landslides and the final susceptibility map was produced, depicting vulnerable areas.

1 INTRODUCTION

Landslides are natural phenomena, which in many cases turn into natural hazards, causing thousands of casualties as well as extensive damages to constructions and infrastructures. Varnes, IAEG (1984) defined landslides as 'almost all varieties of mass movements on slope including some such as rock falls, topples and debris flow that involve little or no true sliding'. According to Brabb (1993), approximately 90% of landslide damages can be avoided by the early recognition of the problem. Hence, there is a necessity for landslide hazard assessment in different spatial scales (Pardeshi, Autade & Pardeshi 2013).

An accurate susceptibility map can contribute to landslide investigation and landslide risk management/ assessment, helping in the prevention and, if possible, the mitigation of the disasters. The vulnerable areas can be identified directly and indirectly with a method based on causative factors, by analyzing the historical link between landslide-controlling factors and the distribution of landslides.

Guzzetti et al (1999) makes the assumption that landslide events may be repeated in the future due to the existence of the same conditions that had previously produced them. Therefore, susceptibility

assessments may help with the prediction of the geographical location of upcoming events. Landslide susceptibility does not forecast neither the time of occurrence of a landslide nor the magnitude of the destruction (Guzzetti et al. 2005).

Numerous techniques have been applied for landslide susceptibility mapping such as inventory based mapping, deterministic techniques, probabilistic techniques, heuristic techniques, statistical analysis techniques, and multi criteria decision making techniques (Guzzetti et al. 1999; Kouli et al. 2013; Pardeshi, Autade & Pardeshi 2013). All the above methods can be classified into quantitative, semi-quantitative, and qualitative (Kouli et al. 2013), of which the first critically depends on expert opinions.

Most of the aforementioned techniques have further evolved in the GIS environment, especially in the generation of causative layers, computation of different analysis and assigning of weights, integration of data, and production of landslide susceptibility maps. Such GIS based models are Weighted Overlay, Decision Tree model, Analytical Hierarchy Process (AHP), and physically based landslide hazard models.

These models can also be applied in landslide affected areas in southern Europe and specifically in

Greece. According to the Landslide Hazard Zonation Map of Greece (Koukis et al. 2005), which reflects the recorded events in Greece, the majority of them appear in the mainland, while many events occur in the Aegean islands, which attract a large number of tourist all year round.

For the current study, the area of the Santorini Volcanic Group was chosen, as it presents a spreading urbanization along with increasing tourist visits in a strained environment due to caldera cliffs. Few landslide events have occurred along the caldera causing significant damages on paths and roads and, rarely, casualties (eg. landslide in Oia, 2011).

To sum up, the aim of this study is the assessment of landslide risk of the Volcanic Group of Santorini (Greece) by applying the Analytical Hierarchy Process (AHP) (a multi criteria decision making process) in a Geographical Information System (GIS) environment. Besides the benefit of providing a landslide susceptibility map, local authorities will also gain a handy tool in dealing with landslide hazard.

2 STUDY AREA

The Volcanic Group of Santorini (Thera) is located in the southern Aegean Sea (Figure 1) and currently represents the most active volcanic field of the Hellenic Volcanic Arc (Nomikou et al. 2013). Its most recent large eruption, known as the Minoan Eruption (Late Bronze), occurred 3600 years ago and is particularly well known for the significant impact on the Minoan civilization (Friedrich 2000). The volcanic complex includes the islands of Thera, Therasia, Nea Kameni, Palaia Kameni, and Aspronisi, arranged in a circular shape.

The morphology of the Santorini Volcanic Group is composed of: (i) the internal rocky and steep slopes of Thera, Therasia, and Aspronisi islands, forming the aforementioned caldera ring, characterized by high morphological dip values that approach vertical values in certain locations, and consisting of impressive morphological discontinuities, and (ii) the external sections of the islands, characterized by smooth surfaces of relatively low dipping angles and radial distribution to the volcanic centre, representing the remnant outer slopes of the volcanic cone. The unique morphological plays an important role in landslide rockfall occurrence and determine the landslide hazard in a great extent (Antoniou & Lekkas 2011).

