

NATIONAL TECHNICAL UNIVERSITY OF ATHENS
SCHOOL OF RURAL, SURVEYING AND GEOINFORMATICS ENGINEERING

Multi-Criteria Geospatial Analysis and Web-Based Application for Identifying Suitable Areas for Beekeeping in Aitoloakarnania, Greece

Master Thesis

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Athens, July 2025



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Abstract

This thesis aims to assess the spatial suitability for the development of beekeeping activities in the Regional Unit of Aitoloakarnania, through the integrated application of Geoinformatics methods and multi-criteria decision analysis. The study is part of a broader scientific framework that highlights the importance of beekeeping in the Greek countryside, both as a traditional activity and as a tool for sustainable rural development. By studying examples of international applications (Turkey, Iran, Italy, etc.), a methodological approach was designed, adapted to the geographical and environmental specificities of the study area.

The assessment was based on five thematic criteria: vegetation (NDVI), land surface temperature (LST), slope, distance to roads and distance to settlements. NDVI was calculated from Sentinel-2 imagery, while temperature was derived from MODIS products, processed and resampled at 10 m. The AHP method was applied to assign weights to the criteria, and the final mapping was implemented in QGIS through thematic layer overlay.

Three different suitability scenarios were developed: the original scenario, emphasizing ecological factors (vegetation, slope), the alternative scenario 1, highlighting areas with suitable thermal microclimate, and the alternative scenario 2, prioritizing proximity to infrastructure. Statistical indicators such as mean, standard deviation, coefficient of variation and Shannon entropy index were used to evaluate the maps, revealing the differences between the scenarios in terms of internal consistency and equal distribution of suitability classes.

As part of the field confirmation, informal discussions were held with local beekeepers, who highlighted their own site selection parameters (e.g. access, water, low disturbance). Their hive locations were mapped and compared to the scenario results, enhancing the validity of the model.

Finally, the results were presented through an interactive web application hosted on GitHub Pages, making the work accessible and usable by beekeepers and researchers. This work presents how combining geoinformatics with traditional knowledge can contribute to modern sustainable land use solutions.

Keywords:

Geoinformatics, Beekeeping suitability, Multi-criteria decision analysis, AHP (Analytic Hierarchy Process), NDVI, Land Surface Temperature (LST), QGIS, Interactive web map

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List of Abbreviations

AHP : Analytic Hierarchy Process
AI : Artificial Intelligence
API : Application Programming Interface
CI : Consistency Index
CPU : Central Processing Unit
CR : Consistency Ratio
CRS : Coordinate Reference System
CSS : Cascading Style Sheets
DBMS : Database Management System
DDS : Decision Support Systems
DEM : Digital Elevation Model
ESRI : Environmental Systems Research Institute
GIS : Geographic Information Systems
GPS : Global Positioning System
GPU : Graphics Processing Unit
HTML : Hyper Text Markup Language
LST : Land Surface Temperature
MCDM : Multi-Criteria Decision Making
MODIS : Moderate Resolution Imaging Spectroradiometer
NASA : National Aeronautics and Space Administration
NDVI : Normalized Difference Vegetation Index
OSM : Open Street Map
RAM : Random Access Memory
RI : Random Index
SQL : Structured Query Language
SRTM : Shuttle Radar Topography Mission
UAV : Unmanned Aerial Vehicle
UI : User Interface

1. Geoinformatics

1.1 Geoinformatics

The acquisition, analysis and visualization of geospatial data is some of the key pillars that define Geoinformatics. The results of this multi-analysis are being used continuously in all the fields (Yarus, Yarus & French, 2023). From everyday life to complex situations, the science of geoinformatics provides to the users all those needed tools in order to improve their way of thinking, to solve compound problems and to prevent unwanted situations. Along with the rapid evolution of technology in recent years, Geoinformatics has become widely known as a field of studies because of the sharpening of perception that it offers to users.

Another definition of Geoinformatics states that "Geoinformatics is the science and the technology which develops and uses information science infrastructure to address the problems of Earth sciences such as geography, geodesy, cartography, photogrammetry, GPS, GIS, and related branches of science and engineering. It collects and organizes the data and then analyzes them through computation and geovisualization." (Škoda & Adam, 2020).

Geoinformatics contains a lot of components that are presented in the figure below (Figure 1.1).

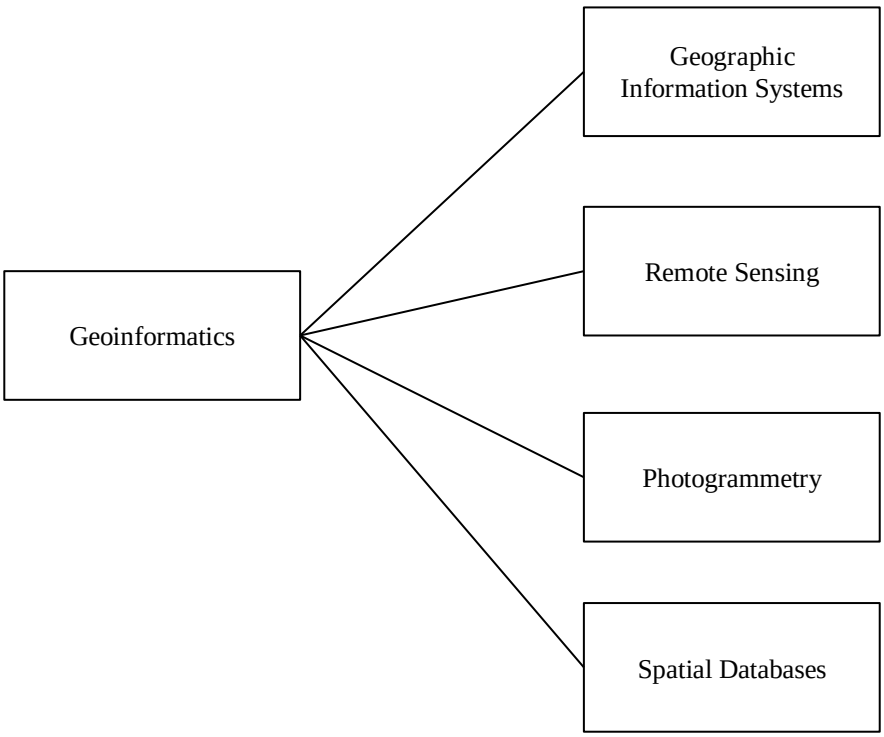


Figure 1.1: Components of Geoinformatics

Each and every of those four (4) components above, contains multiple sub-components. For instance, Remote Sensing is the field of studies that deals with the satellite image processing

in order to get results about the land coverage etc. The following table provides a detailed list of each component of Geoinformatics (table 1.1).

Components of Geoinformatics	**Sub-components of Geoinformatics**
Geographic Information Systems	- Data Storage - Data Management - Data Analysis - Data Visualization - Cartography
Remote Sensing	- Satellite Imagery - Aerial Photography - Hyperspectral Imagery
Photogrammetry	- Aerial Photogrammetry - Terrestrial Photogrammetry - 3D Modeling - Image Processing
Spatial Databases	- Query Language (e.g. SQL) - Spatial Data Structures (e.g. R-Trees) - Database Management Systems (DBMS) - Spatial Indexing

Table 1.1: Detailed list of Geoinformatics components and sub-components

According to the above table, geoinformatics include and use specific fields as sub-components. Though, these fields may also apply to other scientific fields. For instance, data analysis is one sub-component of a typical analysis in the framework of Geoinformatics. However, data analysis is being used in the field of economics and sciences (e.g. Mathematics, Physics, Chemistry) and in every scientific field that is related to calculations and research.

“Geoinformatics” is a compound term containing two different words. First, “Geo” is a prefix that is derived from the Greek word "*Γεω*," meaning "*earth*" or "*land*." It relates to anything that pertains to the Earth's surface or geographical aspects. Secondly, “Informatics” is the part that comes from the word "information" and is often associated with the study or practice of processing, managing, and analyzing information, particularly through computer systems and technology. Thus, by analyzing the above-mentioned, Geoinformatics is a scientific field which is crucial in many related fields.

According to Kaimaris (2014), the applications of Geoinformatics in everyday life may vary, although the most important ones are being presented below:

- Forestry
- Agriculture
- Geology
- Archaeology
- Oceanography

- Topography
- Urban - Spatial Planning
- Environment
- Topography
- Telecommunications
- Public Safety / Disaster Risk Management
- Constructions

To achieve the best outcome, it is suggested to use all the sub-components of Geoinformatics. Along with the rapid evolution of technology, nowadays it is quite easy to use various tools and applications software combined that offer the user the flexibility required.

A major contributor to this evolution is the Environmental Systems Research Institute (ESRI). ESRI is a company founded in 1969 in California, US. Initially, ESRI had the role of a land use consulting firm. However, nowadays the company is widely known for their Geographic Information Systems (GIS) products (ArcGIS).

