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Landslide Susceptibility Assessment of Heraklion Prefecture in Crete, Greece

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Abstract

The purpose of this particular study is the assessment of landslide susceptibility of Heraklion prefecture area of Crete Island through geospatial analysis in order to present the general susceptibility zonation, so that it may be used as a basis in future extensive and detailed landslide susceptibility research, which will lead to the prevention of possible future landslides. In order to accomplish this task, it is essential to study the geological, geomorphological, geotectonic, hydrological and hydrogeological characteristics of the area, as well as the land use and compare this information with real landslide occurrence data from the study area. Based on this study it became clear that the area is defined by medium to very steep slopes and a geotechnical and geological setting that are extremely favorable for landslides. These reasons, as well as the fact that this prefecture is known to be the most densely populated prefecture of Crete Island created great interest in this area for research of this kind to prevent the loss of human life and the structural damage of properties. In order to study the landslide susceptibility of Heraklion prefecture, firstly, a geodatabase, which includes the landslide inventory, was created. The landslide inventory is consisted of previous landslides, which were collected from related geotechnical reports with all the essential spatial and descriptive information (such as locations and causes of the landslides). Furthermore, in this stage of the process, the necessary raster and vector data for the geospatial analysis of the area were obtained. Because the landslide susceptibility is a multifactorial problem it was decided to use a relating method to the problem's nature, which was the methodology of the Analytical Hierarchy Process (AHP), as it is a simple and widely used method for similar studies, *which makes it a great tool for this introductory study. In addition, this method was implemented in a GIS environment. For the purpose of the study, ten (10) triggering factors that cause landslides were defined, followed by the creation of a landslide susceptibility assessment map of the study area, depending on the influence of each factor. In accordance with this map, the highest susceptibility mostly corresponds to the mountainous regions of the prefecture. Finally, the success evaluation of the landslide susceptibility model was determined based on the frequency of landslide occurrences of the medium, high, and very high susceptibility zones. Consequently, the model was characterized as 90.48% successful, according to bibliography and the landslide inventory.*

Keywords*: Heraklion prefecture, AHP, GIS, multi-criteria decision analysis, landslides, susceptibility assessment.*

Περίληψη

Ο σκοπός της συγκεκριμένης έρευνας είναι η εκτίμηση της κατολισθητικής επιδεκτικότητας στην ευρύτερη περιοχή του Ν. Ηρακλείου της Κρήτης μέσω γεωχωρικής ανάλυσης, προκειμένου να αποτυπωθεί η γενική ζώνωση της επιδεκτικότητας, ώστε να μπορεί να χρησιμοποιηθεί ως βάση σε μελλοντικές εκτεταμένες και λεπτομερείς έρευνες κατολισθητικής επιδεκτικότητας, που θα οδηγήσουν στην πρόληψη πιθανών μελλοντικών κατολισθήσεων. Προκειμένου να πραγματοποιηθεί αυτός ο σκοπός είναι σημαντική η συλλογή των γεωλογικών, γεωμορφολογικών, γεωτεκτονικών, υδρολογικών και υδρογεωλογικών χαρακτηριστικών της περιοχής, καθώς και των χρήσεων γης και να γίνει συσχέτιση με πραγματικά δεδομένα κατολισθητικών φαινομένων από την περιοχή μελέτης. Βάσει της έρευνας αυτής έγινε σαφές ότι η περιοχή αυτή χαρακτηρίζεται κυρίως από μέτριες έως απότομες γεωμορφολογικές κλίσεις και γεωτεχνικά και γεωλογικά χαρακτηριστικά που δημιουργούν ιδανικές συνθήκες για την έναρξη κατολισθητικών συμβάντων. Οι παραπάνω λόγοι, καθώς και το γεγονός ότι ο συγκεκριμένος νομός θεωρείται ο πολυπληθέστερος νομός του νησιού, δημιούργησαν ιδιαίτερο ενδιαφέρον για μια τέτοιου είδους έρευνα στην παρούσα περιοχή, προκειμένου να αποφευχθούν ανθρώπινες και υλικές απώλειες, θέτοντας τα κατάλληλα μέτρα πρόληψης και προστασίας από τους αρμόδιους φορείς. Για την επίτευξη του στόχου της συγκεκριμένης μελέτης, αρχικά, δημιουργήθηκε μια γεωβάση, η οποία αποτελεί το γεωευρετήριο των κατολισθήσεων της περιοχής μελέτης. Ειδικότερα, το γεωευρετήριο κατολισθήσεων αποτελείται από προηγούμενες κατολισθήσεις που έχουν καταγραφεί στο παρελθόν και έχουν συλλεχθεί από αντίστοιχες γεωτεχνικές εκθέσεις με όλα τα απαραίτητα περιγραφικά και χωρικά χαρακτηριστικά τους (όπως η θέση και τα αίτια δημιουργίας των *κατολισθήσεων). Επιπλέον, σε αυτό το στάδιο της έρευνας συλλέχθηκαν όλα τα απαραίτητα raster και vector δεδομένα για την γεωχωρική ανάλυση. Το γεγονός ότι η εκτίμηση της κατολισθητικής επιδεκτικότητας μια περιοχής αποτελεί πολυπαραγοντικό πρόβλημα για την επίλυση του προβλήματος αποφασίστηκε να χρησιμοποιηθεί μια αντίστοιχη μεθοδολογία στην φύση του προβλήματος, γνωστή ως «Μεθοδολογία της Αναλυτικής Ιεράρχησης» (Analytical Hierarchy Process – AHP), εφόσον αποτελεί μία αρκετά διαδεδομένη και απλή μέθοδο σε αυτού του είδους έρευνες, που την καθιστά το κατάλληλο εργαλείο για τη συγκεκριμένη πρωταρχική μελέτη. Πιο συγκεκριμένα, η συγκεκριμένη μεθοδολογία χρησιμοποιήθηκε σε περιβάλλον ArcGIS. Επίσης, για τον σκοπό της μελέτης ορίστηκαν δέκα (10) παράγοντες που προκαλούν κατολισθητικά φαινόμενα, που ακολουθείται με την δημιουργία ενός χάρτη κατολισθητικής επιδεκτικότητας του Ν. Ηρακλείου, βασισμένος στην επιρροή του κάθε παράγοντα της περιοχής μελέτης. Κλείνοντας, η εκτίμηση της επιτυχίας του μοντέλου βασίστηκε στην συχνότητα των κατολισθήσεων στις ζώνες μέτρια, υψηλής και πολύ υψηλής κατολισθητικής επιδεκτικότητας. Επομένως, το μοντέλο χαρακτηρίστηκε ως 90,48% επιτυχές, σύμφωνα πάντα με την βιβλιογραφία και το κατολισθητικό γεωευρετήριο της περιοχής μελέτης.*

Λέξεις-Κλειδιά: *Νομός.Ηρακλείου, AHP, Γεωγραφικά Συστήματα Πληροφοριών (Γ.Σ.Π.), πολυπαραγοντική μέθοδος, κατολισθήσεις, εκτίμηση επιδεκτικότητας.*

1. INTRODUCTION

Landslides, along with volcanic eruptions, earthquakes, uncontrolled wildfires, and floods, are considered some of the greatest natural disasters, resulting in the loss of human lives as well as both private and public property. Particularly, landslide events have a severe socio-economic impact on society and thus the provision of remediation measures is considered indispensable. According to Pourghasemi (2012), at least 17% of the fatalities worldwide involve landslide events. Generally, they can occur as a result of either natural or anthropogenic causes, although most researchers are interested in the anthropogenic type due to their greater consequences on human lives. Despite that, in this study all types of landslides have been taken into consideration.

The need for the preservation of human life, as well as the reduction of economic and structural ramifications has led to the development of landslide susceptibility assessment models. According to Nadim, et al. (2006) the accuracy of the model depends on the definition of the triggering factor of the landslides regardless of the type of landslide. A first step to the landslide mitigation process is considered the production of Landslide Susceptibility Maps (Ercanoglu 2005, Rozos et al. 2011). The utilization of aforementioned maps, for instance, point to a safer land use and development reducing the potential hazard. Hence, the term "landslide susceptibility zonation" has been used to describe the development of maps of this kind through delimiting and classifying a part of the earth's surface according to the degree of existing or potential hazard of landslides (or in general from natural disasters), taking into account factors influencing soil movements in the area (Brenning, 2005; Koukis & Sabatakakis, 2007). As technology progresses, landslide susceptibility models are constantly becoming more accurate as more landslides are being registered in a detailed geodatabase which includes all the different factors that caused them as well as their descriptive and spatial features (Fall et al. 2006).

A very useful tool for the construction of landslide susceptibility maps is the use of Geographic Information Systems (GIS), which was used in this research. A wide variety of techniques are used in a GIS environment resulting in a map representing the susceptibility of a study area in landslides. These techniques are separated in three major categories which consist of qualitative, semi-quantitative and quantitative mapping methods (Remondo et al. 2008; Zezere et al. 2008; Kouli et al. 2010; Kouli et al. 2013; Antoniou et al. 2017). The first category concerns the experience and opinion of an expert and includes methods such as Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC) (generally known as multi-criteria decision making techniques) while quantitative techniques take into consideration mathematical expressions of the correlation between causal factors and landslides and consists of inventory based mapping, deterministic techniques, probabilistic techniques, heuristic techniques, statistical analysis techniques. In this specific research a combination of qualitative and quantitative techniques has been used in the construction of the landslide susceptibility assessment map of the study area such as landslide inventory mapping, AHP analysis and statistical approach. Specifically, after the classification and the class distribution of a collection of factors responsible for landslide events was accomplished, the AHP method was used to determine their relationship to each other and the overall zonation of the landslide susceptibility of the study area. This was done through a pairwise comparison of the factors, which were then ranked according to their level of overall importance and impact. Additionally, an inventory of landslides events from the study area was used to evaluate the success of the landslide susceptibility model, based on a statistical analysis, which determined the number of landslide events that occurred within zones of medium to very high susceptibility.

According to Koukis & Sabatakakis (2007) most landslides in Greece tends to occur in the mainland areas of the country as well as many islands in the Aegean Sea due to their geomorphological and geotectonic setting, thus landslide susceptibility assessment in these locations is extremely important. In accordance to this, the area of Heraklion prefecture of Crete Island in Greece was chosen for this study. The island's geotectonic setting and structure and geomorphological attributes, in combination with the dense population of this prefecture makes this study area one of major importance when it comes to the assessment of its susceptibility to landslide events. Such events have occurred in proximity to the relatively dense road network of the prefecture as well as populated areas causing structural damages and endangering human lives, hence the interest in the prefecture of Heraklion.

The goal of this study is the assessment of landslide susceptibility of Heraklion prefecture, Greece, through geospatial analysis in combination with the application of the AHP method for the construction of a detailed zonation map, which can be used in predetermining future landslide events based on the zones of greater susceptibility, thus avoiding human loss and structural damage.

2. STUDY AREA

Heraklion prefecture is in Crete Island, which is the southernmost island of Greece. Crete Island is found at the edge of the Hellenic Volcanic Arc in the southern Aegean Sea, where the African tectonic plate is being subducted under the Eurasian tectonic plate (Fig. 1; Sarris et al. 2005; Zygouri et al. 2016; Ganas et al, 2017). The island is surrounded by four seas. Towards the northern coastline the Cretan Sea can be found, while the southern coastline meets the Libyan Sea. The eastern and western sides of the island are bordered by the Carpathian and Myrtoan seas respectively (Sarris et al. 2005; Roditaki, 2011). The study area is located at the center of the island and consists of many, highly populated residential areas, such as Heraklion, Aghia Varvara, Epano Archanes, Moires and Malia, which are known as popular tourist destinations. This prefecture is also considered as the most densely populated prefecture of the island with a total population of 305.490 residents and a total area of 2.641 km^2 according to data from the Hellenic Statistical Authority (2011) (Roditaki, 2011).

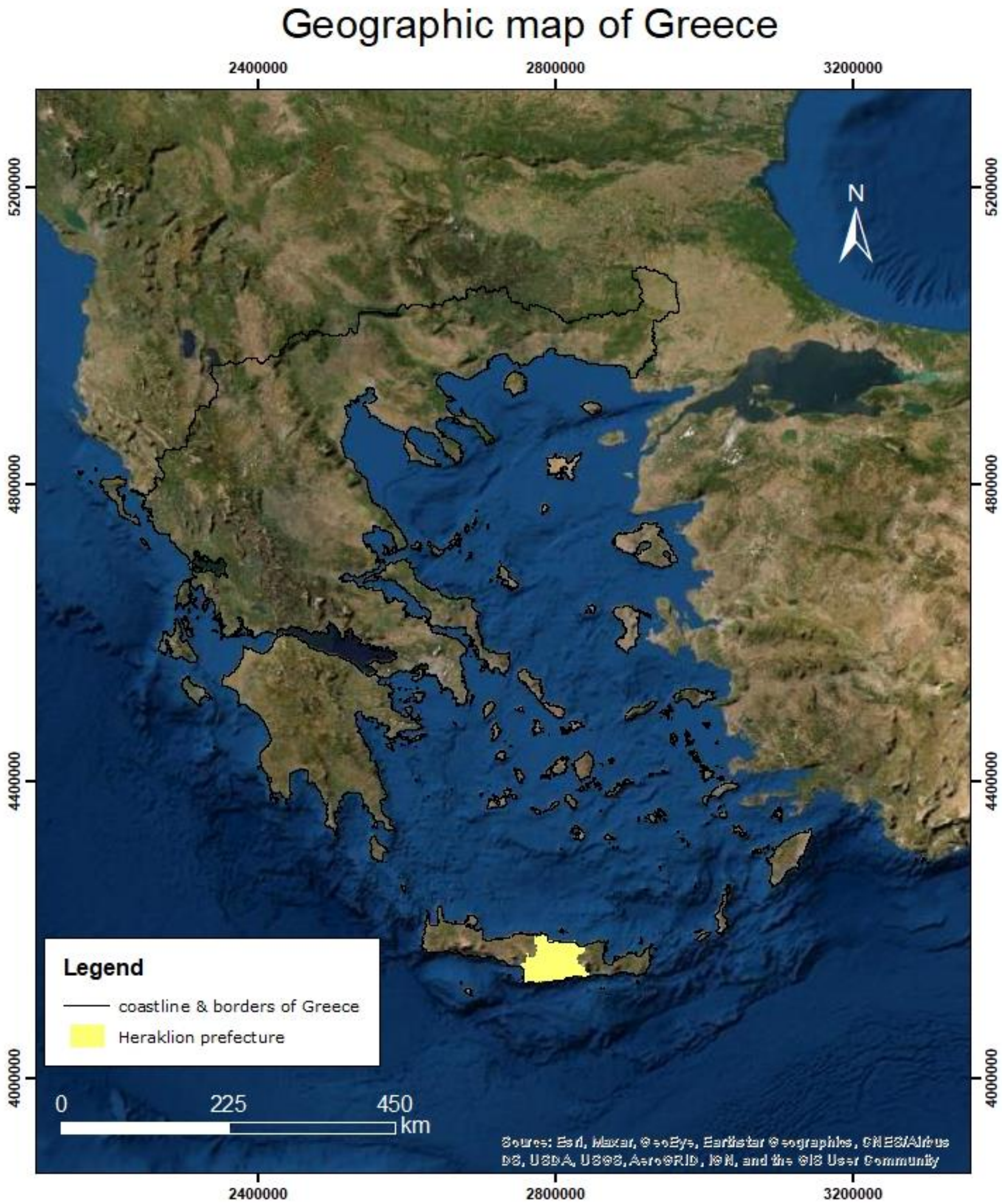

Fig. 1: The geographic map of Greece pinpointing the study area. Coordinate system: WGS 84 World Mercator.