Druitt et al. (1999) described the geological

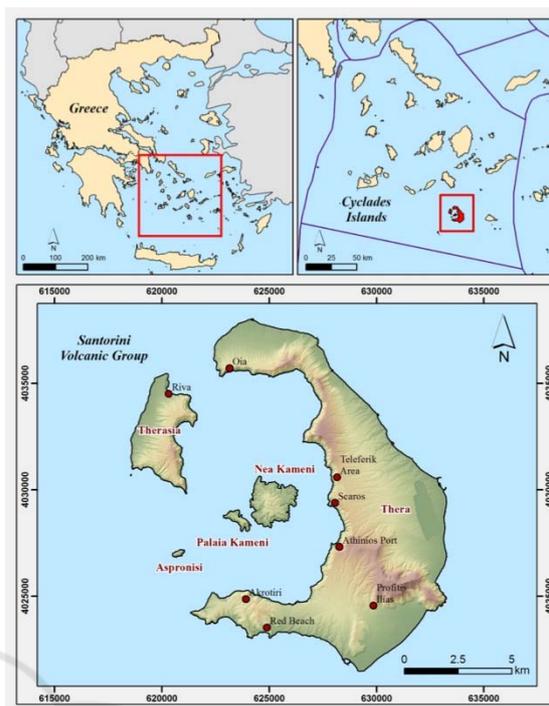


Figure 1: Location of the Volcanic Group of Santorini (Cyclades, Greece).

evolution of the volcanic field of Santorini. The young Akrotiri volcanic strata (650–550 ka BP) are hydrothermally altered silicic tuffs and lava flows. A stratocone complex emerged in the northern half of the volcanic field between 530 and 430 ka BP. Major explosive activity began around 360 ka BP. Since that time, about 12 large (few cubic kilometers or more) explosive eruptions have occurred, alternating with periods of constructional intra-caldera activity (Druitt 2014). Repeated effusion in the northern part of the volcanic field constructed a 10 km³ shield volcano (the Skaros shield) that by 54 ka BP had reached a height of 350 m above present-day sea level. This volcano was capped, between 45 and 23 ka BP, by a 2 km³ dyke-fed succession of dacitic lavas (Therasia dome complex) that reached a thickness of up to 200 m on the western flank of the edifice. At 22 ka, a >10 km³ dacitic explosive eruption (Cape Riva eruption) collapsed the Skaros–Therasia edifice, forming a caldera (Druitt & Francaviglia 1992; Druitt et al. 1999; Fabbro, Druitt, & Scaillet 2013). About 18 ky of reduced magmatic output then ensued, prior to the 3.6 ka Minoan eruption. The 22 ka caldera dominated the morphology of northern Santorini in the late Bronze Age prior to the Minoan eruption. Several eruptive phases followed the birth of Kameni islands (Palaia and Nea), both onshore and offshore, and the latest

one occurred in 1950 AD (Pyle & Elliott 2006; Nomikou et al. 2014 and references therein). The LBA caldera is 10x7 km wide, comprises of three flat-floored basins around the Kameni edifices, and is connected to the sea by three straits (one to the NW and two to the SW) (Nomikou et al. 2016).

There are no officially recorded landslides from any local authority (i.e. Municipality of Santorini), however a number of events have been found through the use of bibliography.

Although landslide hazard is not uniformly distributed along the caldera slopes (Lekkas 2009), Stergianos (2016) has made a serious effort to document as many landslides occurring throughout the island as possible. Two main regions can be distinguished due to frequent rockfall events: Teleferik area and Athinios port (Lekkas, Alexoudi & Lialiaris 2013; Lekkas 2009), with the lateral movement causing damages to roads and vehicles. Oia is another area where rockfalls occur (Lekkas et al. 2010), and it is the only one where a fatal incident was documented in 2011, in Oia port, when a rockfall led to the loss of a tourist's life. One last event worth mentioning occurred in the Red Beach area, south of Akrotiri, which was closed to the public due to extensive rockfalls.

Most of the aforementioned events are located along the caldera's cliffs, as expected. It is of utmost importance to note that the recorded landslides mainly affect human activities and infrastructures, such as residential areas and road/path networks. Moreover, in many cases there was no exact location of the events identified, but only a description of them, which leads us to allocate them approximately (Figure 2).

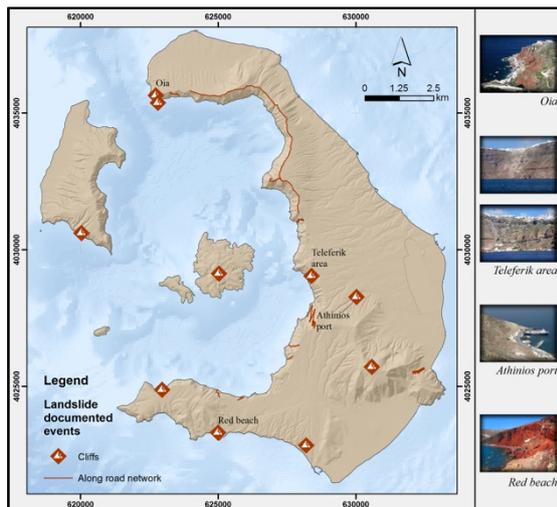


Figure 2: Approximate location of documented landslide events found through bibliography.

3 METHODOLOGY

The Methodology that was used can be divided into two stages.