1.2 Geographic Information Systems

According to Bonham-Carter (1994), "Geographic Information Systems (GIS) is a computer system for managing spatial data, providing useful knowledge and supporting decision-making based on spatial data in resource management, land-use planning, transportation, and geosciences". Even though this specific definition is 30 years old, it applies to the current situation precisely. Despite the fact that GIS is part of Geoinformatics, which is a relatively recent field of studies, it has its own history through the years that have already passed. ESRI made an approach in 2019 (ESRI, n.d.), to document this history, from the creation of the first maps thousands of years ago to the present day. The following table (table 1.2), includes specific references from the ESRI time-series table, with an emphasis on the turning points in the evolution of GIS.

Year	Milestone	Description
-	The first maps	Early maps used for exploration, strategy, and planning lay the foundation for geographic information systems.
1854	Early spatial analysis	Cholera cases in London, marking a critical point in spatial analysis to trace disease origins.
1963	The first GIS	Roger Tomlinson coins the term "geographic information system" while working on a land use project in Canada, pioneering GIS as a concept.
1969	Esri is founded	Jack and Laura Dangermond establish Esri, creating GIS tools to support land use planning and environmental protection.
1982	ARC/INFO is released	Esri releases ARC/INFO, its first commercial GIS software, standardizing GIS implementation and marking its transformation into a software company.

2005	Google Maps	The launch of Google Maps and Google Earth popularizes GIS, making it accessible and interactive for everyday users.
2020	GIS supports COVID-19 response	Johns Hopkins University's ArcGIS-powered COVID-19 dashboard, viewed over a trillion times, highlights GIS as an essential public health and tracking tool.
Today	GIS is everywhere	GIS is a global tool in government, industry, and academia, and billions of maps are made daily. Almost all universities offer GIS courses, underscoring its widespread impact.

Table 1.2: History of GIS

As mentioned in the table above, the creation of the first maps appeared thousands of years ago because people wanted to map their everyday life, the places they were hunting, their settlements etc. Hence the basic need of mapping is something that exists in human life until today but with a bit more complexity. For instance, COVID-19 was a tough situation for the world but through this situation, GIS entered into everyone's household through the news agencies worldwide (live maps of the spatial distribution of the virus).

As early as 1987 the categorization of the components of a GIS system had been made. GIS components include input, storage, analysis, and output, with spatial analysis being the key component (Goodchild, 1987). Based on the glossary of Infosys BPM, GIS as an entity, consists of several essential elements that work together (Infosys BPM, n.d.). These elements are:

Hardware

Hardware constitutes the structural component of GIS. It contains the computers, the servers, and the data storage devices which allow the geospatial data to be stored and operated. Nowadays that the geospatial data are bigger and more complex, it is necessary for the user to own a high-performance computer which must contain a competent Central Processing Unit (CPU) and a Graphics Processing Unit (GPU) along with a decent amount of Random Access Memory (RAM). In order to perform complex spatial analyses with large datasets, the hardware must meet the above-mentioned requirements. However, in recent years, cloud networks have been instrumental in the completion of many time-consuming operations. Many companies (including ESRI) have launched web (cloud) GIS applications which are able to transfer and process large data stored in a cloud storage, simultaneously from many users of the same cloud network. This was a breakthrough back in the days that it first appeared. Though, it is crucial for big organizations, multinational corporations, government agencies and of course research institutions.

Software

Software is the second most important element because it is the tool that performs the spatial analysis and without it, hardware becomes redundant. In particular, software consists of

specific programs that perform data management, data processing and data visualization functions. As mentioned above, ESRI was one of the most innovative companies that brought to the surface the GIS software, named ArcGIS. Since the inception of the company and the software launch, the name has changed quite a few times (ARC/INFO, ArcMap and ArcGIS Pro which is the latest and newest product). However, in contrast with ESRI's ArcGIS Pro which is a commercial software and requests startup (buying) and annual licensing costs (maintenance), there are open-source softwares that are free to use such as QGIS. Even though there is plenty of GIS softwares (e.g. GRASS GIS, Erdas Imagine) that can handle geospatial data, ArcGIS Pro and QGIS are the most common ones to use. Generally, GIS software can manage geospatial data to perform analyses and visualizations and complex calculations. Thus, the selection of the proper GIS software depends on the nature of the study and the user preferences. User preferences fall into the fact that some prioritise advanced analytical capabilities and others emphasise ease of use and accessibility.

Data

Data is as important as hardware and software, and in the field of Geoinformatics, they can be categorized into two types. Geospatial data contain the geographic location of features on earth (geometry) and being represented in polygons, lines, polylines (vector data) or through satellite images and aerial imagery (raster data). The following figures (fig. 1.2 & 1.3) present the comparison of vector and raster data and an example of satellite image respectively.

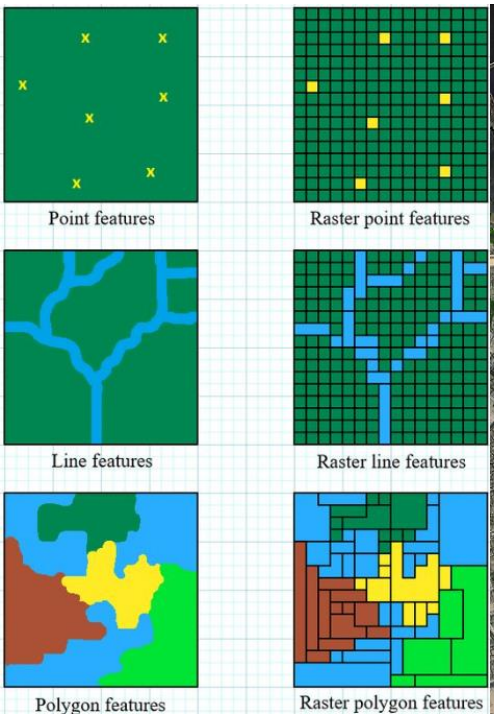


Figure 1.2: Comparison of vector and raster data (Source: https://fsqatar.com/).

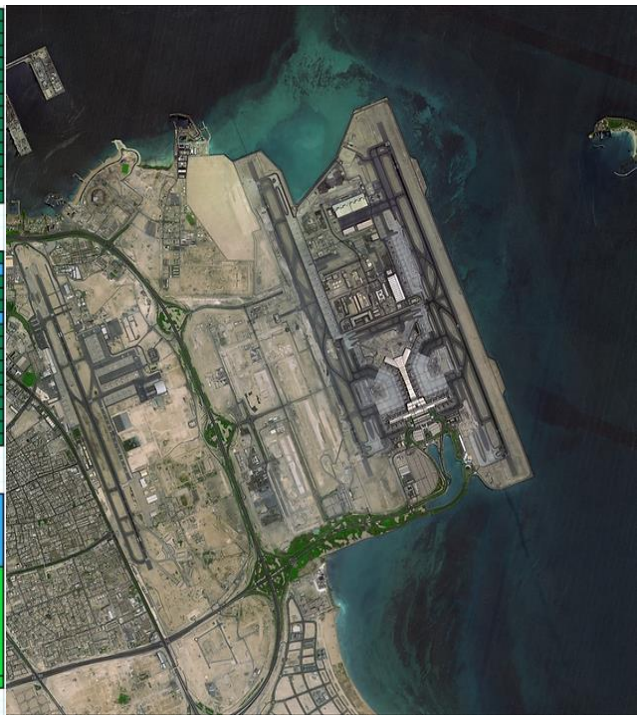


Figure 1.3: Satellite image for spatial analysis (Akhund, 2022)

Attribute data provide information about demographics, economics, politics and environmental and social characteristics. Using both types of data, allows users to perform high quality

analysis in order to solve complex issues such as the allocation of refugee camps, the distribution of products in the market etc. It is quite important to mention that in order to collect this data, equipment such as GPS and UAVs are required. This is fundamental as the quality, accuracy, and relevance of the data directly impact the effectiveness and reliability of GIS analyses and insights.

Methods

GIS methods refer to the tools and strategies employed to work with spatial data, enabling its analysis and application to real-world challenges. These methods vary depending on the project's objectives but generally involve key steps such as data collection, cleaning, georeferencing, and classification. Subsequent analysis may utilize techniques like buffering to create zones around points of interest, overlay analysis to explore interactions between datasets, interpolation to estimate missing values, and network analysis to map connections and flows within systems like transportation or utilities. In addition to technical considerations, GIS methodologies emphasize the importance of data accuracy, ethical practices, and adherence to quality standards. These principles are particularly significant in fields such as environmental management, urban planning, and emergency response, where GIS insights can directly influence decision-making and outcomes. By adhering to robust and reliable methodologies, GIS ensures the production of accurate, meaningful, and actionable outputs.