2.1. Geomorphological Setting of the Study Area

The Island of Crete is generally represented by a rather mountainous relief consisting of many mountain ranges, a geomorphological trend that can also be noticed in the prefecture of Heraklion (Fig. 2). Heraklion prefecture consists of two of the main mountain ranges of Crete Island, the Idi – Psiloritis (2456 m) mountains forming the western border of the prefecture (Sarris et al. 2005) and the mountain of Diktis – Selena (2147 m) forming the eastern border respectively (Fassoulas, 2001; Polichronaki et al. 2009; Roditaki, 2011). Another noteworthy mountain range that forms the southernmost border of Heraklion prefecture is the Asteroussia Mountains (1231 m).

Additionally, the study area includes two main basins enclosed by the mountain ranges. The first basin, known as Heraklion Basin, is located between the mountains of Idi – Psiloritis and Diktis – Selena and can be found at the northern coast of the study area. This basin is noteworthy because the city of Heraklion (which is also the capital of the entire island and includes one of the main harbors of the Crete) is built within it, in close proximity to the coastline. The second basin of the study area is the Messara basin which is located at the south and west part of the prefecture, trending west – east, enclosed by the mountains of Idi – Psiloritis and Asteroussia (Fassoulas, 2001; Polichronaki et al. 2009; Roditaki, 2011). Generally, the study area is characterized by a hilly relief that includes both mountain ranges and basins. As expected, the relative relief of the area changes between the mountainous areas and the basins of the prefecture. Specifically, the mountains are characterized by moderate to steep slopes ranging from 15 - 45° while relatively flat areas, such as the main basins present rather gentle slopes ranging from 0 - 15°. The river network of Heraklion prefecture is quite densely distributed across the area with the density decreasing slightly towards the eastern border (Polichronaki, 2009). The majority of the area's surface runoff is dominated by seasonal torrential rivers (Polichronaki, 2009) while the main rivers are the Giofyros river which is located in Heraklion basin and Geropotamos river in Messara basin (Roditaki, 2011).

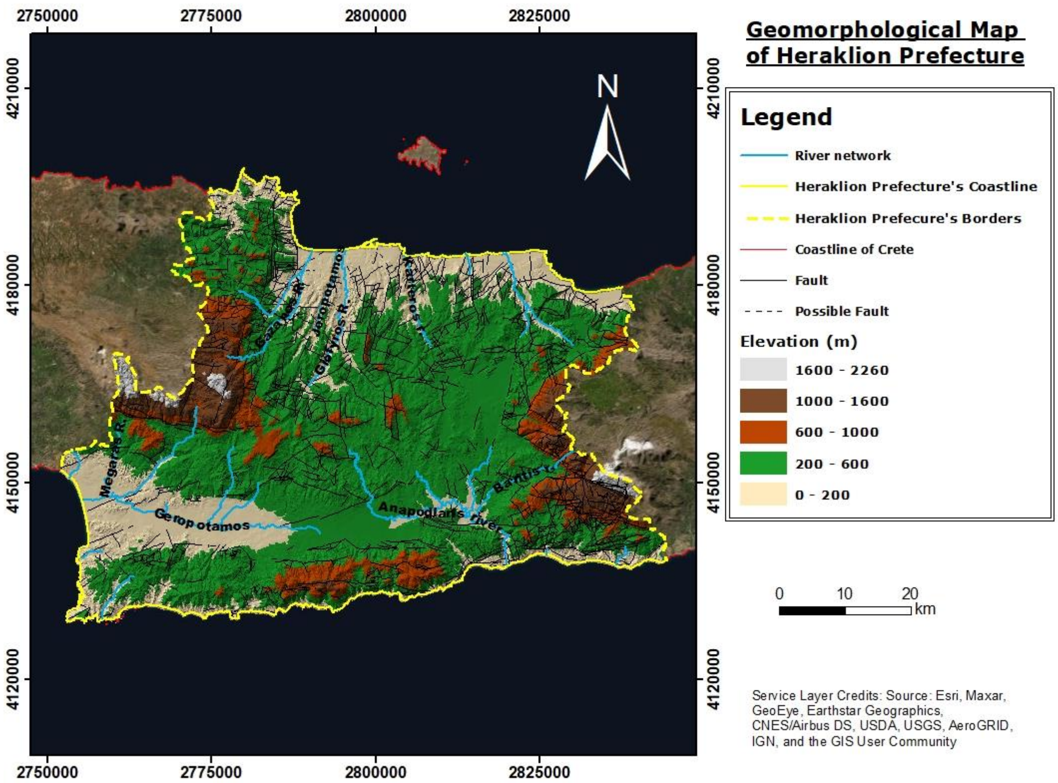

Fig. 2: Geomorphological map of Heraklion prefecture.

2.2. Geological Setting

The island of Crete belongs in the geotectonic zone of the outer Hellenides and the outer tectonometamorphic belt of Greece. Crete follows the main principals of the geological setting of Greece, according to which, lithologies formed during and prior to the Alpine Orogenetic event (Alpine and Pre-alpine formations respectively) have been covered by lithologies formed after the Alpine Orogenesis (Post-alpine formations). The Alpine and Pre-alpine formations were divided into three main series of units and nappes, the *lower series*, the *upper series* and the *uppermost nappes of Crete* (Sarris et al. 2005; van Hinsbergenn & Meulenkamp, 2006; Papanikolaou & Vassilakis, 2010; Fig. 3). The Lower series include the geotectonic unit of Crete-Mani, also known as "Plattenkalk unit" (which is believed to be the metamorphosed equivalent of the Ionian unit) consisting of phyllites, quartzites, schists, limestones, dolomites, marbles and flysch (Carboniferous – Oligocene), forming the base of the island's geological formations. Placed over Crete-Mani unit is the Trypali unit, while the uppermost unit of the lower series is the Phyllites-Quartzites, also known as "Arna nappe" (which is believed to be the metamorphosed equivalent of the Gavrovo-Tripolis unit). The latter consists mostly of schists, phyllites and quartzites (Paleozoic) (Sarris et al. 2005; Roditaki, 2011; Papanikolaou, 2014). The Upper series is placed over the lower series and consists of the lower Gavrovo-Tripolis unit which is made of a basal volcano-sedimentary formation (Ravdoucha beds), a main body of neritic limestones and dolomites and flysch (Upper Triassic – Upper Eocene) (Sarris et al, 2005; van Hinsbergenn & Meulenkamp, 2006; Papanikolaou & Vassilakis, 2010; Roditaki, 2011; Papanikolaou, 2014) and the Upper Pindos-Ethia unit. The latter consists mainly of pelagic limestones and dolomites, cherts, radiolarites, mudstones and flysch (Triassic – Eocene) (Sarris et al. 2005; Papanikolaou, 2014; Roditaki, 2011).

The Uppermost Nappes of Crete are a series of nappes thrusted over the Lower and Upper series and includes the nappes of Arvi, Vatos, Miamou, Preveli, Spili and Asteroussia. These nappes consist mostly of metamorphosed sedimentary, volcanic and volcano-sedimentary formations, as well as metamorphosed flysch and marbles. Over these nappes an ophiolitic nappe can be found consisting of serpentinites, peridotites, gabbro and dolerites (Sarris et al. 2005; Papanikolaou & Vassilakis, 2010; Papanikolaou, 2014). On top to the aforementioned series and nappes the Post-alpine formations have been deposited, which include Neogene and Quaternary loose sediments, such as alluvial deposits, fluviolacustrine deposits, marine sediments and terraces and sedimentary formations (Fassoulas, 2001; Sarris et al. 2005; van Hinsbergenn & Meulenkamp, 2006; Roditaki, 2011). The area of Heraklion prefecture contains all the units, nappes and formations that were analyzed above, except for the Trypali unit which appears only in the western part of the island.

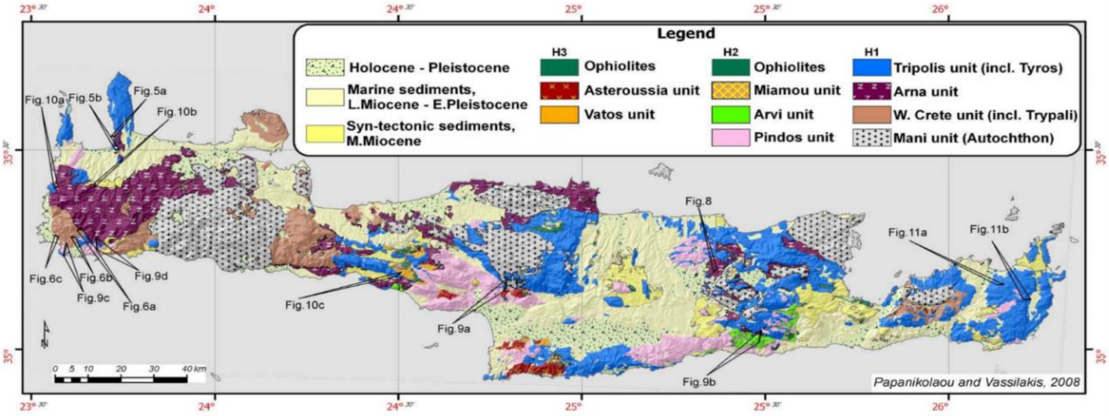

Fig. 3: Geological map of Crete (Papanikolaou & Vassilakis, 2010).

2.3. Tectonic Structure and Seismological Setting

Both the tectonic structure and the seismological setting of Heraklion prefecture have been developed and established by the geotectonic history of Crete Island based on its proximity to the subduction zone of the African and Eurasian plates. Due to the subduction of the African tectonic plate under the Eurasian plate a tectonic uplift event occurred during the Quaternary, affecting the geomorphological and tectonic setting of the entire island. This event was followed by an eustatic event at the Upper Quaternary, which can be identified by the marine terraces found at the coastline of Crete, aiding in the development of the island’s tectonic structures. As a result, a vast network of thickly distributed normal faults was formed leading to the Alpine formations of Heraklion prefecture’s mountainous ranges coming into contact with the Neogene and Quaternary deposits of the various basins (Caputo, et al., 2010). These normal faults have been separated into three categories according to their direction (Fassoulas, 2001; Kokinou, et al., 2008; Caputo, et al., 2010; Fig. 4). *The First category* refers to normal faults of an East – West (E – W) direction (Fassoulas, 2001; Kokinou, et al., 2008). These faults tend to intercept faults of a North – South (N – S) direction (Fassoulas, 2001) and are responsible for an extensional tectonic setting in a N – S direction (Caputo et al., 2010). *The Second category* includes normal faults trending N – S, NNE – SSW and NNW – SSE (Fassoulas, 2001; Kokinou, et al., 2008; Kokinou et al., 2013), which are responsible for a compressional tectonic setting in an E – W direction (Caputo, et al., 2010). Finally, the Third category of normal faults follows the directions NE – SW and NW – SE. These faults are the youngest group, cutting through the faults of the first two categories. The distribution of seismological epicenters in Heraklion, as well as in the sea follows both the tectonic trends of the prefecture and the effects of the subduction zone to the south of the island (Fig. 5). Specifically, a greater amount of densely amassed seismic occurrences has been recorded at the Libyan Sea in comparison to the Cretan Sea due to the Libyan Sea being closer to the subduction zone, which is a structure known for causing frequent earthquakes (Delibasis, et al., 1999; Kokinou, et al., 2008). Likewise, the seismological setting of the prefecture tends to follow the trend of earthquakes being more frequent in at the southern part of the area due to the aforementioned reason (Delibasis, et al., 1999). Additionally, there's an increasing trend of seismic occurrences towards the eastern part of the prefecture, which is caused by the dense distribution of second category normal faults in this area (Delibasis, et al., 1999; Kokinou, et al., 2008).

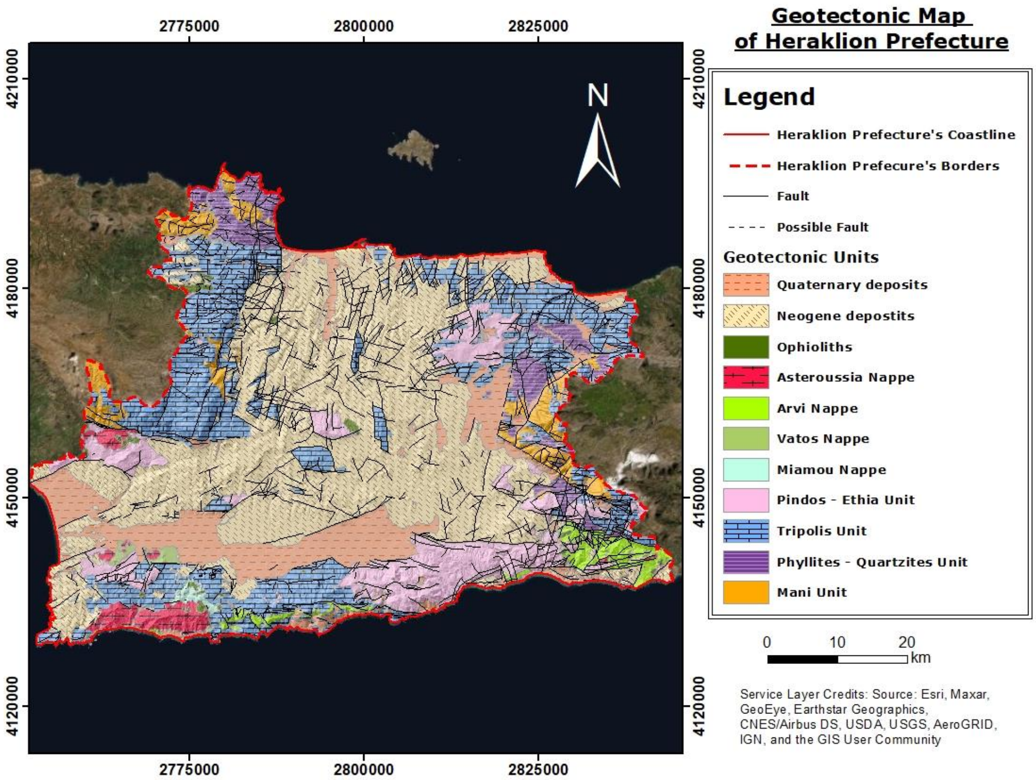

Fig. 4: Geotectonic map of Heraklion prefecture. Coordinate system: WGS 84 World Mercator.