In the first one, all necessary vector and raster data were collected and imported in a Geographical Information System, specifically in ArcGIS - ArcMap 10.5 (<https://goo.gl/k9tAW1>). Then, once the factors that would be taken into account were defined, a categorization of the data according to their susceptibility to landslides was made. Each category was normalized to 100 per cent, so that calibration would have the same scale in all factors.

In order to produce the maps that represent each factor, Model Builder, an ArcToolbox tool of ArcMap 10.5 (ArcGIS platform, ESRI) was used.

The Pairwise Comparison Method is used in Stage 2 in determining the weights for the criteria (Saaty 1980) and in producing the susceptibility map. The criterion for choosing the pairwise comparison matrix was that it takes the pairwise comparisons as an input and produces the relative weights as an output, and the Analytic Hierarchy Process (AHP) provides a mathematical method of translating this matrix into a vector of relative weights for the criteria.

4 CONDITIONING FACTORS

In order to investigate the landslide risk of the Santorini Volcanic Group, the morphology of the area was taken into account because it influences both initiation and runout of landslides.

For this reason, a Digital Elevation Model (DEM) was used to derive topographic factors other than simply elevation, including slopes, aspects, curvature, and hillshade. The DEM was derived from the area's Orthophoto map (2012) of the National Cadastre & Mapping Agency S.A., having a ground resolution of 5m.

Apart from the morphology factors of the area, the lithology, land cover, road network, mean annual rainfall, drainage network, fault zones, and soil thickness were used as follows (Table 1):

Table 1: Conditioning factors that were taken into account for landslide susceptibility mapping.

Factors	Classes	Rank Values	Normalization Rates
Lithology	Beaches	0	0
	Limestones and marbles	1	25
	Metapelites	2	50
	Tuff	2	50
	Pumice	2	50
	Lava	3	75
	Scoriae	4	100
	Scree	4	100
Slope Gradient (degrees)	≤15	1	25
	16-35	2	50
	36-55	3	75
	>55	4	100
Land Cover	Airports	1	10
	Sport and leisure facilities	1	10
	Natural grasslands	2	20
	Sclerophyllous vegetation	2	20
	Non-irrigated arable land	3	30
	Land principally occupied by agriculture, with significant areas of natural vegetation	4	40
	Pastures	5	50
	Vineyards	5	50
	Sparsely vegetated areas	6	60
	Complex cultivation patterns	7	70
	Mineral extraction sites	8	80
	Bare rocks	9	90
	Continuous urban fabric	10	100
Discontinuous urban fabric	10	100	
Distance from Road Network	Inside Urban fabric - Buffer 0m	0	0
	Dirt path/road - Buffer 3m	1	33
	Asphalt road - Buffer 10m	2	66
	Pavement - Buffer 5m	3	100
Curvature (m ²)	≤ -30	7	100
	-30 - -10	6	86
	-9 - -5	5	71
	-4.9 - -0.01	4	57
	-0.01 - 0.01	1	14
	0.02 - 10	2	29
> 10	3	43	
Mean Annual Rainfall	0-200m (170.6mm)	1	33
	201-400 (370.6mm)	2	66
	401-600 (570.6mm)	3	100
Distance from Streams	>20m	0	0
	≤ 20m	1	100
Proximity to Fault Zones	>50m	0	0
	≤ 50m	1	100
Aspect (degrees)	-1	0	0
	22.6 - 292.5	0	0
	0 - 22.5	1	100
	292.6 - 360	1	100

4.1 Lithology

Lithology is a major controlling factor for landslides. In the present study the geological formations of the Santorini Volcanic Group were derived from the geological map of Druitt et al., 1999.

Formations were grouped in regards to the stratigraphy, geotechnical characteristics, and the stability of each formation.

Even though lava formations are considered as hard and stiff rocks, due to the fragmentation they are favorable to rock falls.

Loose and high erodible formations like scoriae and scree are prone to landsliding, since they are unconsolidated formations. Also, dykes, subvertical sheet-like intrusion of magma which are located mainly across the northern cliffs of the caldera, were given a high risk value. On the contrary, tuff is an impermeable formation, thus it is not likely that landslides will occur. In the same category metapelites are also included; although they normally have good geotechnical characteristics, they are weathered in the study area.

All the formations mentioned above dominate the caldera cliffs, making them susceptible to landslides. The rest of the Santorini Volcanic Group is formed by volcanic formations, with the exception of the Mesozoic limestones in the northeastern part of Profitis Ilias, which are presented with a low risk.

4.2 Slope Gradient

As slope increases shear stress in unconsolidated soil cover, increases as well. Generally, landslides are not expected to occur on gentle slopes due to lower shear stress (Ladas, Fountoulis & Mariolagos 2007).

According to statistical approach (Mpliona 2008), landslides in Greece occur mostly in 16-35° slopes, while >35° slopes include both landslide and rockfall phenomena.