People

The people component of GIS encompasses everyone involved in its creation, management, and use, ranging from specialized analysts and developers to casual users and decision-makers. GIS professionals bring together expertise in areas such as spatial analysis, data management, and domain-specific applications like urban planning, environmental science, or logistics. Their role requires a solid understanding of the software’s capabilities, the limitations of the data, and the methodologies used to ensure accurate conclusions and well-informed recommendations. At the same time, the increasing accessibility of GIS technology has allowed non-specialist users to play a growing role in basic tasks like mapping, spatial queries, and decision support in everyday situations. To fully realize the potential of GIS across various sectors, training and knowledge-sharing initiatives are crucial. These efforts empower both expert users and casual participants to utilize GIS effectively, enhancing its impact in diverse applications.

1.3 Satellite Images

Satellite imagery is a powerful tool for gathering geographical and geopolitical information and shaping how we imagine places, spaces, and sites in the world (Shim, 2014). Mainly, satellite imagery refers to images of earth captured by satellites. Then, by using remote sensing techniques, the user is able to obtain crucial information about land use, vegetation etc. Satellite imagery provides various applications and fields of studies with data:

- Urban Planning
- Agriculture
- Environmental Studies (Risk Management, Climate Crisis)

The importance of the data from satellite images is that in most cases (if the processing has been carried with all the necessary specifications and requirements) they are valid and can be used with no restrictions. In fact, using satellite data can provide the user the flexibility to choose images without clouds (that affect the processing and the results) and different date of capture. In the following table (table 1.3) the most significant and important satellites according to NASA (n.d.) (active and inactive) are being presented.

Satellite	**Launch Date**	**Decommission Date**	**Purpose**
Explorer 6	14/8/1959	1959-10-01	First satellite to capture Earth's images from orbit
TIROS-1	1/4/1960	1960-06-15	First weather satellite
Landsat 1	23/7/1972	1978-01-06	First satellite in the Landsat program for Earth observation
SPOT-1	22/2/1986	1990-11-20	First satellite in the SPOT program for commercial imagery
ERS-1	17/7/1991	2000-03-10	Radar satellite for Earth observation
Envisat	1/3/2002	2012-04-08	Multi-purpose Earth observation satellite
Terra	18/12/1999	Active	Earth science satellite for climate and land monitoring
Aqua	4/5/2002	Active	Earth science satellite for water cycle studies
Sentinel-2A	23/6/2015	Active	High-resolution optical satellite for environmental monitoring
WorldView-4	11/11/2016	2021-04-01	High-resolution satellite for commercial imagery

Table 1.3: Significant satellites (active and inactive)

The satellites that are mentioned in the table above, are those that resulted in the change and in the evolution of Geoinformatics in general. Some of them have a number next to the name of the satellite. That may refer to the more recent launch of the same program or mission (e.g. Sentinel). In essence, Sentinel-2A (fig. 1.4) is not a direct successor to a single mission but a synthesis of advancements from earlier programs, integrating lessons learned and new technology to meet modern Earth observation needs.

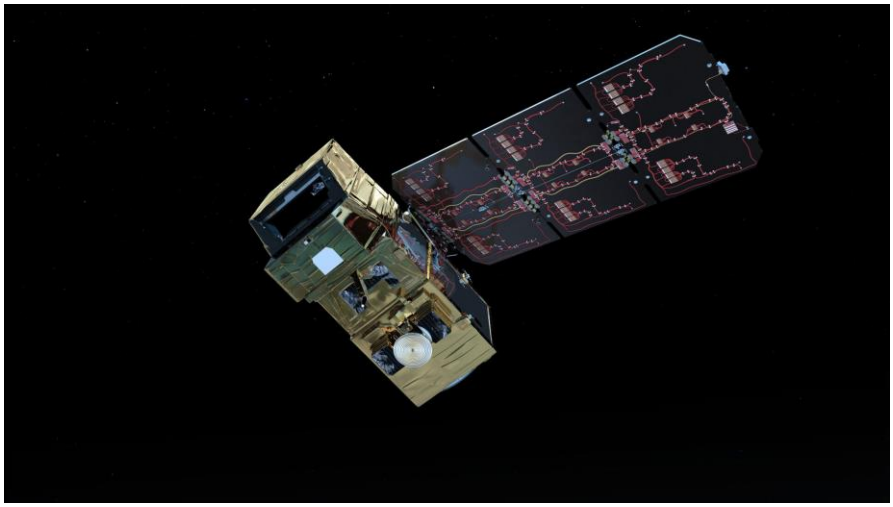


Figure 1.4: Illustration of Sentinel 2A (Souce: https://www.esa.int)

1.4 Applications of Geoinformatics

The use of Geoinformatics in everyday life has become widespread in recent years. Through the applications of geoinformatics has changed the way of interaction with the world. Some of these most important applications appear in:

Urban Planning

Geoinformatics facilitates sustainable urban development by analyzing spatial data to optimize land use, infrastructure development, and resource allocation. Applications of geoinformatics help urban planners to visualize and assess environmental impacts. This can lead to more informed and strategic decisions that will affect the society and the environment. It enables urban planners to visualize growth patterns and assess environmental impacts, leading to more informed decisions (Kushwaha, 2008). The following figure (fig. 1.5) presents an example of a Web-GIS application for urban planning that contains all the necessary information for the engineers and urban planners (institutional framework, land use, regulatory framework).



Figure 1.5: Example of Web-GIS application called "E-Poleodomia" (Source: http://gis.epoleodomia.gov.gr)

Agriculture

In agriculture, geoinformatics supports precision farming by providing data on soil conditions, crop health, and weather patterns. Farmers can optimize inputs like water and fertilizers, leading to increased yields and sustainable practices. The use of geoinformatics in agriculture can be implemented by farmers (given that they know how to use high-tech equipment and softwares) through remote sensing and classification techniques in order to explore the vegetation of their area of interest. Furthermore, engineers, agronomists, and employees in public services or institutions are able to use specialized GIS softwares and techniques to study and monitor specific places. It is very common for farmers to approach scientists like urban planners, agronomists and environmental engineers in order to identify the optimum location for their crops.

Transportation and Navigation

Geoinformatics underpins navigation systems, providing route optimization and traffic management. It enhances logistics by enabling efficient fleet management and delivery planning (Jiang et al., 2023). Though, the most common and important application that refers to transportation and navigation is Google Maps. Geospatial technology, machine learning, and user-contributed data are combined in order to create a highly interactive, accurate, and real-time mapping service. Its ability to provide satellite views, street-level imagery, and real-time traffic updates makes it an essential tool for navigation and location-based services.

Public Health

In public health, geoinformatics is used to track disease outbreaks, plan healthcare facilities, and analyze health trends. Spatial analysis helps in understanding the spread of diseases and

allocating resources effectively. A great example was COVID-19 that changed the way the world understood the information that was presented through screens, mobile phones and televisions in real time every day for a long period. Many people came into contact with geospatial data during the pandemic. At the same time, despite the fact that the pandemic delayed all the processes, the field of geoinformatics and especially the geographic information systems excelled and evolved. The following figure (fig. 1.6) presents a view from an interactive GIS application.

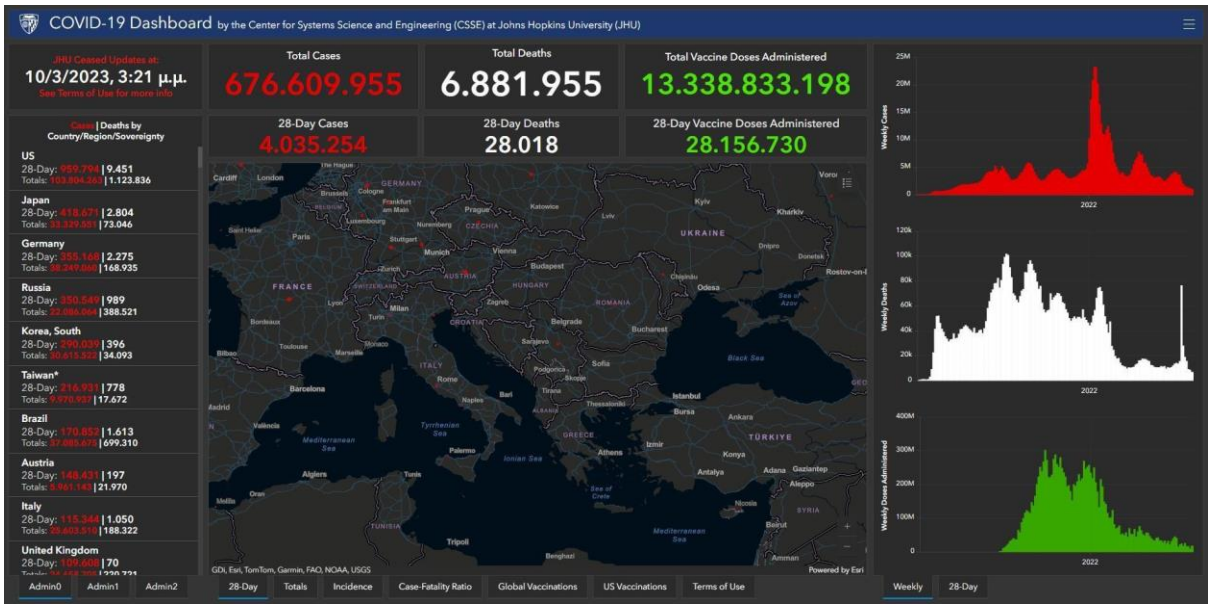


Figure 1.6: COVID-19 Dashboard (interactive Web-GIS application) (Source: https://systems.jhu.edu)

2. Apiculture

2.1 Apiculture

Apiculture is a broader and more holistic term that contains all aspects such as the study of the honeybees, the management, the cultivation and the products of apiculture (Varghese, 2023). Apiculture, commonly known as beekeeping, is the practice of maintaining bee colonies, typically in hives, by humans. It involves the care and management of bees to produce honey and other bee products, as well as providing pollination services for crops (Hill & Webster, 1995). While both terms are correct, apiculture is the general term that concludes everything while beekeeping is a bit more precise about the process of honey cultivation and its derivatives. The agricultural activity called apiculture requires human resources, professional equipment and of course the essential component, honey bees.