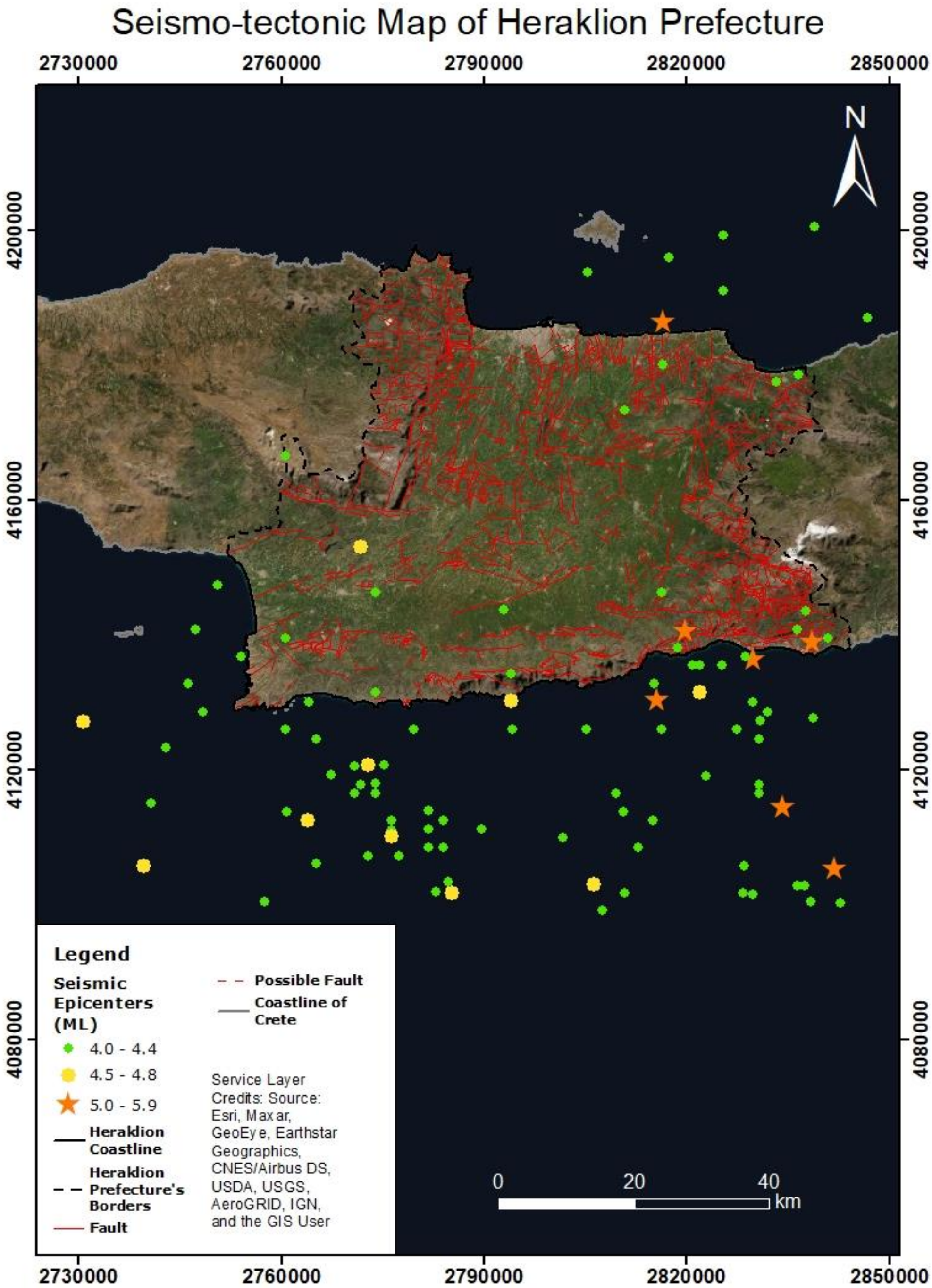

Fig. 5: Seismo-tectonic map of Heraklion prefecture in Crete. Seismic epicenters were collected from year 1964 to 2020 (Seismic data derived from the Earthquake Research - Institute of Geodynamics). Coordinate system: WGS 84 World Mercator.

2.4. Climatological Setting

The climate of Crete Island in general can be considered as a mixture of the Mediterranean climate and the arid African climate. Consequently, due to this climate Crete Island has more sunny days and higher temperatures than the rest regions of the country. In this study, we focus on the mean annual precipitation of Crete Island and particularly for the study area – Heraklion prefecture. In Crete Island the major precipitation events occurs in the winter (December – January), which results in high humidity in the area. In the study area, it is pinpointed that most rainfalls occur in the mountainous area in a western – northern direction of the prefecture and the rainfalls are being slightly reduced in an eastern – southern direction, respectively (Zambetakis, 2009). It can be noticed that in Heraklion prefecture the amount of total precipitation is increased by 43,3 mm per 100 m altitude.

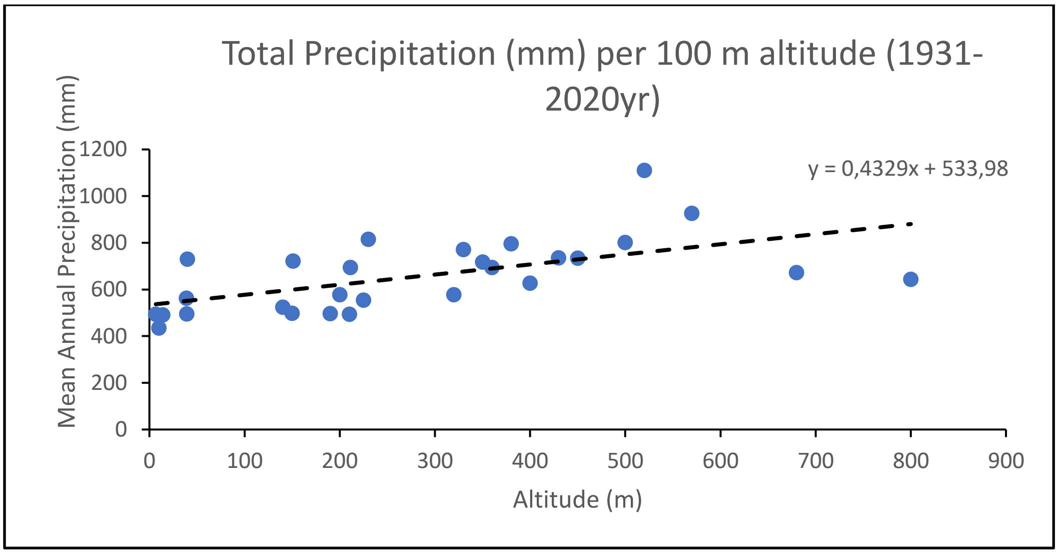

Fig. 6: Diagram of Total Precipitation per 100m altitude of Heraklion prefecture (1931-2020). Sources: **a)** Decentralized Administration of Crete ; **b)** Geoportal of Decentralized Administration of Crete – Webmap of Precipitation Station Data ; **c)** Geoportal of Decentralized Administration of Crete – ArcGIS Precipitation Station Metadata.

3. Data Used and Methodology

3.1. Data Used

For the aim of the study, ten (10) crucial factors were defined that can be considered as potential causes for landslide occurrences according to the geotechnical characteristics of the study area and other similar related scientific research (Fall et al. 2006; Kouli et al. 2010; Kouli et al. 2013; Antoniou et al. 2017; Krassakis & Loupasakis, 2018; Kouhartsiouk & Perdikou, 2020). Specifically, these factors were defined by the geomorphological & geotectonic characteristics of the study area, the mankind activity on the natural environment and the climatological conditions of the study area. To sum up, the ten (10) triggering factors are as follows:

1. Lithology
2. Mean Annual Precipitation (MAP)
3. Land Cover (LC)
4. Proximity to road network
5. Proximity to river network
6. Proximity to tectonic structures
7. Soil Thickness
8. Slope Gradient
9. Aspect
10. Curvature

All these triggering factors in order to be used for the geospatial analysis in ArcMap 10.6 in a Geographic Information Systems environment were selected the following datasets:

- Eight (8) geological maps of Hellenic Survey of Geology & Mineral Exploration (Hellenic Survey of Geology & Mineral Exploration - HSGME (former IGME), 1972; Hellenic Survey of Geology & Mineral Exploration - HSGME (former IGME), 1974; Hellenic Survey of Geology & Mineral Exploration - HSGME (former IGME), 1974; Hellenic Survey of Geology & Mineral Exploration - HSGME (former IGME), 1984; Hellenic Survey of Geology & Mineral Exploration - HSGME (former IGME), 1989; Hellenic Survey of Geology & Mineral Exploration - HSGME (former IGME), 1994; Hellenic Survey of Geology & Mineral Exploration - HSGME (former IGME), 1996; Hellenic Survey of Geology & Mineral Exploration - HSGME (former IGME), 2002) and one (1) geological map of Anoghia, Crete Island (Katsiavrias & Papazeti, 2008) for the geotectonic structure of the prefecture.
- Topographic maps from Hellenic Military Service at a scale of 1: 50.000 with a 20m contour interval, the coastline of Greece and the drainage network of Crete Island.
- Precipitation data of Heraklion prefecture from 1931 – 2020 (Fig. 6).
- The Corine Land Cover Map 2018 (CLC Map 2018) of the European Environment Agency (EEA) https://land.copernicus.eu/pan-european/corine-land-cover/clc2018
- Road Network of Crete from Open Street Map (OSM).
- Maps of soil characteristics of the study area (Karamesouti, 2011; Yassoglou, 2004).

Inventory of previous landslides of the study area from IGME (Nikolaou & Georgopoulou, 1988; Rozos D. , 1981; Zourbakis & Koenakis, 2019; Zourbakis et al. 2020).

3.2. Methodology

In this step all the necessary vector and raster data have been selected and generated from the aforementioned datasets. For the purpose of this study since the landslides can be considered as a multi-criteria problem, Analytical Hierarchy Process (AHP) was used for further analysis of the defined triggering factors of the study. Specifically, according to this method, the characteristics of each defined factor were divided into classes which were then ranked from 1 to 7 (depending on the number of classes defined for each factor), based on their importance on the study problem. The following step was to calibrate the ranking of each factor characteristics so as to create a single standardized scale, ranging from a value of 0 to 100. Then, the triggering factors were ranked from 1 to 9, respectively, making a pairwise comparison (Saaty R. W., 1987; Saaty T. L., 2008).

Table 1: The fundamental scale of the Saaty AHP method (Saaty R. W., 1987).

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	Moderate importance of one over another	Experience and judgment slightly favor one over the other.
5	Essential or strong importance	Experience and judgment strongly favor one over the other.
7	Very strong importance	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice.
9	Extreme importance	The evidence favoring one over the other is of the highest possible validity.
2, 4, 6, 8	Intermediate values	When compromise is needed.

The ranking was based on the ranking method of AHP analysis that was firstly used by Saaty (1980). As an example, the lithology factor map was separated into 5 classes, ranked from 1 (least impactful lithologies) to 5 (most impactful lithologies), while the proximity to river network and slope curvature factor maps were separated into 3 (ranks 1 to 3) and 7 (ranks 1 to 7) classes respectively. However, for the final pairwise comparison to be accurate a common range of values must be used on each class for each factor. As such, a range of values from 0 to 100 was picked in which the highest ranked class of any factor was given a value of 100% while the rest of the classes' ranks were calculated based on this value. Therefore, the ranks 5, 3 and 7 of the three aforementioned factors in this example were all equated to 100% susceptibility, while rank 1 classes of these factors were calculated as being equal to 20%, 33% and 14% landslide susceptibility respectively in the common range of values. As a result, the final pairwise comparison has created a 10 x 10 table, in which the diagonal comparisons that represents the pairwise result of the factor itself are equal to 1 as seen below.

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & \cdots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & \cdots & 1 \end{bmatrix}$$

Where each value of a is equal to:

$$a = \frac{Rank/\text{weight of factor in a line}}{Rank/\text{weight of factor in a row}} \qquad [1]$$

(Saaty R. W., 1987; Saaty T. L., 2008; Sener et al. 2010; Achu et al. 2020). In the previous example, comparing the lithology, proximity to river network and slope curvature factors to the lithology factor, the lithology compared to itself is just as important, therefore it takes a value of 1 when compared to itself. Meanwhile, it was decided that the lithology of the study area is 4 times as important as the proximity to river network and 7 times as important as the slope curvature, therefore, the two factors are given the values of 4 and 7 respectively of Saaty's fundamental scale when compared to lithology. Similarly, the proximity to river network is 1/4, 1 and 5 times as important as the three factors respectively. Likewise, the three factors of the example are 1/7, 1/5 and 1 time less important than the slope curvature of the study area. Thus, these are the values of importance of Saaty's fundamental scale that they are given. The consistency of the pairwise comparisons of the square table is evaluated by the Consistency Ratio (CR), which is obliged to be less than 0.1 and greater than 0. The CR value is equal to:

$$CR = \frac{CI}{RI} \qquad [2]$$

The Consistency Index (CI) is derived from the equation:

$$CI = (\lambda_{max} - n)/(n - 1) \qquad [3]$$

Where λmax is the largest eigenvalue of the matrix and n is the order of the matrix (Sener, et al. 2010; Achu et al. 2020).

The appropriate value of the Consistency Index of a random square matrix (RI) is derived from the table of random RI values published by Saaty (Saaty T. L., 2008) as seen below (Paraskevopoulos, 2021):

Table 2: Random CI (RI) values based on Saaty's matrices.

Number of Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

The final weights in the output process are based on their influence on the study problem. (Saaty R. W., 1987; Vargas, 1990; Saaty T. L., 2008; Sener et al., 2010; Achu et al, 2020). They can be calculated through two mathematical techniques. The first, and more accurate technique utilizes the geometric mean of each line (u_i) and dividing it by the sum of the geometric mean of all rows (u_k) of the matrix calculating the weights of importance of each factor as follows (Saaty R. W., 1987; Saaty T. L., 2008):

$$w_i = \frac{u_i}{\sum_{k=1}^{n} u_k} \qquad [4]$$

where i=1,…,n (n = 10 in this circumstance)

The second method of weight calculation is by using the geometric mean of each line (u_i) and dividing it by the sum of the geometric mean of all lines of the matrix through the following equation (Saaty R. W., 1987; Saaty T. L., 2008):

$$w_i = \frac{u_i}{u_1 + u_2 + \ldots + u_n} \qquad [5]$$

Finally, the susceptibility map was generated by the tool extAhp 20, developed for ArcGIS by Marinoni (2014), using the resulting maps as an input in order to produce the output map – the landslide susceptibility map. The resultant weights for each factor, as well as the CR of the matrix was calculated directly by the aforementioned tool after the desired ranks were imputed.

4. Analysis of the Landslide Susceptibility Factors

After the preparation of the datasets for the study problem, the factor maps were generated as follows, from the factor of the greatest impact to minor, respectively:

4.1. Lithology Layer

The geological structure directly affects the frequency of landslide occurrences, as a result lithology becomes the most important factor for landslide susceptibility. Every geological formation has its own geotechnical and hydrological properties. These ones can render the geological formation more or less prone to landslide phenomena than other formations. For the creation of the lithology layer were used all the necessary geological maps of IGME. The sheets were georeferenced in WGS – 84. Subsequently, the geological formations were digitized and categorized in a single lithological type based on the lithological properties of each formation (Fig. 7). Finally, the different lithological types were reclassified into five (5) classes based on their landslide susceptibility as (Fig. 8): 1) Marine & coastal deposits/Conglomerates, sands, silts, marls & breccias/Loose sediments, 2) Limestones, dolomites & marbles/Gypsums, 3) Ophiolites/Magmatic rocks within sediments, 4) Granitic intrusions/Flysch, 5) Schists, phyllites, quartzites & gneiss.

4.2. Slope Gradient

It is proven that as the slope gradient increases with presence of relatively unstable formation such as unconsolidated soil cover or fractured formations, the number of landslides increases as well (Kouli et al. 2010; Kouli et al. 2013; Antoniou et al. 2017; Psomiadis et al. 2020). The slope layer was generated by a 30m - DEM, which was created by the topographic contours, and the Slope tool in the Arctoolbox from 3D Analyst (Fig. 10). The topographic contours were created using 9 geological map sheets of the study area and were imported in the “Create TIN” tool to create the DEM of the area in 30 x 30 m cell size.