A slope map was processed from the 5m-DEM (in degrees) with values ranging from 0° to 85°. Slope values were classified into four classes according to Table 1. The caldera cliffs and the southeastern part of the island (composed of Profitis Ilias limestones) are characterized by steep slopes. On the contrary, most parts of the island are characterized by gentle slopes (0° – 15°).

4.3 Land Cover

Land cover is considered to be an important landslide-controlling factor since it affects the hydrological conditions and the soil strength (Ladas, Fountoulis & Mariolagos 2007). Additionally, urban areas reduce infiltration, increasing runoff erosion. In the Santorini Volcanic Group, settlements on top of caldera cliffs add an extra weight, weakening the bedrock structure and increasing the susceptibility of landsliding. Sparsely vegetated areas are generally prone to erosion and present greater instability.

In this study, The Corine Land Cover map 2012 (CLC2012) of the European Environment Agency

(EEA, Copenhagen, 2012; <http://www.eea.europa.eu>) was adopted for the assignment of the land use classes, which was updated with the help of the orthophoto map. The evaluation of cover types was conducted according to Table 1. Highest values were given to areas covered by urban fabric and bare rocks which dominate the caldera cliffs and Kameni Islands. Lower weights were assigned to natural and semi-natural areas. Cultivations/Agricultural areas distributed randomly in Santorini, were given moderate values.

4.4 Distance from Road Network

Another evaluation factor related to the occurrence of landslides is the distance from the road network. It is considered that landslide susceptibility decreases when increasing the distance from the main roads located on steep slopes (Ladas, Fountoulis & Mariolakos 2007).

Road construction is also related to extensive excavations, application of static and dynamic loads, vegetation removal etc. along natural and engineered slopes. These landslide triggering actions (WP/WLI 1994) were considered in the design of the landslide susceptibility maps by introducing a road network buffer zones data layer.

The road network was derived from OpenStreetMaps, an open data source platform (<https://goo.gl/ozDBYc>), and updated with the help of the orthophoto map. Roads in steep slope areas increase the proneness to mass movements. Documented landslides in Santorini island occurred in areas close to road networks (either asphalt roads or paths). Three distance classes, 3, 5, and 10 meters were used according to the type of road as shown in Table 1. Roads which appear inside the urban fabric were not taken into account, as they were included in the Land Cover factor.

4.5 Curvature

Curvature values represent the morphology of the topography. They can be calculated in terms of plan curvature (which is perpendicular to the direction of the maximum slope), profile curvature (which is in the direction of the maximum slope) and general curvature (Ladas, Fountoulis & Mariolakos 2007).

In this study the general curvature was used since it combines the characteristics of the first two. Curvature was selected as a factor as it affects the hydrological conditions of the soil cover (Ladas, Fountoulis & Mariolakos 2007) and it was derived from the 5m-DEM. Potentially, the soil cover on a

concave slope can contain more water and retain it for a longer period than a convex slope, thus the first ones are favorable to landslides.

In the Santorini Volcanic Group curvature ranges from -653 to 633 m^{-1} . However, the majority of values are within -30 to 10 m^{-1} and they are classified based to natural breaks classification method. Negative values of the general curvature represent convex slopes while positive values correspond to concave slopes. The first ones are mostly observed on the caldera cliffs and at Profitis Ilias hill, as well as along the drainage network. Curvature was divided into 7 classes accordingly to Table 1.

4.6 Mean Annual Rainfall

Rainfall is an important factor, because as water passes through discontinuities, it widens the holes and leads to their destabilization, triggering landslides. Although the mean annual rainfall of the surrounding area is about 460mm (SSW, 2015), in a few extreme events rainfalls of approximately 570mm have been recorded, which they could not be ignored.

To interpolate the mean annual rainfall across the Santorini Volcanic Group, the Thira meteorological station data (National Weather Service, 36° 25' 3" N, 25° 25' 55" E, altitude 37m, gauging period 1931-2002) were processed and rainfall information was calibrated with the altitude using the 5m-DEM (Karamesouti 2011), dividing the area into zones per 200m of altitude (Table 1) based on low precipitation gradient. High risk areas are located mainly in the SE part of the Volcanic Group.

4.7 Distance from Streams

It is assumed that the seasonal flow regime of streams and gullies in the basin presents noteworthy erosive processes, leading to superficial mass wasting phenomena in areas adjacent to drainage channels (Kouli et al., 2013). Fluvial erosion is one of the most common triggering factors of the landslides (WP/WLI 1994), and it usually affects the slope's toe.

The drainage network was derived from the 5m-DEM and then corrected using the orthophoto map. It was classified in two distance classes; 20 meters away from streams, as they present periodic flow therefore reduced corrosivity and the rest of the areas (Table 1). Streams are located mainly at the eastern and southern part of Thera Island and at the western part of Thirasia Island, while the absence of

streams along the caldera cliffs is noticeable, as well as the presence of water erosion that formed narrow channel-like canyons on volcanic rock surfaces.