Bees

The honeybee colony is composed of three different types of bees. First and foremost, the Queen is the most important bee, because she is responsible for the colony's growth. Secondly, workers are the female bees that perform all the necessary tasks in order to preserve the function of the hive. Thirdly, drones are the male bees that are responsible to mate with the queen. Every honeybee colony must contain one Queen. The following figure illustrates the different types of honey bees (figure 2.1).

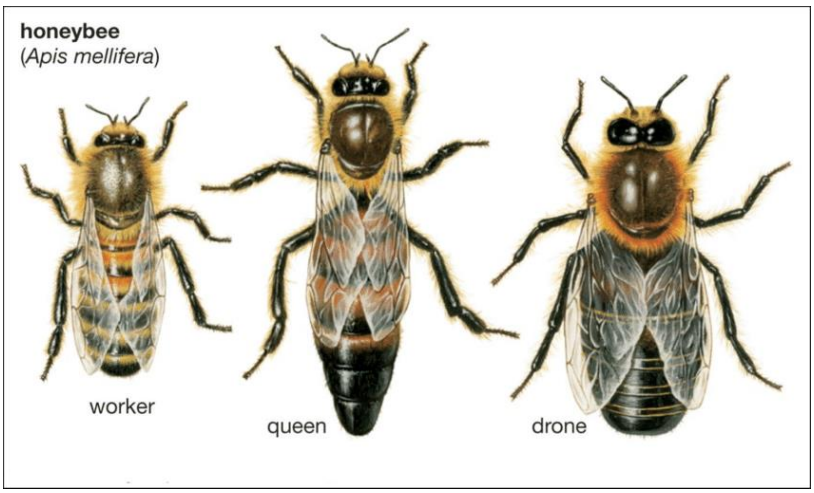


Figure 2.1: Different types of bees inside a colony (Bhokray, 2016)

Equipment

The "house" of bees is the hive. Inside the hive there are the hive frames that are being used by the bees in order to store the honey that they create. Hence, these two (hive and hive frames) are the bare minimum that are necessary for beekeeping. Honey harvest is the procedure that beekeepers remove the hive frames which are full of honey from the hive and transfer them in order to extract honey. In order to remove the hive frames, it is necessary to use a protective

suit, mask and smoker. Through smokers, beekeepers emit smoke that makes bees less aggressive while removing the frames from the hive. The last steps of the procedure require the extraction equipment, which is a knife and a honey extractor. Depending on the type of beekeeping that takes place, a means of transport such as a truck and additional equipment may be required. The following figure (figure 2.2) presents all the equipment needed in the most common cases of honey harvest.



Figure 2.2: Bare minimum equipment (protective suit, hive, gloves, hive tool, brush, smoker) for the honey harvest procedure (Source: https://ktbeekeeping.com.au).

Human Resources

In general, the human factor is as important as bees in apiculture. First of all, it is quite demanding manual labour which becomes intense in the summer. Secondly, it contains a risk because sometimes bees can become dangerous and turn against the beekeeper. Thirdly, it requires very good management as to where the hives will be placed, when the honey harvest will be performed, how to avoid the presence of pests (e.g. varroa mites or diseases) and the strategy around sitting in general. Today apiculture is taught in universities through many departments related to agronomy because the needs of the bees and the best siting of hives require an approach strategic and methodical at the same time.

2.2 History of Apiculture

The relationship between bees and humans is estimated to be about 14.000 years old according to archaeological studies (Pager, 1976). Historical records in particular, indicate beekeeping (honey hunting and harvesting) around 10.000 BC. The first finding that led researchers to draw firm conclusions about the appearance of beekeeping for the first time was a cave painting found in Valencia in the beginning of the 20th century (figure 2.3).



Figure 2.3: Beekeeping as presented in the cave painting found in Cave of the Spider (Cueva de la Arana) in Spain.

While the accurate date of the appearance of apiculture is still unknown, researchers indicate that as far as history has been recorded, honey as a product of apiculture was used as a sweetener in recipes and as a treatment to wounds. As indicated by Kritsky (2017), apiculture has a significant impact from Antiquity through the Middle Ages and up to Modern History. One of the most important historical milestones for apiculture relates to 2450 BC in Egypt. In particular, the oldest evidence of apiculture is a relief from the Sun Temple of the Fifth Dynasty pharaoh Newossere Any that was discovered in 1898 south of the Great Pyramid of Giza. It depicts beekeepers working in hives, processing honey and sealing the honey in containers for storage. The relief shows that beekeeping was an established profession by the Fifth Dynasty, suggesting that beekeeping practices began or were introduced to Egypt centuries earlier (Kritsky, 2017).

The history of beekeeping is vast and very important, for this reason some historical milestones are presented below

Prehistoric Times

Evidence from cave paintings, such as in the Cueva de la Arana, Valencia testified that humans were harvesting honey from 6000 BC. Many studies have been implemented in order to examine the probability of some other evidence to demonstrate different conclusions (Crane, 1999).

Ancient Egypt (-2400 BC)

Egyptians managed bees in clay and cylindrical hives (figure 2.4) and used honey for food, medicine, and religious offerings. Honey appears in hieroglyphic inscriptions as a symbol of wealth and power (Crane, 1999).



Figure 2.4: Beekeeping shown in a tomb in Pabasa, Egypt (after Gene Kritsky).

Ancient Greece (-700 BCE)

Greeks developed techniques for harvesting honey and honey wax (figure 2.5). Aristotle in the History of Animals included bees and the way they operate.



Figure 2.5: Horizontal cylindrical hive excavated in Athens, Greece (after Gene Kritsky).

Medieval Europe

European beekeepers used woven skeps (basket-like structures) to house bees, focusing on honey and wax production for monastic and local use. The following figure (figure 2.6) presents European beekeepers in the 16th century using bee skeps in beekeeping.



Figure 2.6: Beekeeping in Medieval Europe (Source: https://www.smb.museum)

18th-19th Century

François Huber studied bee behavior, and Lorenzo Langstroth invented the movable-frame hive in 1851, revolutionizing hive management and honey extraction (Crane, 1999).

20th Century

Beekeeping became more mechanized, with innovations like centrifugal honey extractors, artificial feeders, and large-scale apiary management to meet rising honey demand (Crane, 1999).

21st Century

Focus shifted to sustainable practices, urban beekeeping on rooftops, and the use of bees for crop pollination. Technology like hive sensors and AI are improving beekeeping. Beekeepers who are eager to use smart devices and techniques in the field, are able to augment their production and minimize the risk of failure.

2.3 Apiculture in Greece

It is presumed that beekeeping spread to Ancient Greece from Ancient Egypt where it was already flourishing. Greece had mainly trading relationships with Egypt, hence the art of beekeeping was transmitted to Greece through the traders who conducted itineraries between these countries.

The history of apiculture in Greece dates back to 5.500 BC (Crane, 1999). Harissis and Harissis (2009) mentioned that during the Minoan civilization (circa 2000-1400 BC) there had already been well-established organized beekeeping practices. Furthermore, excavations that took

place in Knossos revealed clay beehives. These findings were crucial because they provided some of the first examples of managed apiculture across Europe. Amouretti (1986) stated that by the Mycenaean era (circa 1600-1100 BC), beekeeping had already become standard practice, while Linear B tablets had been presenting honey as an important and very precious asset to own. This was the period that consolidated the role of honey in Greek culture and economy.

Phipps (2019) mentioned that Greece was probably the first country that moveable combs has been recorded. Greece has a significant tradition in beekeeping and every region has its own culture and techniques. Greek beekeepers created "Koffinia Hives" which were cylindrical (like a basket) by using wicker and cow dung. Unlike the rest of the world which were using wooden moveable hives, Greeks invented Koffinia as a better solution because they were offering excellent insulation for the bee colony and sloping sides. As a result, bees were able to build their combs in a more natural and free way than in the rectangle frames of the regular wooden frames (Phipps, 2019).