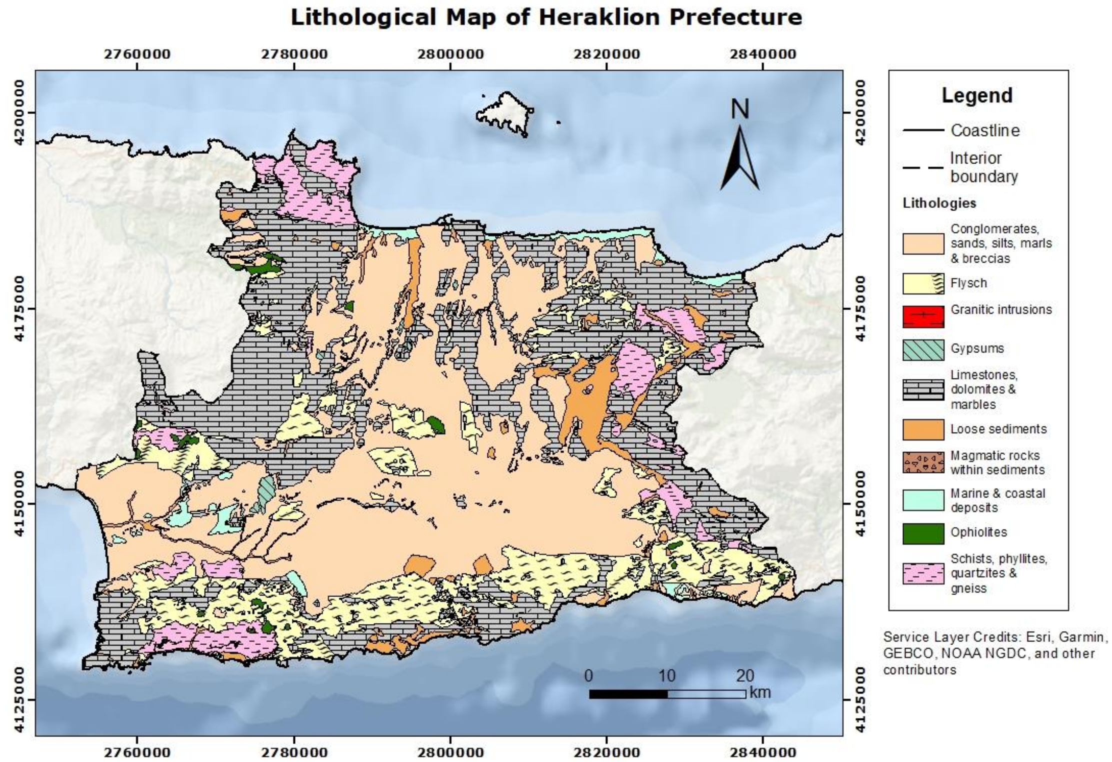

Fig. 7: Map of the simplified lithological units of Heraklion prefecture in Crete. Coordinate system: WGS 84 World Mercator.

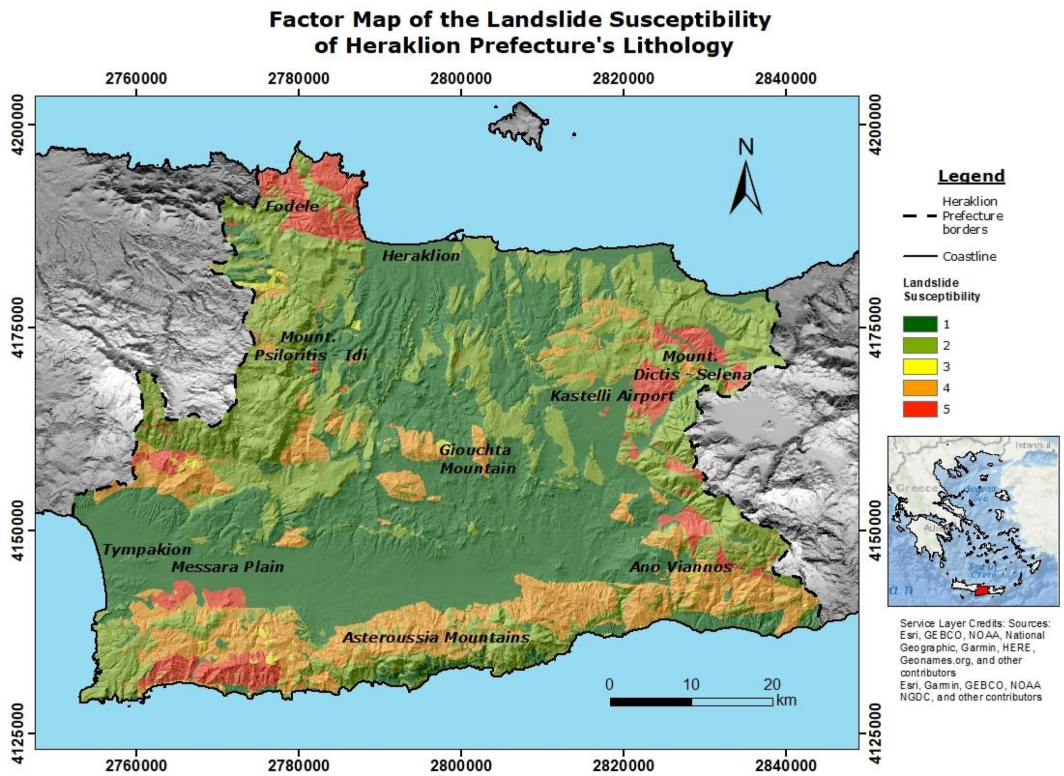

Fig. 8: Lithology factor map. Coordinate system: WGS 84 World Mercator.

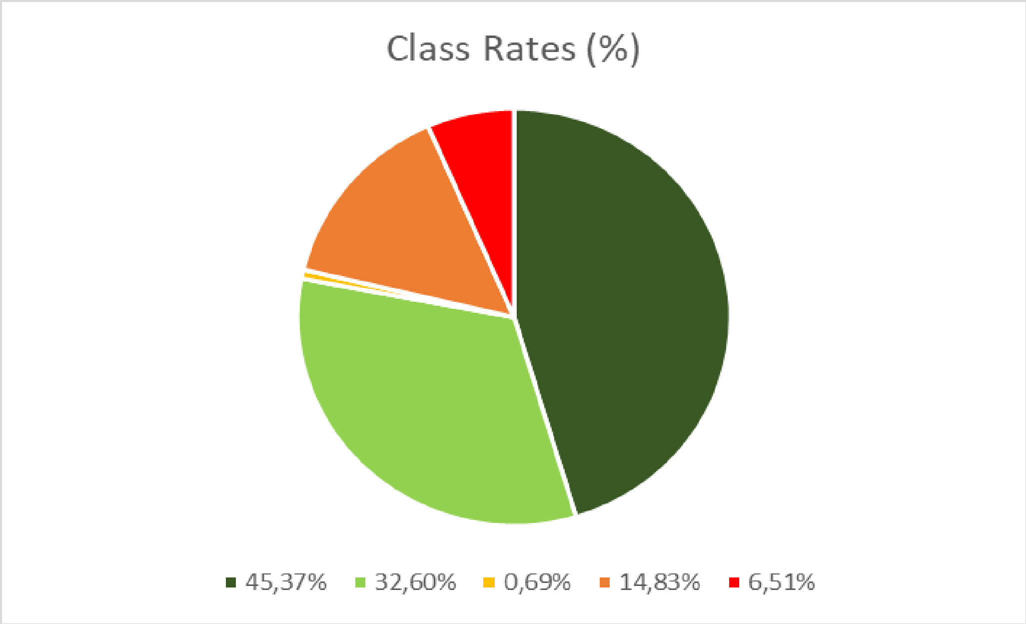

Fig. 9: Class area rates (%) of lithology factor map based on the landslide susceptibility distribution in the study area.

The generated DEM was then inputted in the Slope tool in order to create a raster file of the necessary slope gradient values. Generally, in the centre of Heraklion prefecture slopes are gentle and moderate steep, ranging from 0 - 30°, and in its border, specifically in western – eastern and southern parts where the mountain ranges are located, slopes are becoming steeper, ranging from 31 - > 61°.

Finally, the slope layer was reclassified and ranked according to relative research and bibliography (Koukis & Sabatakakis, 2007; Rozos et al. 2008; Krassakis & Loupasakis, 2018). The slope values were divided into six (6) classes (Fig. 11): 1) 0 – 5°, 2) 6 – 15°, 3) 16 – 30°, 4) 31 – 45°, 5) 46 – 60°, 6) > 61°.

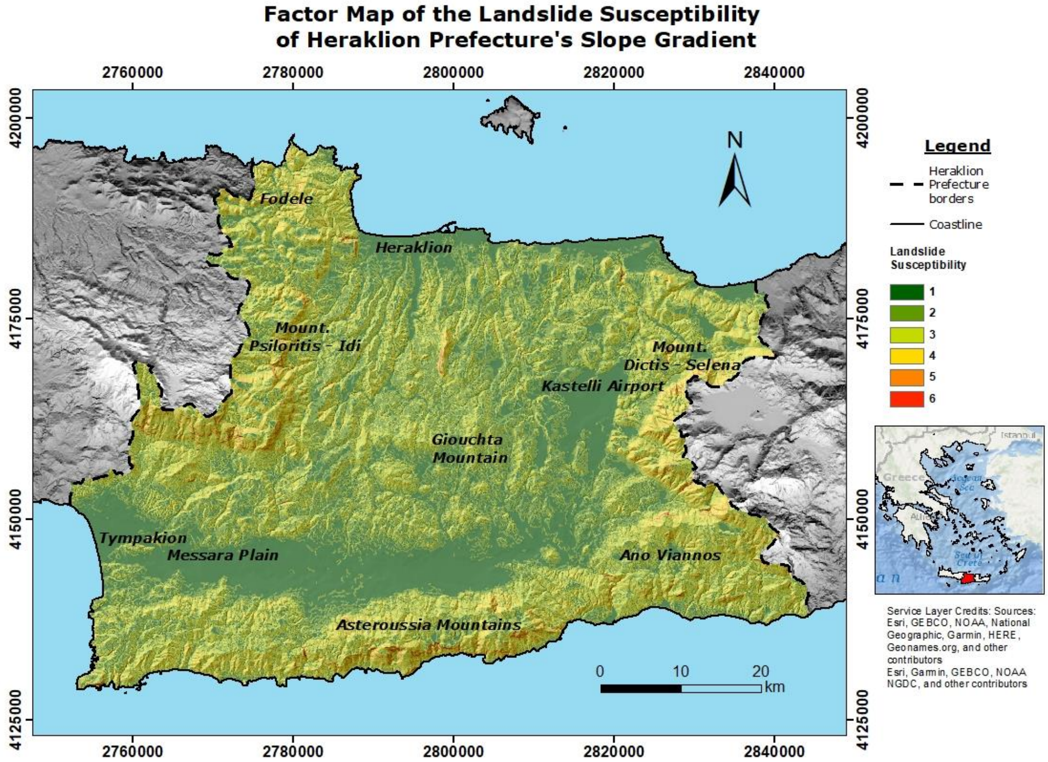

Fig. 10: Slope gradient factor map. Coordinate system: WGS 84 World Mercator.

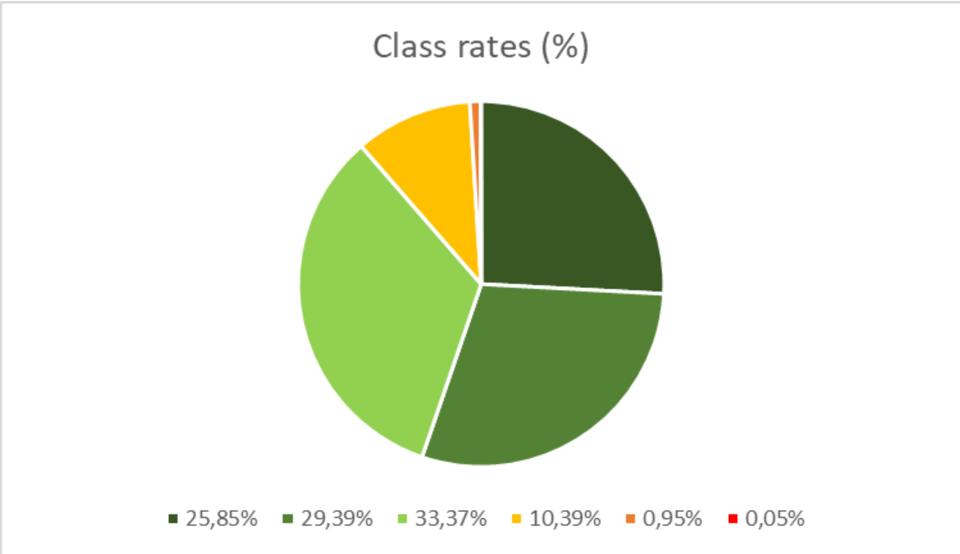

Fig. 11: Class area rates (%) of slope gradient factor map based on the landslide susceptibility distribution in the study area.

4.3. Proximity to Tectonic Structures

Tectonic structures are responsible for steep slopes, joints and shear zones in highly fractured rock formations, leading to possible landslides (Ladas et al. 2007; Antoniou et al. 2017). The tectonic structures were digitized by using the respective geological maps of IGME (Fig. 12; 13) and then, the buffer zones were created along with three (3) classes (Krassakis & Loupasakis, 2018): 1) > 500 m, 2) 250 – 500 m, 3) < 250 m.

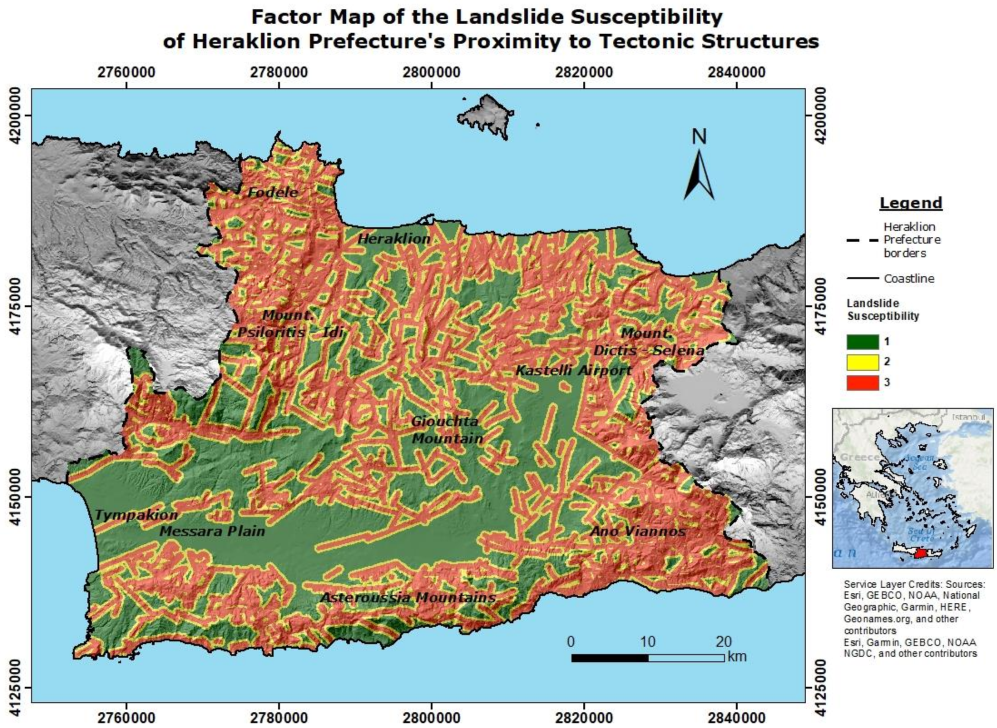

Fig. 12: Proximity to faults factor map. Coordinate system: WGS 84 World Mercator.

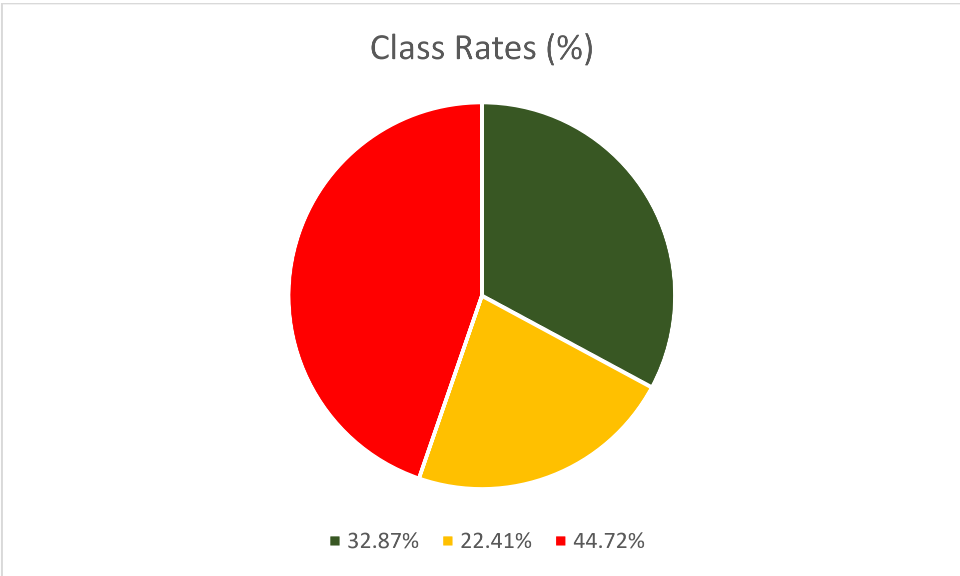

Fig. 13: Class area rates (%) of proximity to tectonic structures factor map based on the landslide susceptibility distribution in the study area.