4.8 Proximity to Fault Zones

Landslides can be produced by tectonic factors such as thrusts and major faults, which create steep slopes and sheared zones of weakened and fractured rocks, leading to landslide potential (Ladas, Fountoulis & Mariolakos 2007).

Fault lines were digitized in vector format from the geological map of Druitt et al. (1999), where the presence of the major NE-SW Kolumbo fault zone in the northern part of Santorini island is noticeable. The buffered layer was classified into two distance classes; 50 meters away from faults, as they present low activation rate and the rest of the areas (Table 1). Other major fault zones are not distinguishable on the island due to the existence of several volcanic formations.

4.9 Aspect

Considering the influence of the aspect it can be assumed that it has an effect on the degree of saturation and evapotranspiration of the slopes. It is generally considered that the N and NW facing slopes in Greece are prone to landsliding due to their shadier and colder conditions that favor the accumulation and preservation of soil moisture. Thus, landslides are expected to be more common on the North and NW-facing slopes, due to larger water accumulation (Ladas, Fountoulis & Mariolakos 2007).

The aspect map was derived from the 5m-DEM and has been divided into two classes (Table 1). Relatively the northern part of the study area is dominated by high risk aspect slope faces.

4.10 Soil Thickness

The Soil factor corresponds to soil thickness and was derived from the Soil Associations Map of Greece, in a scale of 1:500.000 (Yassoglou 2004). Due to the fact that soil thickness is less than 15m all over the Volcanic Group, which is considered as not prone to landslides, it was decided not to take the value into account when calculating the final landslide susceptibility map.

5 FACTOR ANALYSIS

Model Builder, an ArcToolbox tool of ArcMap 10.5 (ArcGIS platform, ESRI) was used to create the spatial distribution of each factor. Model Builder is a visual programming language for building geoprocessing workflows to create, edit, and manage geoprocessing models that automate those tools (<https://goo.gl/D4JISL>).

A toolbox was created, containing a unique model for each factor (Figure 3). Each model consists of a workflow that strings together sequences of the appropriate geoprocessing tools, feeding the output of one tool into another as input, taking into account the respective data variables.

Having completed all the contributed factor maps, the relative contribution of each one was taken into account.

Landslides are influenced by many factors (preparatory or triggering) which vary significantly from region to region. It is therefore difficult to determine each factor's relative contribution in landslide occurrence and assign the respective weights.

Consequently, the multi criteria decision making approach is of high importance in susceptibility mapping. The Analytical Hierarchy Process (AHP) is a popular semi-qualitative method which introduces objectivity in weight assignment through pair wise comparisons and relies on the judgment of the experts to derive priority scales (Barredo et al. 2000, Ayalew et al. 2005, Akgun & Bulut 2007, Saaty 2008).

AHP is divided into two stages: (a) construction of a pair wise comparison matrix, and (b) determining weights and obtaining overall priority. Absolute numbers (from 1 to 9) were assigned to each landslide related factor based on its relative importance and comparison matrices were constructed to compute the Consistency Ratio (CR) and the Consistency Index (CI).

The resulting maps of 5m resolution for each factor (Figure 4) were used as input in the Analytic Hierarchy Process tool extAhp 20, developed for ArcGIS by Marinoni (2014), in order to determine the weight of each factor and to produce the susceptibility map (Table 2).

In this table, factors are listed in order of importance. For example, lithology is the most important one, slope is the second one, etc. The numbers in each cell correspond to the degree of preference between the two relevant factors. In the last column the assigned weights for each factor and the computed consistency ratio (CR) are shown.