According to the Ministry of Rural Development and Food (2022), Greece is in the second place among EU countries in the possession of beehives and produces more than 14.000 tons of honey annually.

2.4 Precision Apiculture

Precision Apiculture (Beekeeping) is a sub-branch of Precision Agriculture, focusing on monitoring individual bee colonies to minimize resource consumption and maximize productivity (Zacepins et al., 2015). In modern apiculture, advanced technologies and innovative practices are integrated in order to augment and enhance their productivity. Precision apiculture or precision beekeeping refers to the advanced apiary management strategy incorporating smart systems and devices along with advanced techniques of data processing in a more holistic perspective. Furthermore, parameters such as temperature, humidity and weight are crucial and are being used in precision beekeeping. Beekeepers place advanced sensors (equipped with microprocessors and mobile data cards) inside the hives. The sensors collect and record the necessary data and then send the results to the beekeepers. This can be achieved with either messaging or smart apps (Catania & Valone, 2020).

The collected data from the sensors are subject to processing by using specific systems. These systems belong to Decision Support Systems (DDS), which are responsible for the interpretation of the collected data in an understandable way for the beekeepers in order to make real-time decisions.

The main objective of using smart devices and advanced sensors in the spectrum of precision beekeeping is to provide real-time data on the health of the bee colony and the environment of the hive. Hence, it is crucial to measure and control parameters such as weight, temperature and humidity along with vibrations and sounds (Alleri et al., 2023). The following figure (figure 2.7) presents multiple perspectives of sensors and smart hives



Figure 2.7: Illustration of smart hive and advanced sensors placement (Alleri et al., 2023)

In addition to the advantages offered to the beekeeper by precision beekeeping, there are multiple constraints. Some of these constraints are due to challenges of knowledge, equipment, cost and technical complexity. As regards knowledge and technical complexity, integrating various sensors and data analysis tools can be a barrier for many beekeepers. The combination of data from multiple sensors to produce meaningful insights represents a significant challenge. The refinement of data fusion methods is necessary to accommodate the imperfect and heterogeneous data collected from different sources. (Danieli et al., 2023). Furthermore, concerning the equipment, one of the main challenges in the adoption of Precision Beekeeping is the high cost of purchasing and maintaining the necessary devices, tools and sensors. Though, the benefits of precision beekeeping are significant while the production and the management of the apiaries can be maximized if the necessary expertise exists.

Apiculture, like all other branches of agriculture, depends largely upon the natural resources of the location, and the favorableness or unfavorableness of any particular season, no matter how skillful the management, may make great differences in the year's return (Benton, 1905)

2.5 Geoinformatics and Apiculture

Along with the evolution of technology, geoinformatics has been used in apicultural practices in order to enhance hive management, to optimize site selection (suitability) and to augment the overall productivity. The above-mentioned techniques refer to GIS, remote sensing products, spatiotemporal analysis, which are progressively being implemented in beekeeping to confront various issues and optimize decision-making procedures.

The implementation of GIS in apiculture received widespread attention at the beginning of the 21st century, as researchers and professional beekeepers acknowledged its potential for the spatial analysis of data related to beekeeping. GIS enables the mapping of floral resources, the identification of optimal beekeeping locations, and the monitoring of environmental factors that affect bee health (Abou-Shaara, 2019). By analyzing land use patterns, vegetation types, and climate data, GIS allows beekeepers to make informed decisions about hive placement and management strategies.

A major benefit of using geoinformatics in apiculture is the ability to select adequate sites for apiaries. By assessing factors such as proximity to nectar and pollen sources, availability of water, and environmental risk protection, GIS aids in the identification of the optimal locations that support colony health and honey production (Abou-Shaara, 2019). Furthermore, GIS-based models can evaluate the influence of landscape structure on pollination services, assuring that hives are located in areas that maximize both bee foraging efficiency and pollination of crops (Joseph et al., 2020).

Remote sensing technologies supplement GIS by delivering up-to-date information on vegetation health and soil phenology. High-resolution satellite imagery and aerial photography permit the surveillance of plant resource availability and the detecting of changes in land use that may affect bee foraging patterns (Abou-Shaara, 2019). Such information is crucial for the adjustment of hive locations and their management practices in response to environmental changes.

Geoinformatics also has a vital contribution to the management of diseases and pests in apiaries. Geospatial analysis can detect emerging patterns in the distribution of diseases, such as the American mealybug, or pest infestations, such as Varroa destructor mites. Prompt detection via spatial monitoring enables early interventions, decreasing colony losses and sustaining colony health (Duma et al., 2024).

Interactive GIS-based maps have also been devised to assist with beekeeping activities, by providing real-time data on hive health, ambient factors and managerial tasks. Such tools strengthen decision-making and enable effective planning of beekeeping operations, resulting in improved productivity and sustainability (Kotovs & Zacepins, 2023).

The integration of geoinformatics in apiculture has also contributed significantly to the suitability assessment of areas for beekeeping. Utilizing the Analytic Hierarchy Process (AHP) along with GIS, researchers can assess multiple criteria-such as climatic conditions, crop variation, and land use-to identify the most suitable areas for the establishment of apiaries (Roque et al., 2024). That approach advocates expanding beekeeping into new areas by minimizing the potential risks related to unfavorable environmental conditions.

In summary, the implementation of geoinformatics in apiculture has effectively revolutionized traditional beekeeping practices by providing tools for accurate spatial analysis and decision support. Ranging from the optimization of beehive site selection to the observation of

environmental changes and the management of diseases, geoinformatics enhances the efficiency and sustainability of apiculture operations. As technology continues to evolve, the incorporation of geoinformatics into beekeeping is likely to have an increasingly vital role in supporting both honey production and pollination services.

3. State of the Art

3.1 Site Suitability Analysis for Beekeeping via AHP: Konya Example (Sarı & Ceylan, 2017)

The current study underlines the significance of beekeeping in supporting agricultural productivity and biodiversity while providing economic benefits to rural areas. The emphasis is on identifying suitable areas for beekeeping in Konya, Turkey, by integrating ecological, social and economic factors into land use planning. The research uses a combination of GIS and the analytical hierarchy process (AHP) to address the complexities of site selection for beekeeping. Turkey has considerable potential for apiculture, due to its diverse vegetation and appropriate environmental conditions. Notwithstanding this potential, the Turkish apiculture field has not fully utilized these resources, making it essential to develop improved management and planning strategies.

The study area (figure 3.1), Konya, is a significant agricultural hub in Turkey, known for its extensive plains and large arable lands. According to the Turkish Statistical Institute, the region encompasses 18.618,142 km2 of land dedicated to grain farming, 207,665 km2 for vegetable gardens, and 412,918 km2 for fruits and spices, making up a total of 19.239,667 km2 of cultivable land. The area's forests are primarily located in its mountainous regions and consist of tree species such as Black Pine, Oak, Red Pine, Juniper, Cedar, and Fir.

The natural vegetation of Konya is diverse and includes species such as *Alcea pallida*, *Amaranthus retroflexus*, *Astragalus alepecuroides*, *Cirsium arvense*, *Euphorbia amygdaloides*, and *Taraxacum serotinum*. These plants play a significant role in the ecological system of the area, contributing to the region's suitability for beekeeping by providing a variety of nectar and pollen sources.

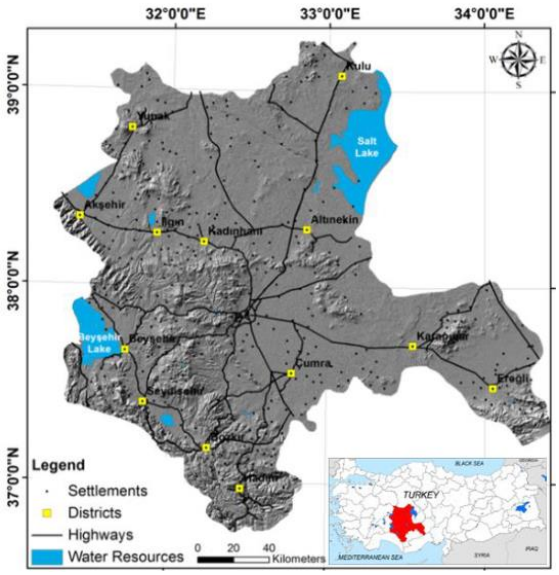


Figure 3.1: Study Area (Sari & Ceylan, 2017)

The study identified several critical factors influencing the suitability of a location for beekeeping. These factors are illustrated in the following table, selected based on their impact on beekeeping activities and their selections, are strategic because it concerns the maximisation of production (table 3.1)

Criteria	**Reason of selection**
Aspect	When sunlight exposure is maximized, beehives are protected from cold and ensure that the ideal temperature is prevailing for the hire activity.
Elevation	Elevation is crucial for the efficiency of honey production. Extreme heights can decline productivity of bees due to harsh meteorological conditions and reduced vegetation.
Flora	Forests and natural vegetation is better than agricultural areas and urban sites due to lack of pesticide risks.
Distance to Roads and Settlements	In order to maximize the productivity of honey bees and to ensure the quality of honey, hives must be located away from urban centers and major roads in order to prevent the exposure to greenhouse gases, noise and pollution.
Distance to Water	Proximity to water is necessary in order to maintain the optimal environment for honey production.
Slope	Slope affects vegetation and topographical stability which is crucial for beehive site selection.
Precipitation	Rainfall is also necessary for supporting the growth of vegetation.