4.4. Mean Annual Precipitation

Mean Annual Precipitation is also considered a severe factor that causes landslide phenomena. Particularly, the passage of the meteoric water through the discontinuities triggers the widening of them, leading to rock failure and landslides as well (Antoniou et al. 2017). Also, a quite dangerous type of landslides that occurs during heavy rainfalls is soil liquefaction. This type in Heraklion prefecture, which is caused by swelling clays, happens mainly in marly formations.

To interpolate the rainfall data, the IDW was used method, because the data were not evenly distributed (Fig. 14). Afterwards, the interpolated raster was reclassified into five (5) classes based on the Natural Breaks (Jenks) method (Fig. 15): 1) < 595 mm, 2) 596 – 675 mm, 3) 676 – 756 mm, 4) 757 – 854 mm, 5) > 855 mm, giving the higher rank to the fifth class. Through this classification method, the Reclassify tool that was used, automatically picks the most favorable classes based on the range of inputted values. In this case a range of mean annual precipitation values was used, which were derived from the precipitation records of Heraklion prefecture's rainfall and precipitation stations.

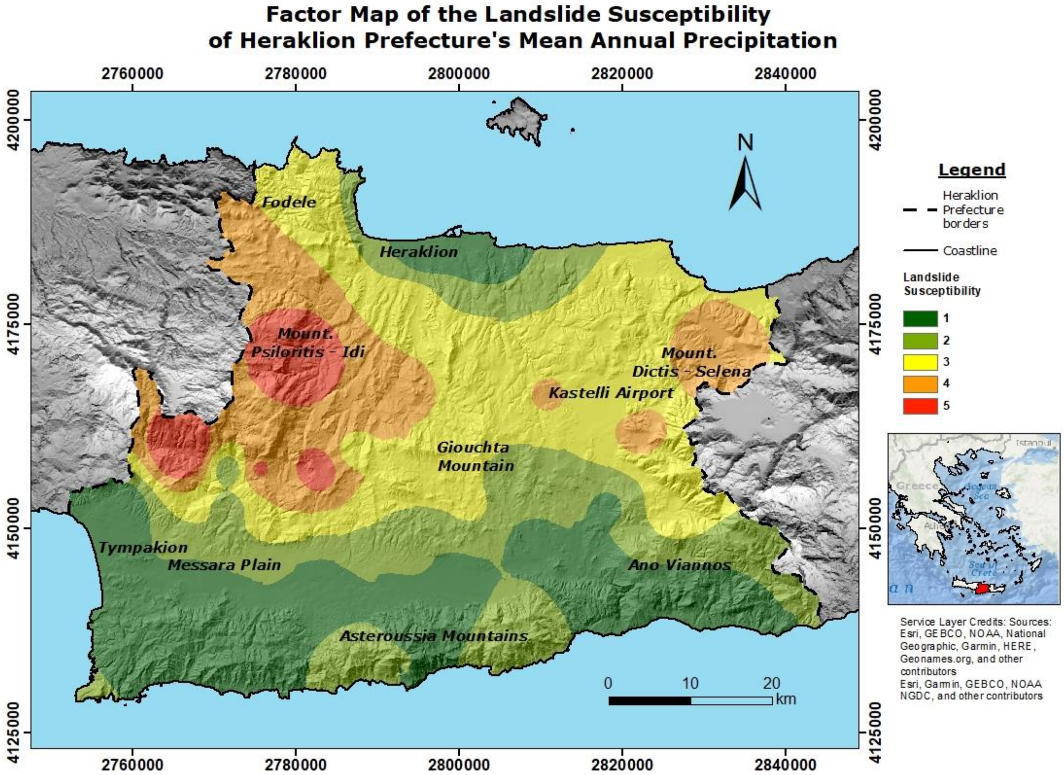

Fig. 14: Mean annual precipitation factor map. Coordinate system: WGS 84 World Mercator.

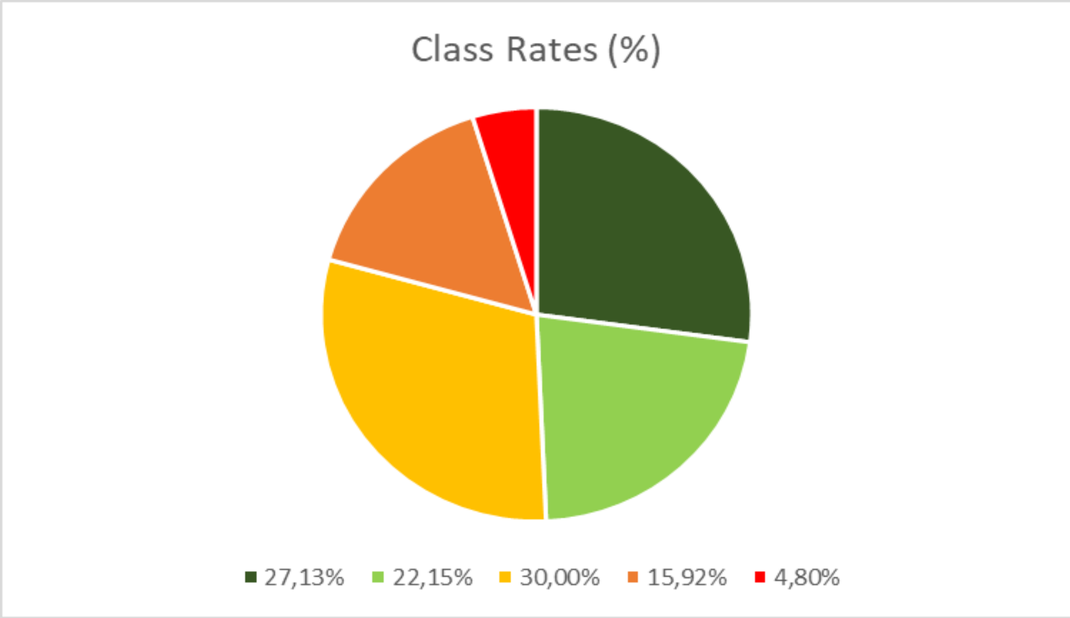

Fig. 15: Class area rates (%) of mean annual precipitation factor map based on the landslide susceptibility distribution in the study area.

4.5. Proximity to River Network

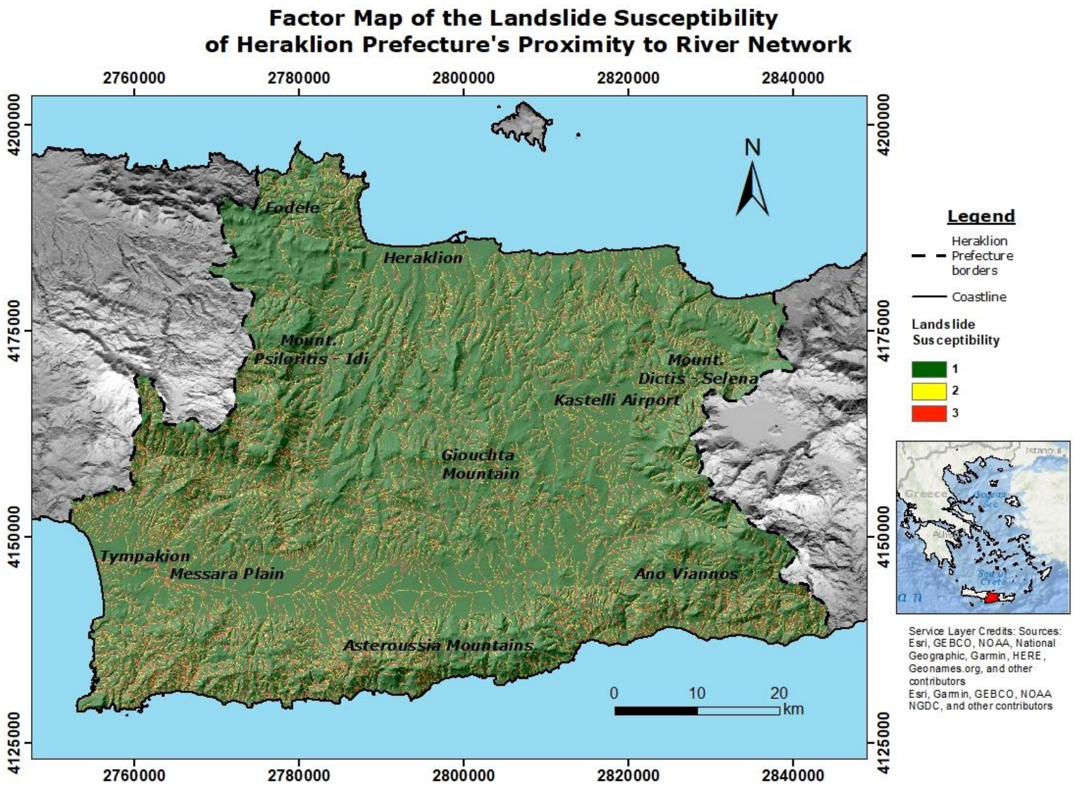

Fig. 16: Proximity to river network factor map. Coordinate system: WGS 84 World Mercator.

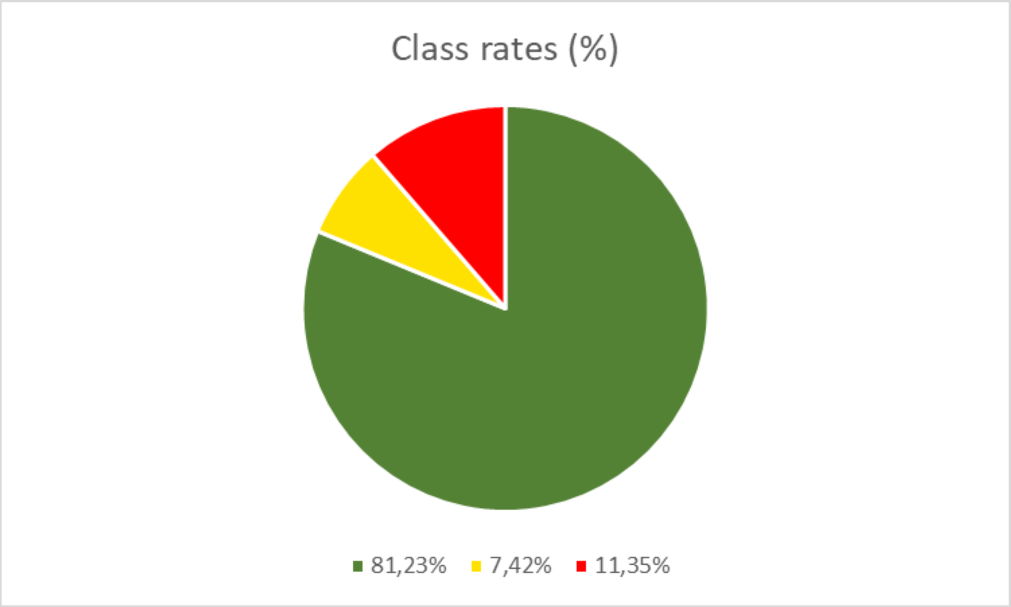

Fig. 17: Class area rates (%) of proximity to river network factor map based on the landslide susceptibility distribution in the study area.

4.6. Proximity to Road Network

The construction of an area's main road network is considered a human-caused intervention on the natural environment which requires the excavation of natural slopes. This process causes an increase of the shear stress which is responsible for altering the structural integrity of the excavated slope, often resulting in its failure (Antoniou et al. 2017).

Data from Open Street Map (OSM) were used in the construction of a thematic map after removing the unnecessary roads that were not associated with human excavations or were located on flat areas. The final data collection used consisted of the main road network of Heraklion prefecture, such as high-speed roads and highways based on their proximity to steep slopes or rough relative relief (Fig. 18).

Based on the consideration that slopes near the main road network are more likely to cause landslides, the factor map was separated into 3 zones of decreasing landslide likelihood, according to the related bibliography (Krassakis & Loupasakis, 2018; Fig. 19), as follows: 1) < 30 m, 2) 30 – 50 m, 3) > 50 m.

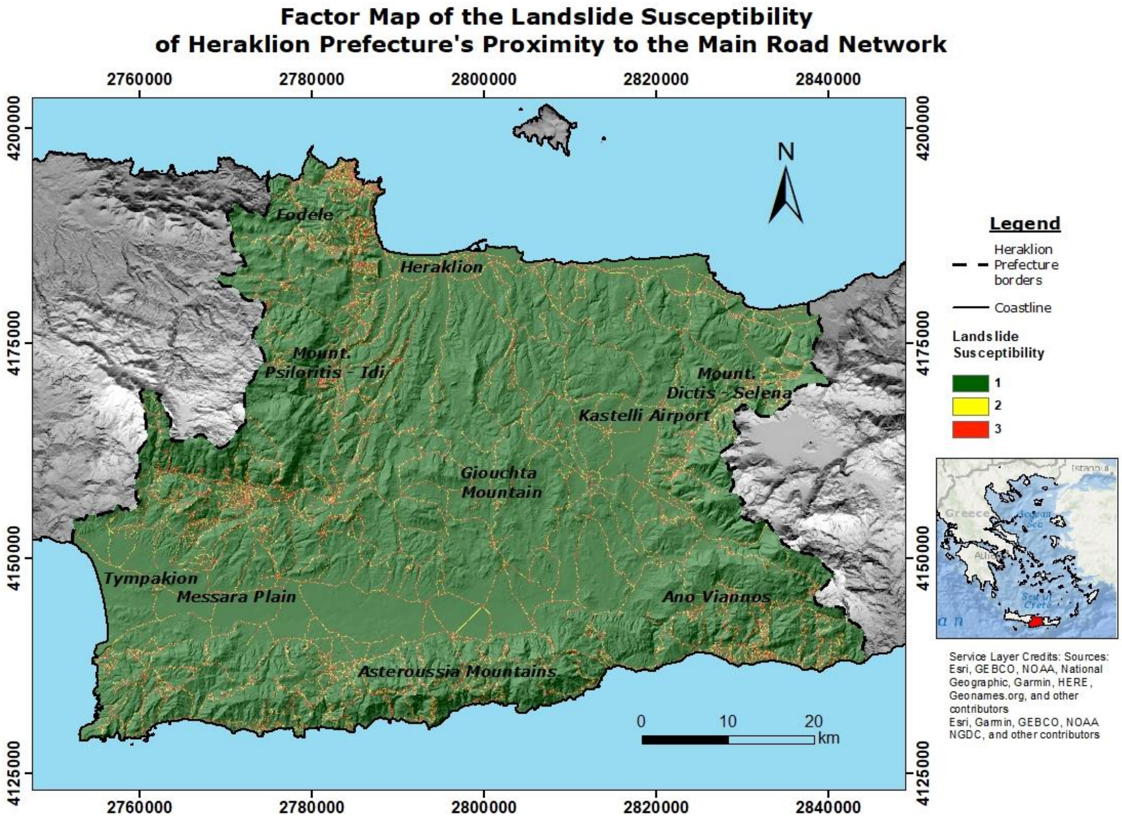

Fig. 18: Proximity to the main road network factor map. Coordinate system: WGS 84 World Mercator.