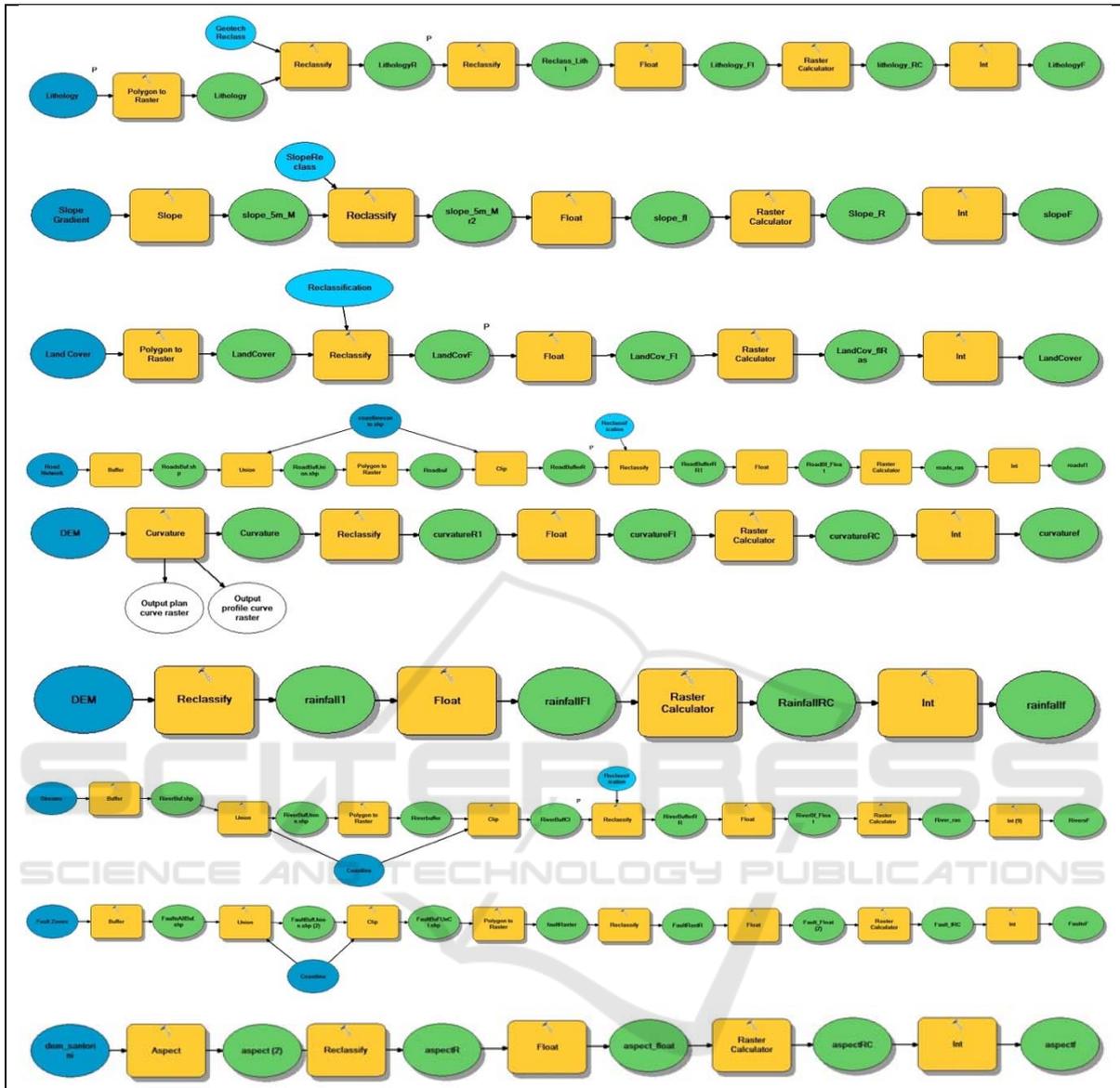


Figure 3: The models that created through Model Builder (ArcMap 10.), in order to produce the final map for each factor.

6 THE SUSCEPTIBILITY MAP

All the aforementioned factors processed with the AHP methodology resulted in the generation of the Landslide Risk Assessment Map of the Santorini Volcanic Group, in which the study area is classified according to the degree of landslide risk, pinpointing the problematic regions for further analysis (field observations, detailed mapping, etc.) (Figure 5).

The final map illustrates that the spatial distribution of landslide risk was classified into five categories: very high, high, moderate, low, and very

low. Classification was based on a frequency histogram of landslide risk values, of which the higher the value, the more susceptible the area is to landsliding.

Generally, caldera cliffs display high risk values. The internal northern cliffs of Thera Island and the eastern ones of Thirasia Island display high landslide risk due to the effect of the three most important factors (lithology, slope, and land cover), with very high risk values to be scattered along Thera’s cliffs.

Moderate to high values occurred mainly on Nea Kameni island (slope and lithology factors), along

the caldera rim (land cover and road network factors) and scattered throughout Thera and Thirasia island due to land cover and drainage network. Low and very low risk areas dominate the rest of the Santorini Volcanic Group.

7 CONCLUSIONS

In order to produce a landslide risk assessment map of the Santorini Volcanic Group, nine causative factors were taken into account by using the AHP methodology in a GIS environment.