Table 3.1: AHP Criteria list (Sari & Ceylan, 2017; Own Edit)

Each criterion reflects the environmental, topographic, and meteorological conditions necessary for successful beekeeping.

The authors of this scientific research used Analytical Hierarchy Process (AHP), which is a decision-making framework,. used to prioritize the criteria for beekeeping suitability. AHP involves the following steps:

1. **Pairwise Comparison Matrix**:
    - Criteria are compared against each other on a scale from 1 to 9, where values represent their relative importance (e.g., 1 for equal importance, 9 for extreme importance).
2. **Normalization**:
    - Each element in the comparison matrix is divided by the sum of its column, creating a normalized matrix. The rows of this matrix are then summed and averaged to calculate the weights of each criterion.
3. **Consistency Check**:

- To ensure that the comparisons are logically consistent, a Consistency Index (CI) is calculated using the eigenvalues of the matrix. CI is defined as: CI = $(\lambda_{max} - n) / n - 1$ where λ_{max} is the maximum eigenvalue, and n is the number of criteria

4. **Random Index (RI)**:
    - The RI value is used to measure randomness in the comparisons. A CR value less than 0.1 indicates acceptable consistency; otherwise, the matrix must be revised.
5. **Weight Assignment**:
    - The calculated weights are used to rank the criteria based on their importance. For instance, flora and water resources might receive higher weights than slope or aspect.

Through this systematic approach, AHP provides a structured method for assigning priorities to multiple criteria, ensuring that decisions are both rational and consistent.

The study applied GIS and AHP methods to generate suitability maps for beekeeping in Konya, using ArcGIS software to process and reclassify spatial data. Each of the selected criteria was visualized as an individual layer and classified into suitability classes. These classes range from highly suitable (depicted in green) to non-suitable (depicted in red), as shown in the maps provided. This classification process ensures that areas with the highest potential for beekeeping are easily distinguishable (figure 3.2).

Generating Suitability Maps

To create the suitability maps, the weights of each criterion were calculated using the AHP pairwise comparison method. This method involved assigning relative importance values between 1 and 9 to each pair of criteria, which were then used to generate a normalized matrix. The final weights were calculated as a percentage, ensuring their sum equals 1.

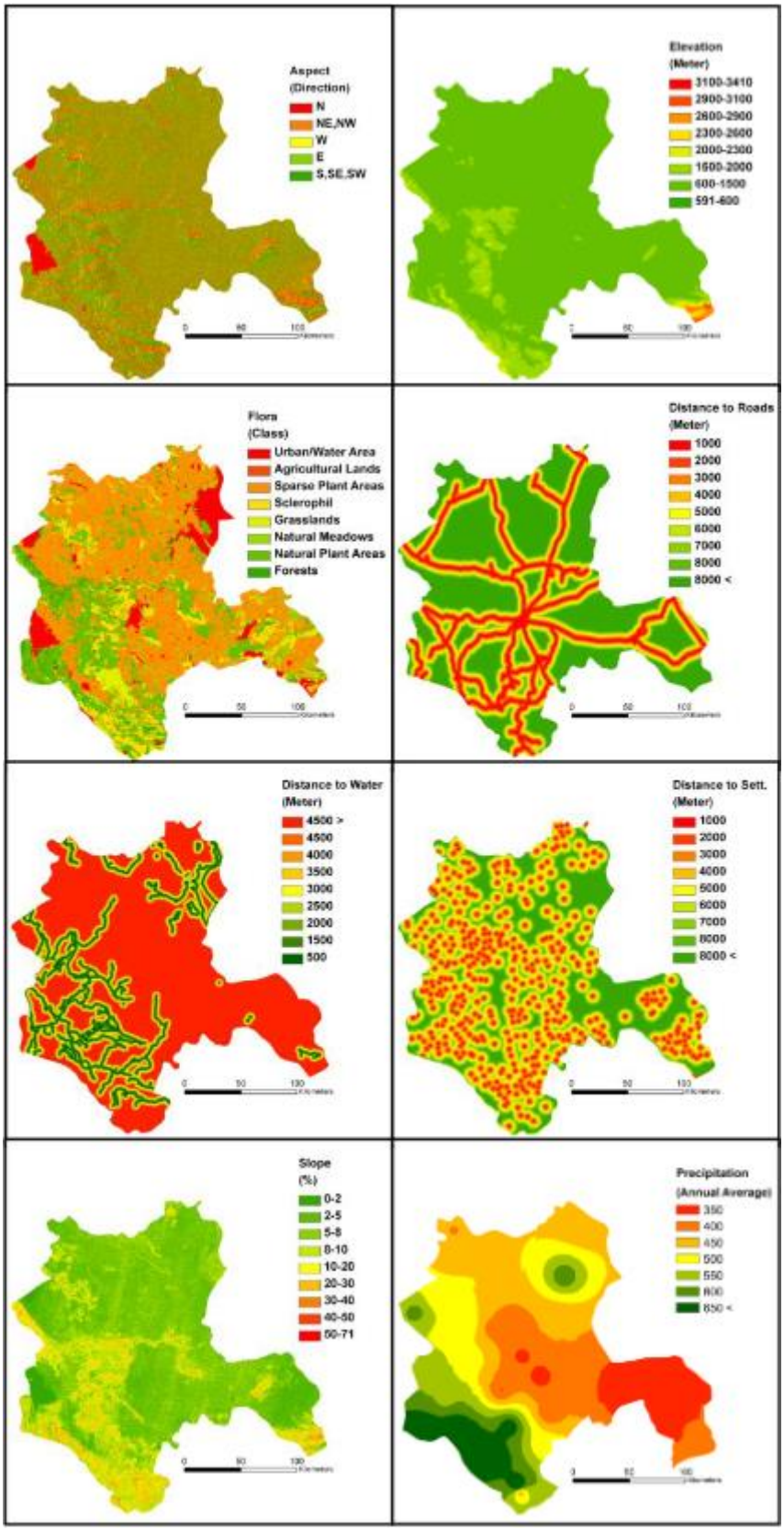


Figure 3.2: Criteria Maps (Sarı & Ceylan, 2017)

The weights assigned to each criterion reflect their relative importance for beekeeping:

- Flora: The most critical factor, accounting for 44% of the total weight, due to its direct impact on honeybee productivity and honey quality.
- Distance to water resources: Essential for hive cooling and hydration, with a weight of 15%.
- Aspect: Contributing 12%, as south-facing slopes provide better light exposure and protection from cold winds.
- Elevation: Weighted at 10%, affecting vegetation and flowering patterns.
- Precipitation: Important for sustaining vegetation, assigned a weight of 7.6%.
- Slope: Weighted at 4.4%, influencing terrain stability and accessibility.
- Distance to roads and settlements: Assigned lower weights of 3.9% and 3.3%, respectively, as they primarily affect operational logistics and urban pollution avoidance.

The consistency of the weights was validated using a consistency ratio (CR). The calculated CR of 0.081 indicated a high level of consistency, ensuring that the weighting process was reliable. The weighted layers were overlaid in ArcGIS to generate the final suitability map. This map integrated all criteria to produce a comprehensive visualization of potential beekeeping sites in Konya. The resulting suitability zones identified areas that are highly favorable for beekeeping activities while minimizing risks such as inadequate water access or insufficient floral resources. The final map offers a practical decision-making tool for beekeepers and policymakers, enabling targeted planning for sustainable beekeeping practices in the region.

The suitability analysis for beekeeping in the Konya region revealed that 48% of the area is classified as suitable, while the remaining 52% is not suitable according to the Analytical Hierarchy Process (AHP) calculations. The results underscore the importance of specific criteria in determining suitability. The flora criterion, which accounted for 44% of the total weight, emerged as the most significant factor. Other major contributors include distance to water resources at 14.6% and aspect at 10%, collectively defining around 70% of the suitability. Factors like distance to roads and distance to settlements had a lesser impact, with weights of 3.9% and 3.3%, respectively, due to their indirect influence on beekeeping suitability. The total suitability map (figure 3.3) was created by integrating the weights of each criterion, clearly demarcating areas of high suitability in green and low suitability in red. The generated map provides a spatially explicit visualization of potential beekeeping sites, guiding decision-making for both existing and future apiary locations.