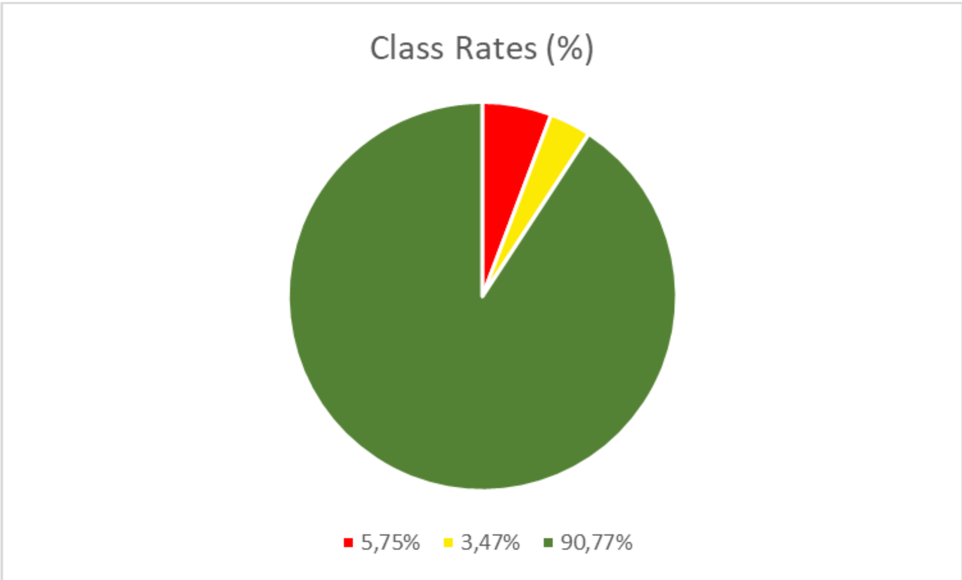

Fig. 19: Class area rates (%) of proximity to the main road network factor map based on the landslide susceptibility distribution in the study area.

4.7. Land Cover

The land cover of the study area refers to the different uses of the land by humans and the ways they affect the stability of the slopes. Generally, it is believed that construction sites, such as tunnel excavations as well as mineral extraction sites tend to weaken the slopes and cause landslides (Koukis & Sabatakakis, 2007). The borrowing roots of forested areas also have dire consequences on the stability of the rocks underneath them. On the contrary, plantation areas and artificial/urban areas are usually found on flat surfaces, thus are considered almost harmless land uses. The data used for the construction of the land cover map originated from CORINE of 2018. The data were simplified by combining the rather wide variety of land uses into general categories. This process was done using the codes provided by CORINE and resulted in the following general land use categories (Fig. 20; Fig. 21): 1) Urban areas, Artificial areas, Water affiliated areas, 2) Irrigated land, Plantation areas, 3) Non-irrigated land, Pastures, Cultivation areas, 4) Sparsely vegetated or barren natural areas and 5) Construction or mineral extraction sites, Vegetation areas & forests. The ranking of the land use categories was based on related bibliography (Kouli et al. 2010).

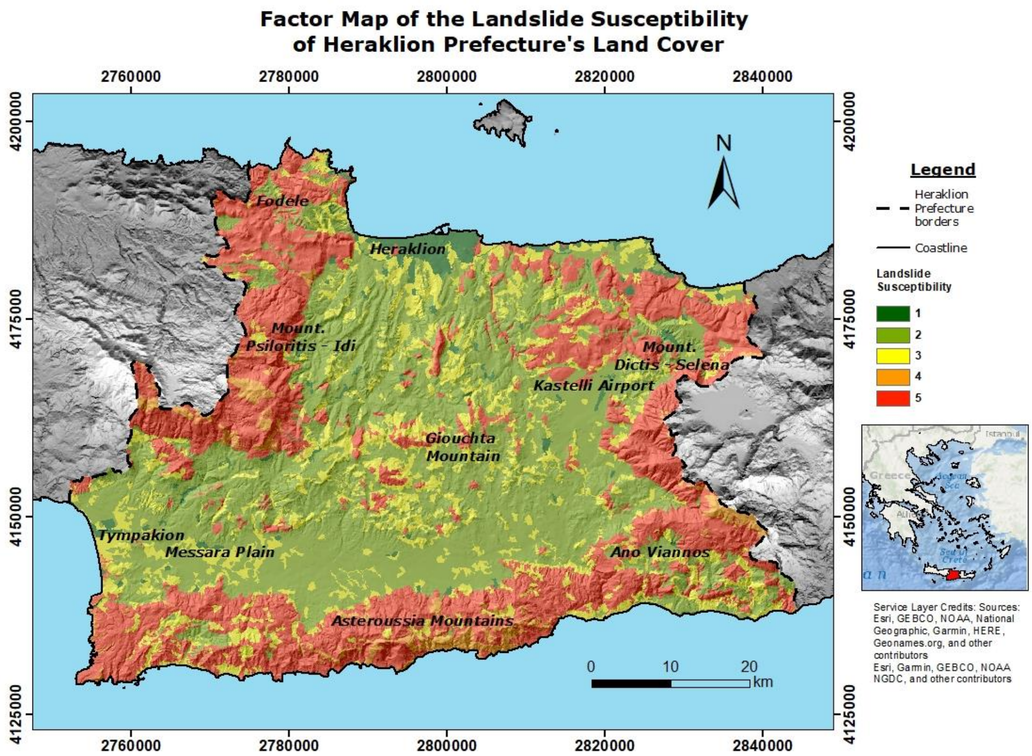

Fig. 20: Land cover factor map. Coordinate system: WGS 84 World Mercator.

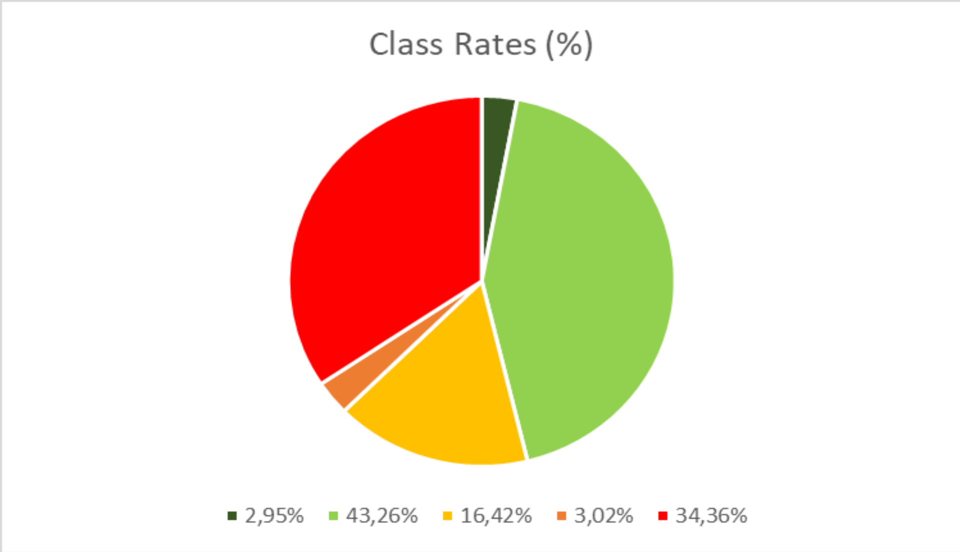

Fig. 21: Class area rates (%) of land cover factor map based on the landslide susceptibility distribution in the study area.

4.8. Aspect

The aspect of the slopes of the study area is a factor that indirectly affects the stability of the slopes and leads to landslide occurrences based on their prolonged exposure to climatic conditions on certain orientations (Rozos et al. 2008; Kouli et al. 2010; Antoniou et al. 2017; Krassakis & Loupasakis, 2018). Slopes exposed to precipitation are often saturated with water which causes a decrease of the mechanical strength of the slopes resulting in landslides (Kouli et al. 2010; Antoniou et al. 2017). Likewise, alterations between periods of extreme snowfall and prolonged sunlight cause alterations of a slope's temperature reducing its stability (Rozos et al. 2008; Krassakis & Loupasakis, 2018). Lastly, certain slope orientations are more susceptible to weathering, thus are in great risk (Rozos et al. 2008; Kouli et al. 2010; Antoniou et al. 2017; Krassakis & Loupasakis, 2018).

The factor map for the aspect of the study area's slopes was created using the aforementioned 30m-DEM (Fig. 22) while the aspect categories were defined using related bibliography (Rozos et al. 2008; Krassakis & Loupasakis, 2018) based on the understanding that, in Greece, slopes of a NNE-SSW and NE-SW orientation are more susceptible to landslides. Therefore, the following slope aspect categories were defined (Fig. 23): 1) -1°, 2) 225° - 275°, 3) 45° - 90°, 4) 90° - 135° & 275° - 315°, 5) 315° - 0°, 6) 0° - 45° & 135° - 225°.

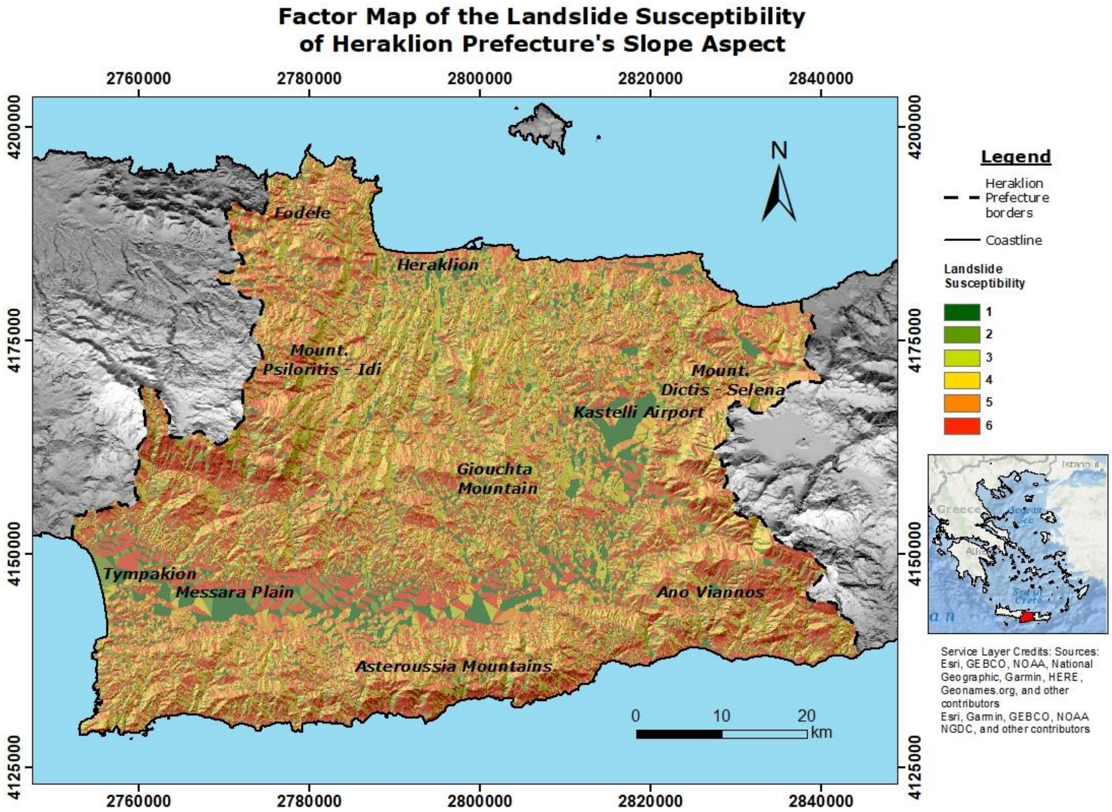

Fig. 22: Slope aspect factor map. Coordinate system: WGS 84 World Mercator.

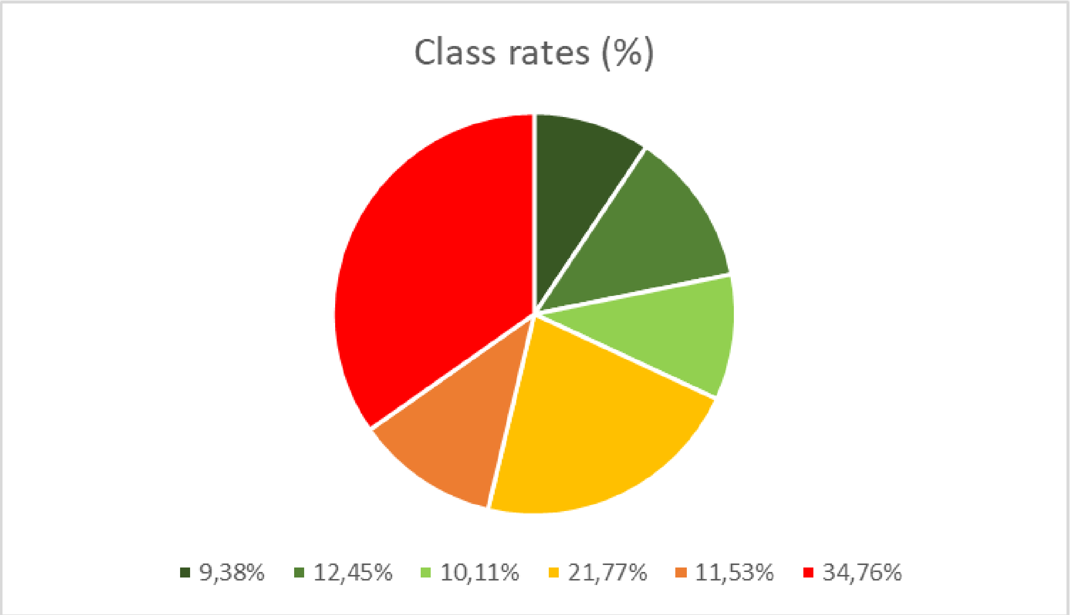

Fig. 23: Class area rates (%) of slope aspect factor map based on the landslide susceptibility distribution in the study area.

4.9. Curvature

The curvature of the slopes of the study area affects the stability of the slopes based on their ability to concentrate large quantities of water. Specifically, concave slopes tend to concentrate greater amounts of water compared to convex slopes, thus becoming more saturated and more unstable which results in an increase in landslide occurrences related to concave slopes (Ladas et al. 2007; Antoniou et al. 2017). The slope curvature map was constructed using the same 30m-DEM as the one used for the slope gradient and slope aspect maps which showed that Heraklion prefecture is characterized by curvature values of -16.25 - 24.08.

It is important to note that positive values refer to convex slopes, negative values refer to concave values and zero (0) refers to flat areas. The slope curvature was separated into 7 classes using the Natural Breaks (Jenks) method which were later corrected in order to identify the flat areas more clearly (Fig. 24, Fig. 25, 26). This correction resulted in a class of values in the range of 1) -0.01 - 0.01 which refers to the flat areas and 4 classes with a steady value difference of 1.5 (or -1.5) as follows: 2) 0.01 – 1.5, 3) 1.5 – 3, 4) > 3, 5) -1.5 - -0.01, 6) -3 - -1.5 and 7) < -3.

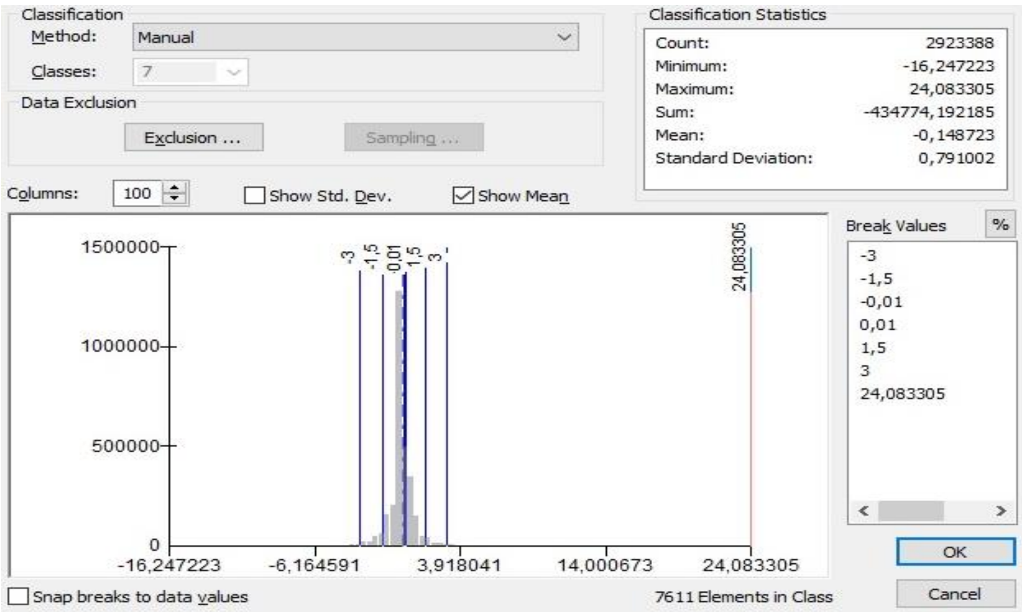

Fig. 24: Histogram of the corrected classification of the slope curvature values of Heraklion prefecture.