The susceptibility map shows that landslide risk is not uniformly distributed along the caldera cliffs and it is compatible with the distribution of

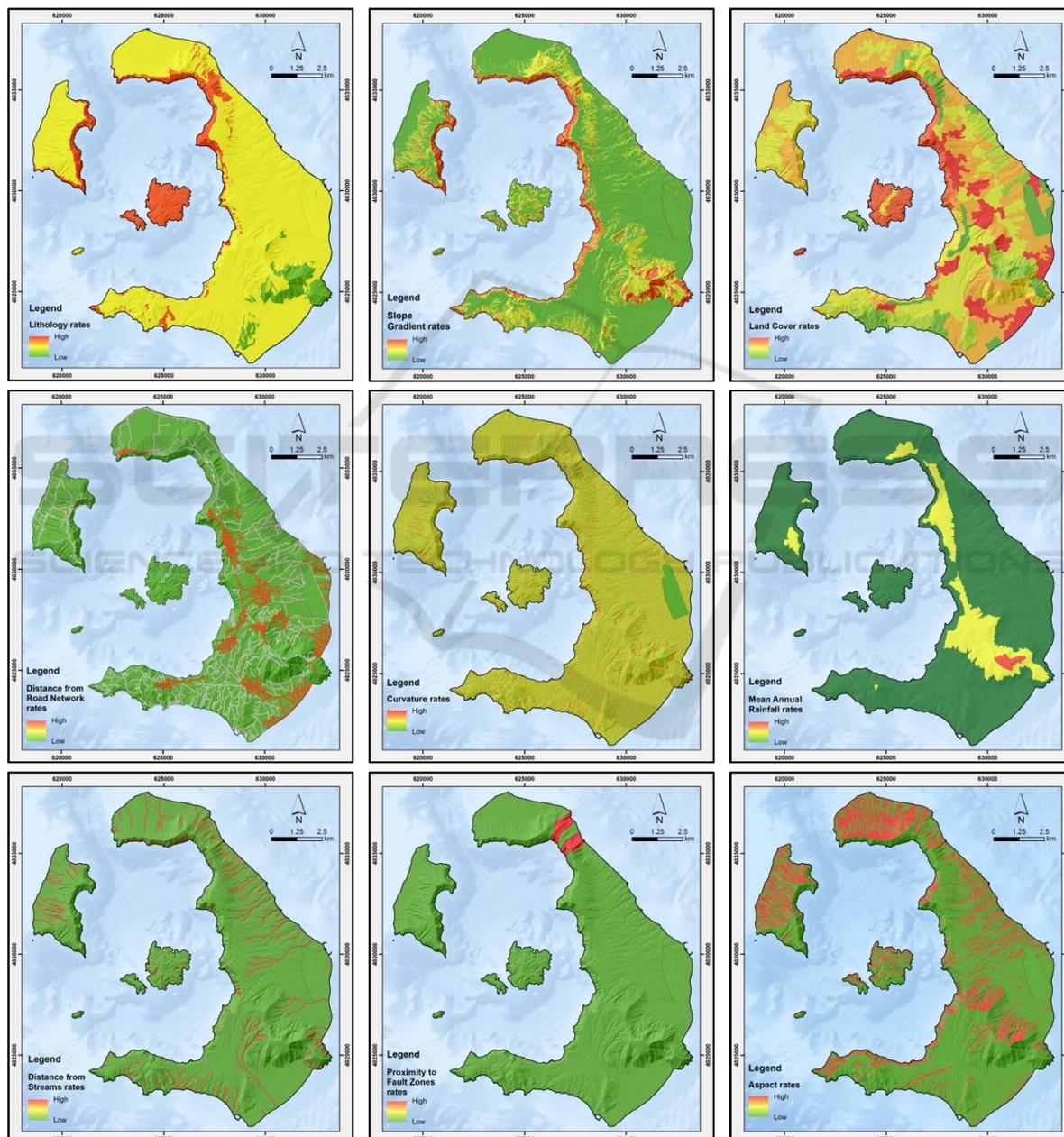


Figure 4: Contribution factors for Santorini susceptibility mapping, categorized according to the normalization rates of Table 1.

Table 2: The contribution factors and the corresponding weights, according to the AHP method.

Factors	Lithology	Slope Gradient	Land Cover	Distance from Road Network	Curvature	Mean Annual Rainfall	Distance from Streams	Proximity to Fault Zones	Aspect	Weights
Lithology	1	2	3	4	5	6	6	7	8	28.80%
Slope Gradient	1/2	1	2	3	4	4	6	7	8	20.60%
Land Cover	1/3	1/2	1	3	5	5	5	8	8	18.40%
Distance from Road Network	1/4	1/3	1/3	1	4	4	4	6	8	12.10%
Curvature	1/5	1/3	1/5	1/4	1	3	3	6	7	7.50%
Mean Annual Rainfall	1/6	1/4	1/5	1/4	1/3	1	2	4	6	4.90%
Distance from Streams	1/6	1/5	1/5	1/4	1/3	1/3	1	3	6	3.90%
Proximity to Fault Zones	1/7	1/6	1/8	1/6	1/6	1/7	1/8	1	4	2.30%
Aspect	1/8	1/7	1/8	1/8	1/7	1/6	1/6	1/7	1	1.40%
CR=0.09										

documented past landslide events. The main factors which contribute to the phenomena are the following:

- Geotechnical conditions of the lithological composition of the geological formations, which vary perpendicularly along the caldera.
- The large morphological dip values, although they are not uniformly distributed along the caldera.