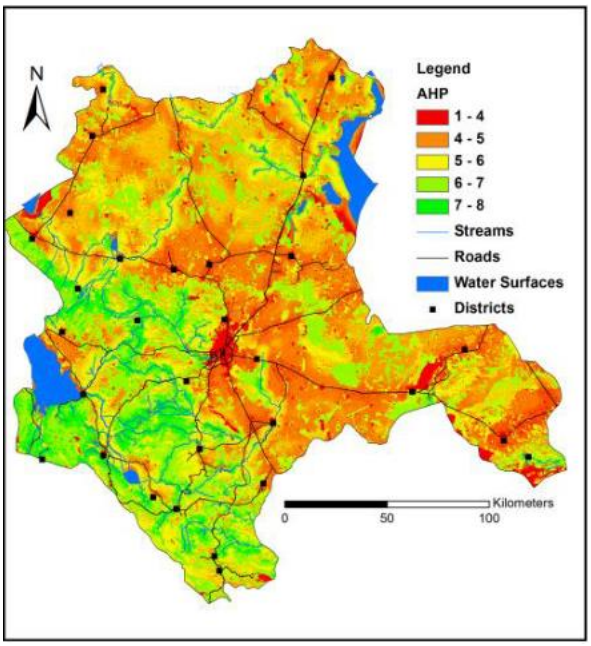


Figure 3.3: Suitability map (Sarı & Ceylan, 2017)

To validate the reliability of the suitability analysis, the study compared the generated suitability maps with Turkish Statistical Institute (TUIK) apiculture statistics for 2015. This dataset included information on total honey production, total wax counts, total beekeeper counts (district-level). Districts such as Bozkır, Hadim, Seydişehir, Beyşehir, and Meram demonstrated the highest levels of honey production and overlapped with areas classified as highly suitable in the AHP-generated maps. This strong overlap reinforces the reliability of the analysis.

The study employed correlation analysis to assess the relationship between AHP suitability scores and beekeeping statistics. The results showed a correlation of 0.70 (r-value) between total beekeeper count and suitability values, indicating a strong relationship. Furthermore, honey production and wax counts also correlated positively, with r-values of 0.61 and 0.54, respectively. The high correlation with beekeeper counts is attributed to the fact that beekeepers must register with the Ministry of Food, Agriculture, and Livestock, providing accurate data on their locations. Another method of validation involved integrating data on 117 existing beekeeper locations, recorded between May and September 2016. These locations were overlaid on the suitability maps, revealing a significant intersection with high-suitability zones.

In conclusion, the results of this study affirm the accuracy and practical utility of the AHP-GIS framework in identifying suitable beekeeping sites. The strong correlation with apiculture statistics and the overlap with existing beekeeping locations validate the methodology, offering a reliable tool for enhancing beekeeping management and sustainability in the Konya region.

3.2 Apicultural Site Zonation Using GIS and Multi-Criteria Decision Analysis (Noor, Mansor, & Shafri, 2008)

The aim of this study was to locate suitable sites for beekeeping activity in the State of Selangor, Malaysia. The combination of GIS and Multi-Criteria Decision Analysis was crucial in order to perform the decision-making process. Statistical analysis was performed also in order to assess the effectiveness of the spatial analysis and its results. Integrating AHP inside the spatial analysis in GIS resulted in the classification of land in 4 categories depending on their suitability of beekeeping activity: Non Suitable, Most Suitable (S1), Suitable (S2), Moderately Suitable (S3).

The procedure is initiated by identifying the specific problem, with the objective being defined as pinpointing the most appropriate areas for apiculture based on environmental, accessibility and resource availability criteria. The methodology complies with the FAO guidelines for land suitability classification, while incorporating local conditions to improve the analysis.

The data for this study were acquired from a variety of sources, including satellite imagery, local government datasets and field surveys. These datasets were pre-processed to ensure compatibility with GIS software. Inappropriate areas were masked, and the vector data were converted to raster layers for spatial analysis. The processed data formed the basis for the following analysis steps.

A wide range of criteria were specified as being crucial for the suitability of beekeeping. These include hydrology, road networks, topography and the availability of nectar and pollen sources. Hydrology is especially important, as bees need a stable supply of water for their survival and activity. Areas within 200 m of water bodies were evaluated as particularly suitable. Likewise, accessibility plays a major role, with areas near to roads being preferred for easier transport and apiary management. Land topography, including elevation and slope, influences vegetation, microclimate and overall accessibility, with lowland areas and mild slopes (<10°) considered more suitable. The availability of flowering plants, which provide the necessary nectar and pollen, is another critical factor that directly affects honey production and overall suitability. In addition, certain sites, such as urban areas, mining areas and sites prone to pollution, fire, smoke or noise, were excluded from the analysis to eliminate unsuitable environments for beekeeping. The following table presents the above mentioned criteria (table 3.2).

CRITERION	SUB-CRITERIA	DESCRIPTION	WEIGHT
CLIMATIC	Rainfall	Dry Season	9
		Wet Season	3
PHYSICAL	Topography/ Elevation	Low Land : Below 150m	9
		Hill Land : 150 -300m	5
		High Land: Above 300m	1
	Hydrology Bodies (Water Network)	Best Suited: Below 200m	9
		Moderately Suited : 200-500m	5
		Slightly Suitable : 500-700m	2
		Modifiable : More than 700m	1
EXISTING INFRA-STRUCTURE	Road Networ	Best Suited: Below 5 km	9
		Moderately Suited : 5-10 km	5
		Suitable : 10- 15 km	2
		Unsuitable : More than 15 km	1
FOOD SOURCE/ BEE PLANT	Nectar	High nectar source : N1	9
		Medium nectar source : N2	5
		Low nectar source : N3	3
	Pollen	High nectar source : N1	9
		Medium nectar source : N2	5
		Low nectar source : N3	3
OVERALL CRITERION WEIGHT		Terrain/Topography	1
		Road Networks	2
		Hydrology Networks	4
		Pollen Class	7
		Nectar Class	9

Table 3.2: Criteria and Description (Noor, Mansor, & Shafri, 2008)

The analytical hierarchy process (AHP) was used to prioritize and weigh the identified criteria. A pairwise comparison table was constructed to assess the relative importance of each factor, based on expert input. The assigned weights were normalized and the consistency ratio (CR) was calculated to ensure the reliability of the pairwise comparisons, with an acceptance threshold of CR < 0.1. For example, hydrology may receive the highest weight (e.g. 0.35), reflecting its importance, while other criteria, such as topography or road networks, receive lower weights according to their relative importance.

Each criterion was then normalized using a linear transformation function to normalize the values between 0 and 1. This ensured the consistency of the data range across all criteria. Reclassification was employed to classify the data into suitability categories such as high, medium and low suitability. A multiplier (e.g. 9) was often used to improve the interpretability of the scores.

In the meantime, GIS played a key role in integrating the weighted criteria to create a composite suitability map. Using overlay analysis in ArcGIS, the thematic layers were combined based on the weights derived from the AHP. Buffer zones were created around critical features, such as water sources and roads, to capture their zones of influence. This spatial analysis resulted in a suitability map that depicted the classification of areas into highly suitable, moderately suitable, less suitable, and unsuitable zones. For each criterion, a classification map and a ranking map were created based on the suitability of the area (figure 3.4 - 3.5).

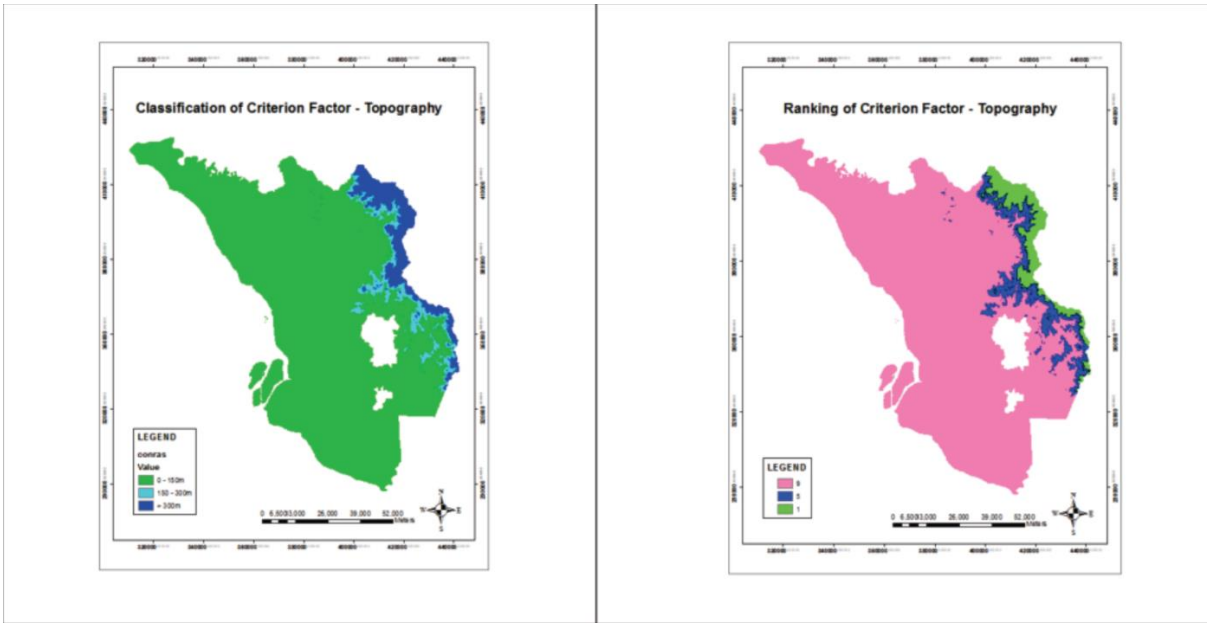


Figure 3.4: Topography Classification and Ranking Map (Noor, Mansor, & Shafri, 2008)