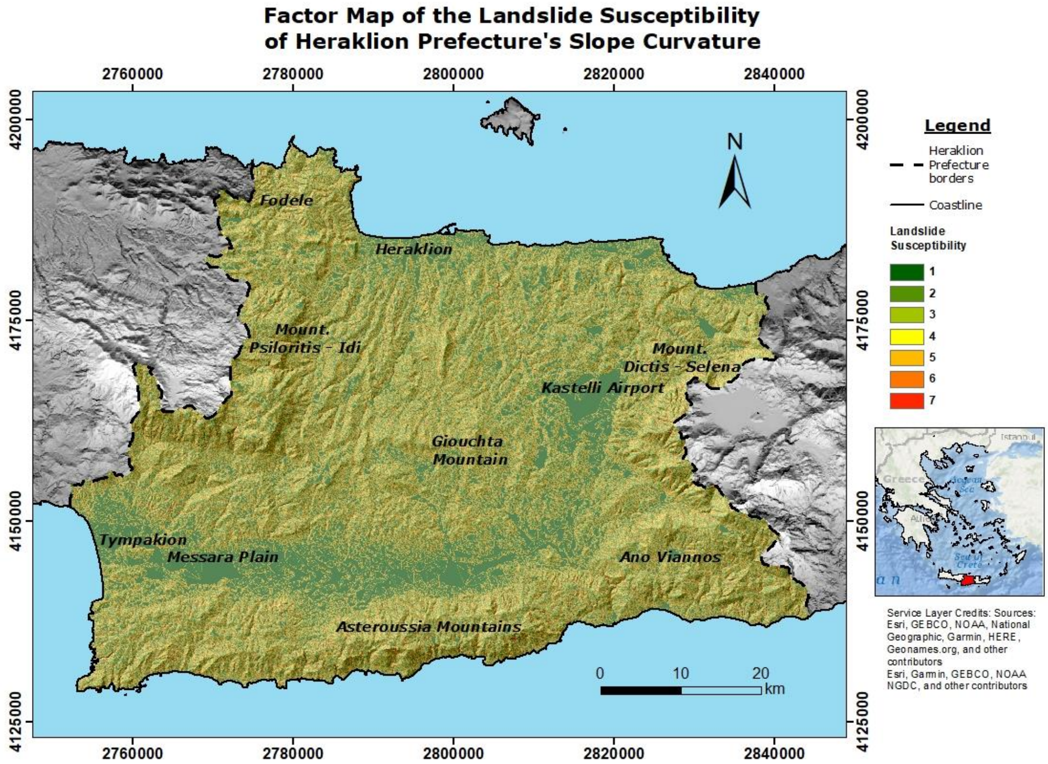

Fig. 25: Slope curvature factor map. Coordinate system: WGS 84 World Mercator.

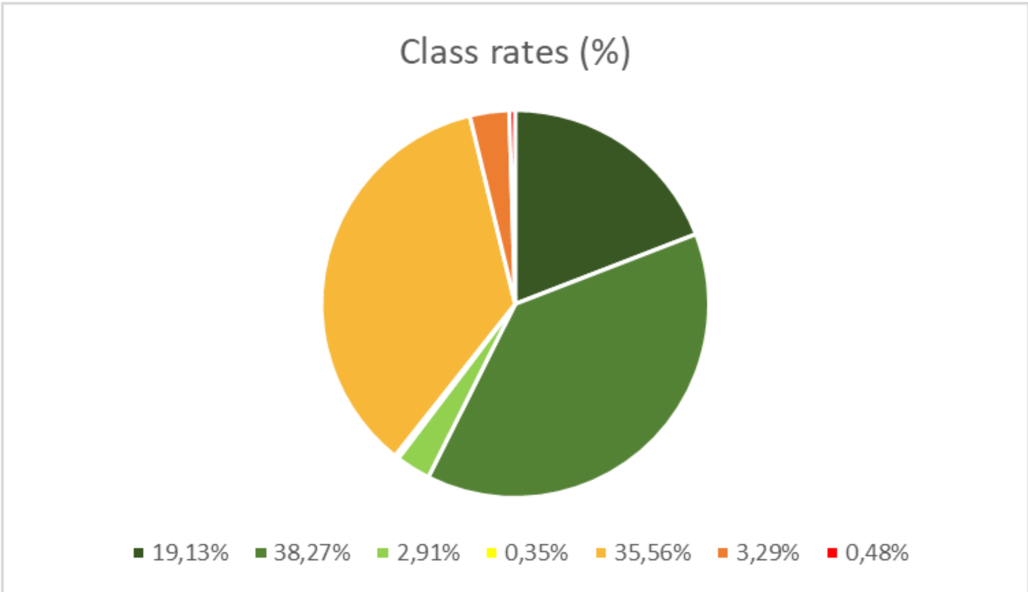

Fig. 26: Class area rates (%) of slope curvature factor map based on the landslide susceptibility distribution in the study area.

4.10. Soil Thickness

The thickness of the study area's soil can affect the areas susceptibility to landslides directly. Specifically, the greater the soil thickness the higher the chances of a landslide occurrence due to how easily thick soil nappes are forced to move through gravity or weathering. The soil thickness factor map was created using the Soil Associations Map of Greece, in a scale of 1:850.000 (Yassoglou, 2004), which was then compared to a soil depth map from bibliographic data (Karamesouti, 2011). This comparison yielded the necessary results, where the soil thickness of the map was separated into 5 classes, based on the bibliography, as follows (Fig. 27; Fig. 28): 1) Very shallow (< 15cm), 2) Shallow (15 – 30cm), 3) Moderately deep (30 – 75cm) και 4) Deep (> 75cm).

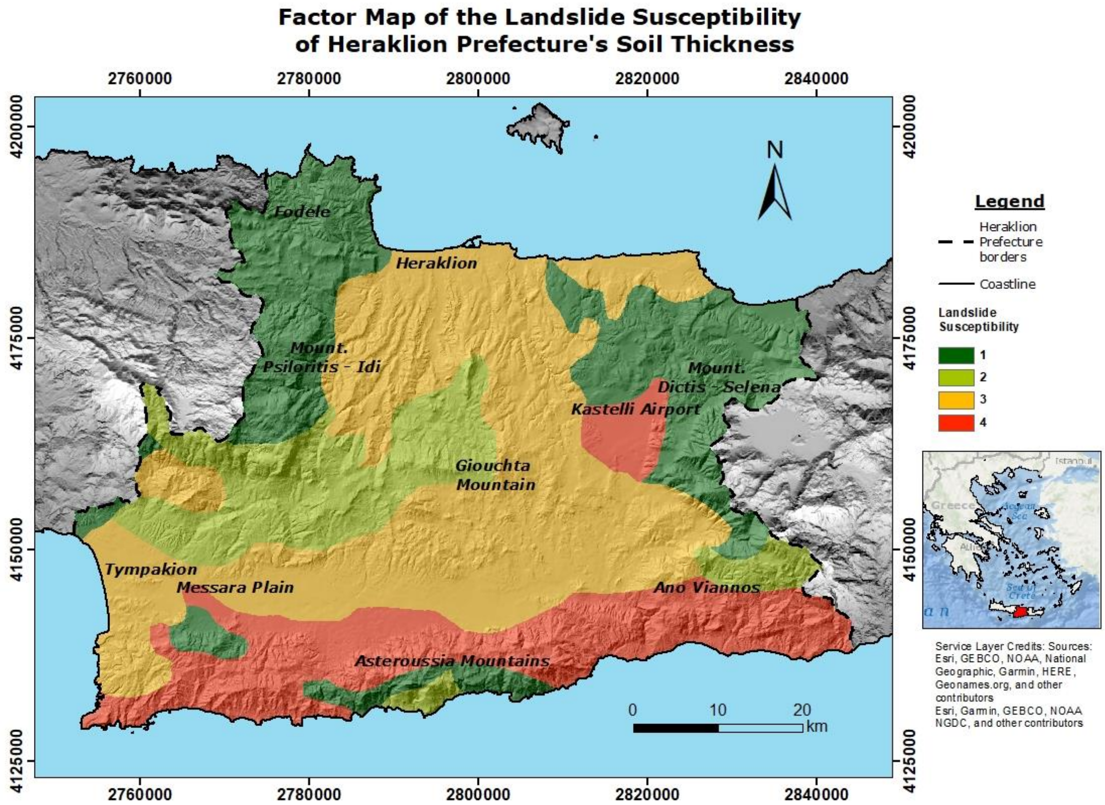

Fig. 27: Soil thickness factor map. Coordinate system: WGS 84 World Mercator.

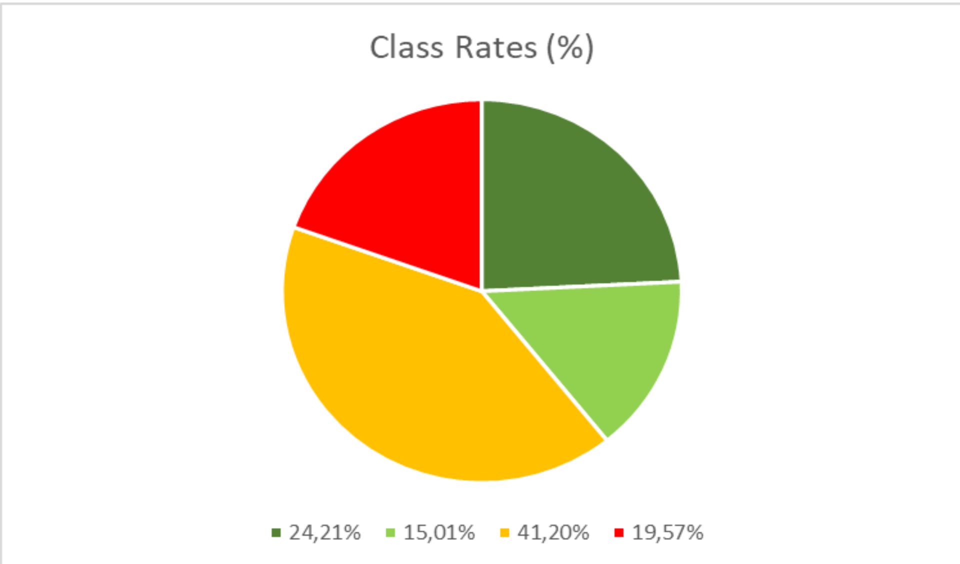

Fig. 28: Class area rates (%) of soil thickness factor map based on the landslide susceptibility distribution in the study area.

Table 3. Landslide triggering factor classification.

Landslide triggering factor classification and related values					
No#	**Landslide Triggering Factor Classes**	**Class Rank Value**	**Normalised Class Rank Value**	**Class Area Percentage (%)**	**Weights of Importance (%)**
1	**Lithology**				**23,738**
	Marine & coastal deposits/Conglomerates, sands, silts, marls & breccias/Loose sediments	1	20	45,37%	
	Limestones, dolomites & marbles/Gypsums	2	40	32,60%	
	Ophiolites/Magmatic rocks within sediments	3	60	0,69%	
	Granitic intrusions/Flysch	4	80	14,83%	
	Schists, phyllites, quartzites & gneiss	5	100	6,51%	
2	**Slope gradient (°)**				**22,908**
	0 - 5°	1	17	25,85%	
	6 - 15°	2	33	29,39%	
	16 - 30°	3	50	33,37%	
	31 - 45°	4	67	10,39%	
	46 - 60°	5	83	0,95%	
	> 61°	6	100	0,05%	
3	**Proximity to tectonic structures (m)**				**19,213**
	> 500m	1	33	32,87%	
	250 - 500m	2	67	22,41%	
	< 250m	3	100	44,72%	
4	**Mean annual precipitation (mm)**				**10,842**
	< 595mm	1	20	27,13%	
	596 - 675mm	2	40	22,15%	
	676 - 756mm	3	60	30,00%	
	757 - 854mm	4	80	15,92%	
	> 855mm	5	100	4,80%	
5	**Proximity to river network (m)**				**7,771**
	> 50m	1	33	81,23%	
	30 - 50m	2	67	7,42%	
	< 30m	3	100	11,35%	
6	**Proximity to main road network (m)**				**6,217**
	> 50m	1	33	90,77%	
	30 - 50m	2	67	3,47%	
	< 30m	3	100	5,75%	
7	**Land cover**				**3,443**
	Urban areas/Artificial areas/Water affiliated areas	1	20	4,49%	
	Irrigated land/Plantation areas	2	40	65,90%	
	Non-irrigated land/Pastures/Cultivation areas	3	60	25,01%	
	Sparsely vegetated or barren natural areas	4	80	4,60%	
	Construction or mineral extraction sites/Vegetation areas & forests	5	100	52,35%	
8	**Slope aspect (°)**				**2,516**
	-1	1	17	9,38%	
	225 - 275	2	33	12,45%	
	45 - 90	3	50	10,11%	
	90 - 135 & 275 - 315	4	67	21,77%	
	315 - 0	5	83	11,53%	
	0 - 45 & 135 - 225	6	100	34,76%	
9	**Slope curvature**				**2,007**
	-0.01 - 0.01	1	14	19,13%	
	0.01 - 1.5	2	29	38,27%	
	1.5 - 3	3	43	2,91%	
	> 3	4	57	0,35%	
	-1.5 - -0.01	5	71	35,56%	
	-3 - -1.5	6	86	3,29%	
	< -3	7	100	0,48%	
10	**Soil thickness (cm)**				**1,346**
	Very shallow	1	25	24,21%	
	Shallow	2	50	15,01%	
	Moderately deep	3	75	41,20%	
	Deep	4	100	19,57%	

5. AHP IMPLEMENTATION – RESULTS

Using ArcMap and the conditions stated in the triggering factor analysis section above, ten (10) factor maps were generated displaying the resulting landslide susceptibility zones in the study area, based on each triggering factor. (Table *3*) These maps were compared to each other to create the final landslide susceptibility model based on the AHP method described previously, taking into consideration bibliographic data in combination with the locations of the recorded landslides and related geotechnical reports from HSGME (former IGME). Specifically, the factors were ranked (as seen in Table *4*). The highest contributing factor is considered to be the Lithology followed by Slope gradient based on bibliographic data (Koukis & Sabatakakis, 2007; Ladas et al. 2007; Rozos et al. 2008; Kouli et al. 2010; Kouli et al. 2013; Antoniou et al. 2017; Krassakis & Loupasakis, 2018) and their direct influence on the stability of the study area's slopes. The third most important triggering factor was considered to be the proximity to tectonic structures due to the high seismicity of the study area resulting in the reduction of slope stability, while the fourth factor is the mean annual precipitation as most of the recorded landslides happened during periods of increased rainfall (Eleftheriou & Mougiaris, 1978; Eleftheriou & Rozos, 1978; Rozos D., 1981; Nikolaou & Georgopoulou, 1988; Zourbakis & Koenakis, 2019).