Human interventions with negative impact, which are represented mainly by expanding the urban fabric.

As Santorini constitutes an active volcano, it is subjected to periodic tremors which strain on the already congested areas. However, it was impossible to model the spatial distribution of this specific factor.

Considering the need for local authorities to manage the landslide risk, a model was built, providing an easy-to-use tool for landslide susceptibility mapping.

In case a single factor or a number of factors change through time, the model gives the opportunity to decision makers to reevaluate the landslide risk according to future conditions. In addition, the model can be easily edited in order to add any other determinant or triggering factor. These options make the model extremely adaptable.

Furthermore, it makes it very easy for other researchers to realize the preliminary landslide risk assessment in other areas, simply by changing either the controlling factors, or their respective weights.

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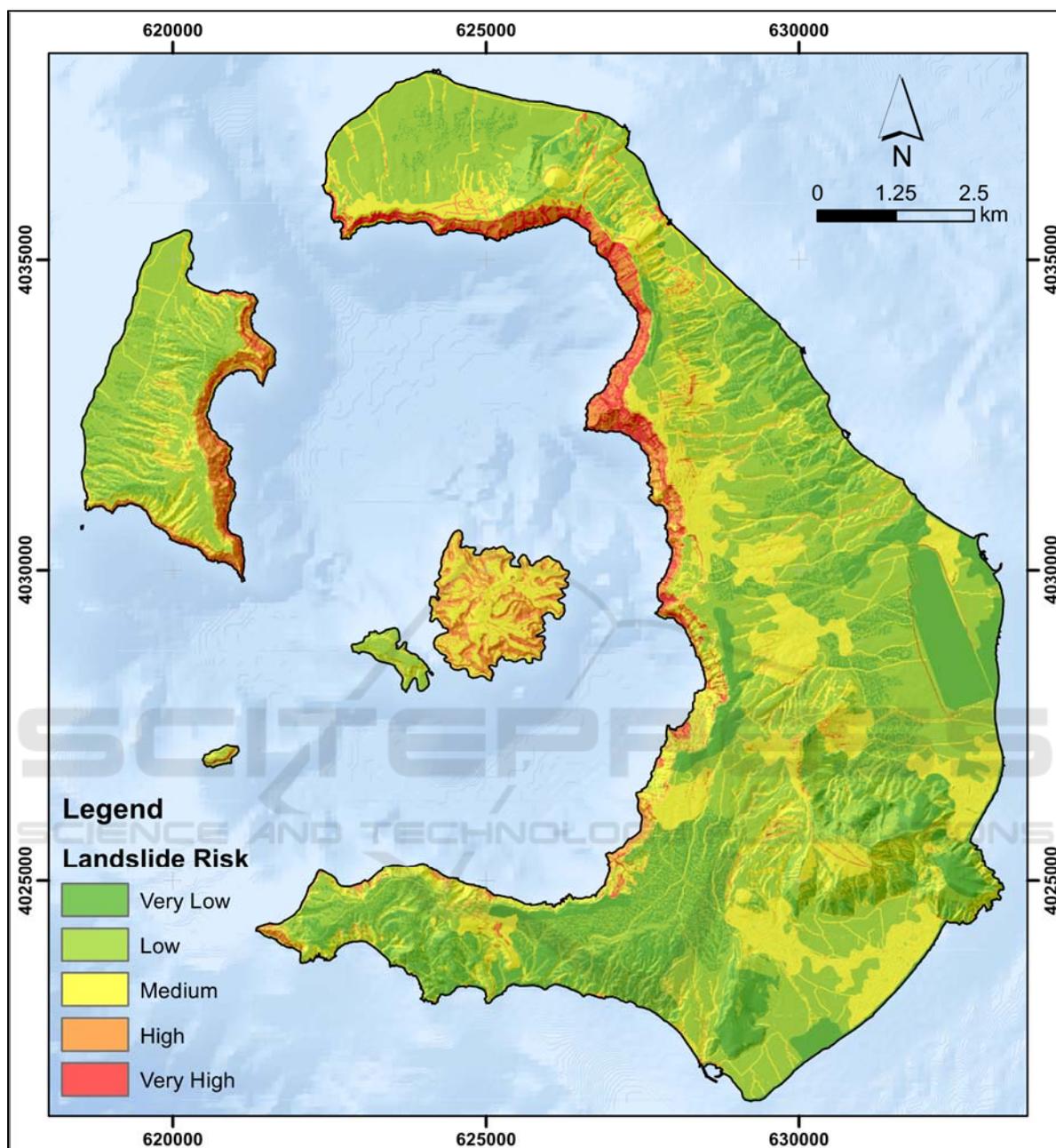


Figure 5: Landslide susceptibility map of the Santorini Volcanic Group.

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