The next factor in a scale of importance is the proximity to streams as decided based on bibliographic data (Kouli et al. 2010) followed by the proximity to the road network and the land cover which were given a similar rank due to their affiliation with human intrusions which are not always affecting the slope stability, thus are not as important as the previous factors. The slope aspect and slope curvature were given a similar rank of contribution lower than the previous factors as they do not have direct influence on the landscape. Finally, the soil thickness is believed to be the least important triggering factor due to the study area not being considered mountainous enough for the soil thickness to have a higher rank of importance in the pairwise comparison (Kouhartsiouk & Perdikou, 2020). Additionally, the soil thickness data that were collected were not detailed enough for this factor to be attributed a higher weight of importance than any other factor contributed to this study, although it still plays a large enough role in landslide susceptibility to be taken into consideration.

Table 4. Landslide triggering factor hierarchy.

Landslide Triggering Factors	Priority - Hierarchy
Lithology	A
Slope gradient (°)	B
Proximity to tectonic structures (m)	C
Mean annual precipitation (mm)	D
Proximity to river network (m)	E
Proximity to main road network (m)	F
Land cover	G
Slope aspect (°)	H
Slope curvature	I
Soil thickness (cm)	J

Based on the aforementioned rankings (as seen in Table 5) and through the use of the extAhp20 - Analytic Hierarchy Process for ArcGIS (https://www.arcgis.com/home/item.html?id=bb3521d775c94b28b69a10cd184b7c1f) tool in an ArcMap 10.6 environment the final landslide susceptibility map of Heraklion prefecture was created as seen below. The map consists of five (5) zones of increasing susceptibility (divided based on the Natural Breaks - Jenks method): 1) Very low, 2) Low, 3) Medium, 4) High and 5) Very high.

Table 5: Pair- wise matrix showing interactions of landslide factors using AHP rating (A: Lithology, B: Slope gradient (°), C: Proximity to tectonic structures (m), D: Mean annual precipitation (mm), E: Proximity to river network (m), F: Proximity to main road network (m), G: Land cover, H: Slope aspect (°), I: Slope curvature, J: Soil thickness (cm)).

Pair-wise comparison of landslide triggering factors and respective hierarchy											
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Weights (%)**
A	1	2	2	3	4	4	6	7	7	9	23,738
B	1/2	1	2	3	5	6	7	7	8	9	22,908
C	1/2	1/2	1	4	4	5	6	7	7	8	19,213
D	1/3	1/3	1/4	1	2	3	5	6	6	7	10,842
E	1/4	1/5	1/4	1/2	1	2	4	5	5	6	7,771
F	1/4	1/6	1/5	1/3	1/2	1	3	5	5	6	6,217
G	1/6	1/7	1/6	1/5	1/4	1/3	1	2	3	5	3,443
H	1/7	1/7	1/7	1/6	1/5	1/5	1/2	1	2	4	2,516
I	1/7	1/8	1/7	1/6	1/5	1/5	1/3	1/2	1	3	2,007
J	1/9	1/9	1/8	1/7	1/6	1/6	1/5	1/4	1/3	1	1,346
										CR	***0,073***

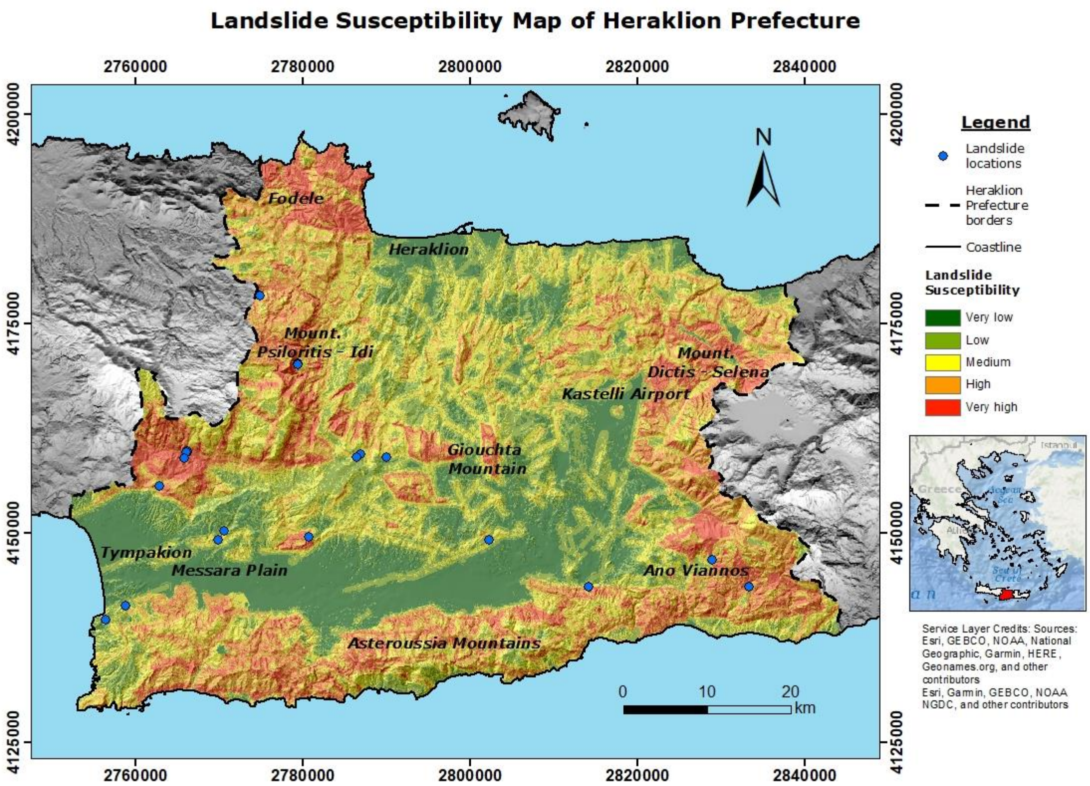

Fig. 29: Resultant map of AHP method. Coordinate system: WGS 84 World Mercator.

As seen in Fig.29, the zones of highest susceptibility to landslides are concentrated, mainly, around the more hilly and mountainous locations of the study area. This is expected from areas of very uneven and rough relative relief caused by relatively steep slopes and karstified or tectonically damaged carbonate rocks, such as the ones constructing Heraklion's mountains. Specifically, zones of high and very high susceptibility (as well as medium susceptibility in some cases) can be seen, for the most part, in the three highest mountain ranges of the prefecture: Psiloritis – Idi, Dictis – Selena and Asteroussia Mountains. Furthermore, three mountainous extrusions at the center of the study area present high susceptibility as well, although they are characterized by less exaggerated relative relief in comparison to the mountain ranges. Most landslide events seem to be following this trend as they are, mostly, occurring on the mountains mentioned previously.

Based on the landslide susceptibility map that was created for this study, the relatively flat areas of the study area, such as the Messara plain and the Heraklion basin are characterized by low and very low susceptibility, up to medium susceptibility around the borders, where they meet the base of the surrounding mountains. This is in accordance with the previous statement, as well as the fact that, these locations present almost no inclination of slopes and are constructed by looser sediments that are unaffected by gravity due to them being on a relatively flat plain. Landslide events that happened in these areas seem to be associated with zones of medium susceptibility due to small extrusions of the landscape.

It is interesting that the largest residential areas, such as the cities of Heraklion and Tympakion are mostly unaffected by landslides as they are constructed within the center of the aforementioned basins and closer to the sea, therefore they have no relation to steep slopes and present very low susceptibility to landslides. In contrast to this, smaller settlements, as well as fairly large towns such as Fodele and Ano Viannos, are built on or very close to the slopes of the highest mountain ranges of the prefecture and are very susceptible to landslides, as is the case with Ano Viannos, where a landslide event was reported very close to the town.

6. DISCUSSION

6.1. Review of the Landslide Susceptibility Assessment Model

As is seen in the final landslide susceptibility map most recorded landslides are located within the zones of Very high and High landslide susceptibility. Specifically, the landslides that occurred in the study area are mostly concentrated in the mountainous areas of Idi - Psiloritis, Asteroussia and Dictis - Selena, as a result of steep slopes, great levels and high frequency of annual precipitation and increased tectonic strain. These factors are in accordance with HSGME (former IGME) technical report observations (Eleftheriou & Mougiaris, 1978; Eleftheriou & Rozou, 1978; Rozos D. , 1981; Nikolaou & Georgopoulou, 1988; Zourbakis & Koenakis, 2019). Furthermore, the affected areas of highest susceptibility, according to the map, are dominated by flysch, schists and limestones. These lithologies are responsible for the recorded landslides according to the technical reports, which state the local high precipitation and extreme tectonic structure affected the stability of the limestones through increased karstification (Eleftheriou & Mougiaris, 1978; Eleftheriou & Rozos, 1978; Rozos D. , 1981; Nikolaou & Georgopoulou, 1988; Zourbakis & Koenakis, 2019). Additionally, the high susceptibility zones seem to be intercepted by a great number of branches of the main river network of the prefecture in high density which aid in the erosion of the aforementioned lithologies.

As can be observed from the resultant map, highly susceptible areas plagued by the majority of recorded landslides, in comparison to Heraklion's land cover, are dominated by mountainous forested areas, as well as plantation and cultivation areas. This is in accordance with the observations in the bibliography that most landslides (59%) in Greece are occurring in hilly cultivation areas (Koukis & Sabatakakis, 2007). Surprisingly however, areas affected by human activity (such as excavation sites and construction areas) are not associated with any of the recorded landslides, even though, logically, they are considered areas of high susceptibility to human caused landslides. This might be explained by the fact that, Heraklion's excavation sites are located in relatively flat surfaces and at a great distance from surrounding slopes, while it is also possible that landslides have occurred in these locations but were not recorded.

Reviewing the landslide susceptibility model based on the aspect and curvature of the slopes in relation to recorded landslides in the high and very high susceptibility zones it is clear that the slopes have an aspect of N to NE, E to SW and W to N, which are of Medium to very high susceptibility. Meanwhile, the curvature of these locations' slopes is of great variety, thus it is difficult to ascertain this factor's clear contribution to the result of the model. Overall, these factors are affecting the stability of the slopes indirectly, making them of lesser importance on the model's accuracy. Moreover, the factor of soil thickness hasn't been taken much into consideration due to the reasons mentioned previously, which is why the unsatisfying distribution of the recorded landslide locations according to the classification of the soil thickness does not affect the validity of the model greatly.

In the case of the Medium landslide susceptibility zones, as expected, a lower number of landslides was recorded. These zones correspond to areas of relatively smooth relief, Medium to low annual precipitation and less dense road network, while they possess high density of river network and tectonic structures. Additionally, the areas of Medium susceptibility are characterized by Neogene marls, clays and conglomerates, lithologies that become very unstable when affected by precipitation and impetuous river flows causing marl liquefaction, clay swelling and conglomerate erosion. According to the technical reports of the recorded landslides in Medium susceptibility zones (Eleftheriou & Mougiaris, 1978; Eleftheriou & Rozou, 1978), the latter's occurrences have been attributed to the aforementioned events, adding to the validity of the model.

As for the zones of Low to Very low landslide susceptibility, as expected, the number of landslides reported is almost none-existent (2 reported occurrences in low susceptibility zones). Thus, the model seems to be fairly accurate in this regard as well.

The overall success of the resultant landslide susceptibility model was evaluated through determining the frequency at which landslides occurred in each susceptibility zone that was defined for the model, based on the recorded data (Table 6).

Table 6. Landslide frequencies (%) per susceptibility zone.

Landslide occurrence per landslide susceptibility zone		
Landslide susceptibility of zone	**Number of landslides**	**Frequency of landslides (%)**
Very low	0	0,00
Low	2	9,52
Medium	7	33,33
High	5	23,81
Very high	7	33,33
Total	**21**	**100,00**

The model's success was determined based on the frequency of landslide occurrences of the Medium, High and Very high susceptibility zones. According to these frequencies, the model was evaluated to be 90.48 % successful.

7. CONCLUSIONS

In conclusion, through the use of ArcMap 10.6 and following the Analytical Hierarchy Process (AHP), a landslide susceptibility assessment map model was constructed for the prefecture of Heraklion in Crete Island based on multiple landslide susceptibility factors. According to the geo-technical reports provided by HSGME (former IGME) the main factors that affect the landslide susceptibility of the study area are: the geological formations, the morphological slope gradients, the proximity to tectonic structures, the mean annual precipitation, as well as the proximity to the road and river networks. This was also observed in the constructed model. Specifically, landslides were happening mostly in mountainous and hilly locations with relatively steep slopes (30° - 60°) and rough terrain. Such locations are the mountain ranges of Psiloritis – Idi (western Heraklion border), Dictis – Selena (eastern Heraklion border), Asteroussia (southern Heraklion border), Ano Viannos (southeastern Heraklion) and the general mountainous area of Fodele. Psiloritis – Idi, Dictis - Selena and Asteroussia mountains present the steepest slopes of the study area (> 61°). Additionally, landslide occurrences were common in areas consisting of flysch and flyschoid formations, marls, clays, schists - phyllites and carbonate rocks with frequent rainfall and increased tectonic deformation. This is due to the fact faulting causes the affected rocks to fracture and become mechanically unstable as well as saturated with water which caused dissolution of the carbonate rocks and erosion of sedimentary rocks. The mountains of Psiloritis – Idi and Dictis – Selena are mainly constructed of carbonate rocks and are characterized by high levels of annual precipitation (> 757 mm and 676 – 756 mm respectively), with Psiloritis – Idi presenting the most mm of rainfall in the entire study area. Furthermore, these areas are disrupted by an extremely dense network of tectonic structures making them the most likely locations to be subjected to landslides. On the other hand, Asteroussia and Ano Viannos are constructed mostly of flysch and flyschoid formations on top of carbonate rocks and low annual precipitation (< 595 mm), but Ano Viannos is extremely tectonically deformed in comparison to Asteroussia. As such, they are relatively dangerous locations due to the present lithology, especially Ano Viannos due to its dense tectonic structure.

Additionally, the Giouchtas mountain at the center of the study area is characterized by flysch surrounded by silts and marls, while presenting medium annual precipitation, as such it is considered an area of high susceptibility due to possible swelling of silty and marly formations when affected by rainfall. The water of the river network of the study area is playing a significant role in the erosion process as well. Moreover, landslides seem to be occurring close to the main road network due to human-caused erosion during its construction. Specifically, Psiloritis – Idi, Dictis – Selena, Ano Viannos and Fodele are near a dense road network, while Psiloritis – Idi, Asteroussia, Ano Viannos and Fodele are the mountainous areas most affiliated with a dense river network. Thus, due to these factors, it is suggested that locations that meet these "requirements" are highly susceptible to landslides. Therefore, all the aforementioned locations of the study area are considered of very high susceptibility to landslides. Particularly, it is proposed that the Psiloritis – Idi Mountain range has the greatest likelihood for landslides to occur. This is due to the fact that this area is of very steep slopes (> 61°), constructed by rocks highly susceptible to karstification (limestones) and presents the highest mean annual precipitation of the study area, as well as being in very close proximity to tectonic structures, river and road networks, which are characterized by great density.

The validity of these results was evaluated through the technical reports, as well as the projection of the recorded landslides in the susceptibility map and the determination of the landslide occurrence frequency of each susceptibility zone. To be more specific, most recorded landslides have occurred within the Psiloritis – Idi mountains and around the borders of the Messara plain, at the southern slopes of Psiloritis – Idi and western slopes of Asteroussia mountains, as well as within the mountainous area of Ano Viannos. Additionally, a few landslide events are located within the Messara plain, which were caused by nearby faults. Overall, the model was determined to be very successful, which was evaluated through the frequency of landslide events in zones of medium to very high susceptibility, resulting in a success rate of 90.48%. However, it is important to note that the total number of recorded landslides was especially small relative to the overall extent of the study area, thus it is not entirely accurate. Nevertheless, this research is an extremely important first evaluation of the general landslide susceptibility of Heraklion prefecture, which can be improved through the collection of a greater number of data of observed landslides and the reevaluation of the model. Furthermore, through a more detailed, thorough recording of landslides and a more detailed landslide susceptibility investigation in a smaller scale, a landslide susceptibility assessment of exceptional accuracy can be achieved.

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