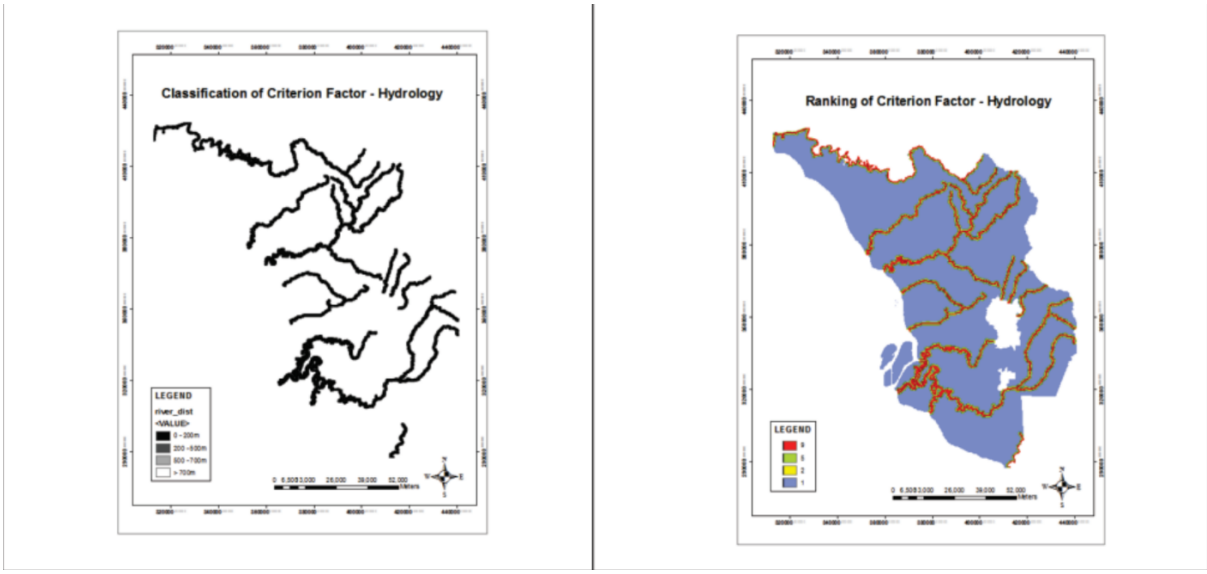


Figure 3.5: Hydrology Classification and Ranking Map (Noor, Mansor, & Shafri, 2008)

The same procedure was employed for the other 3 criteria. The final map was subjected to validation through field surveys and expert input to ensure its consistency with real-life conditions. Adaptations were made where differences were detected, improving the suitability classification. The resulting suitability map provided practical guidance for setting up apiaries, offering information on the best locations for sustainable beekeeping. This comprehensive methodology illustrates the effectiveness of combining GIS and AHP for decision making in agricultural and environmental planning.

Using functions and tools of ArcGIS, previous analysis of each one criterion was integrated into one and the final map was generated (fig. 3.6).

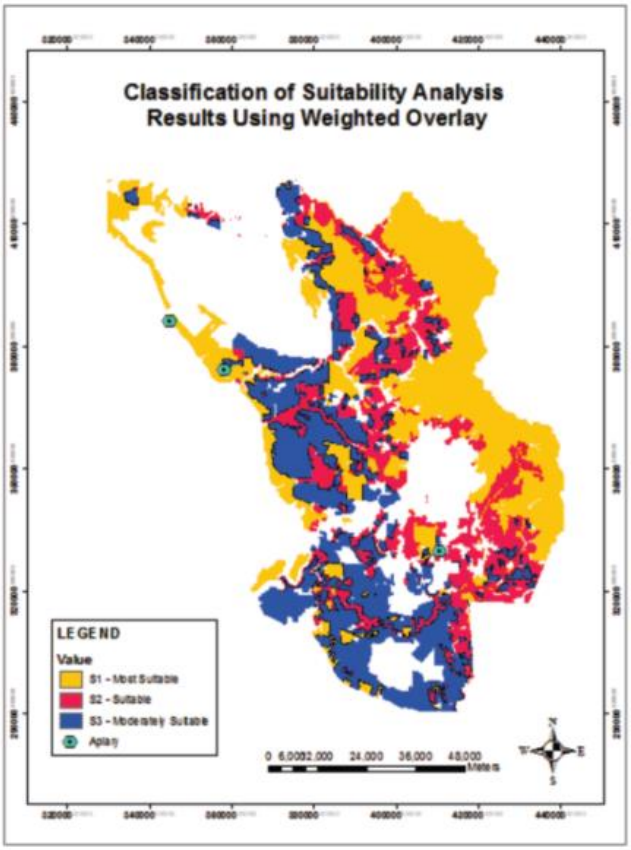


Figure 3.6: Final Suitability Analysis Map (Noor, Mansor, & Shafri, 2008)

The following table contains the percentages of the values that are being presented in the map above (table 3.3). In particular, the percentages are indicated for each one category (S1, S2, S3).

	Weighted Overlay	
Suitability Analysis	Hectares	Percentage
S1 - Most Suitable	109, 166.67	13.72%
S2 - Suitable	216, 757.24	27.24%
S3 - Moderately Suitable	193, 498.15	24.32%
Total Suitable area	519, 422.0589	65.27%
Not Suitable	276, 358.66	34.73%

Table 3.3: Percentages for each category of Suitability Analysis (Noor, Mansor, & Shafri, 2008)

This study incorporates multi-criteria decision-making (MCDA) and GIS technology to assess and identify potential zones for apiculture. By evaluating numerous factors with different significance levels, the study effectively uses GIS and the Analytical Hierarchy Process (AHP) to identify appropriate apiculture areas. The verification of the existing apiaries based on the model showed reliable results, confirming the accuracy of the weight assigned to each criterion.

The AHP methodology allowed the creation of a mathematical model that determines the factors that contribute to the suitability of the apiary. This model can be adapted to specific

needs or different areas, making it a flexible tool for analysing beekeeping zones. The study provides a comprehensive guideline for identifying suitable factors for beekeeping and has the potential to be extended to future research, such as predicting flowering periods for migratory beekeeping. Overall, the assessment and delineation of suitable areas promotes the scalability of beekeeping activities, either on a large or small scale.

3.3 A Novel GIS-Based Approach to Assess Beekeeping Suitability of Mediterranean Lands (Zoccali et al., 2017)

This specific study addresses the decline of insect pollinators, particularly honeybees, which poses a serious threat to food crop stability and biodiversity. Honeybees play a vital role in pollinating over 80% of crops and wild plants in Europe, contributing significantly to the agricultural economy. The decline in honeybee populations is attributed to various factors, including diseases, habitat degradation, the loss of flower-rich landscapes, and the negative impact of agricultural pesticides.

Beekeeping benefits from strategic planning through land suitability analyses. These analyses classify areas based on their potential for beekeeping. The study integrates Multi-Criteria Decision-Making (MCDM) techniques with Geographic Information Systems (GIS) to evaluate the suitability of Mediterranean lands for beekeeping. Using the Analytical Hierarchy Process (AHP), criteria were weighed and classified into suitability classes, offering a systematic approach to decision-making. However, such studies face challenges like data consistency and uncertainty in weighting criteria. To overcome these limitations and restrictions, the study integrates fuzzy logic to augment data standardization and improve decision-making in the context of uncertainty. In order to ensure the safety of valid results of the suitability analysis and to manage the large datasets, a combination of fuzzy logic, AHP and GIS was conducted.

The research focuses on Calabria, a region in Southern Italy with a tradition of rural apiculture but suffering from land degradation and abandonment. By analyzing open-access data, the study provides a reproducible model for identifying profitable areas for beekeeping, adding economic value to marginal lands. This approach demonstrates the potential of GIS-based methodologies to support sustainable apiculture and promote the economic revitalization of Mediterranean rural areas.

The authors of this research created the following figure that contains all the steps and actions that needed to be done (figure 3.7).

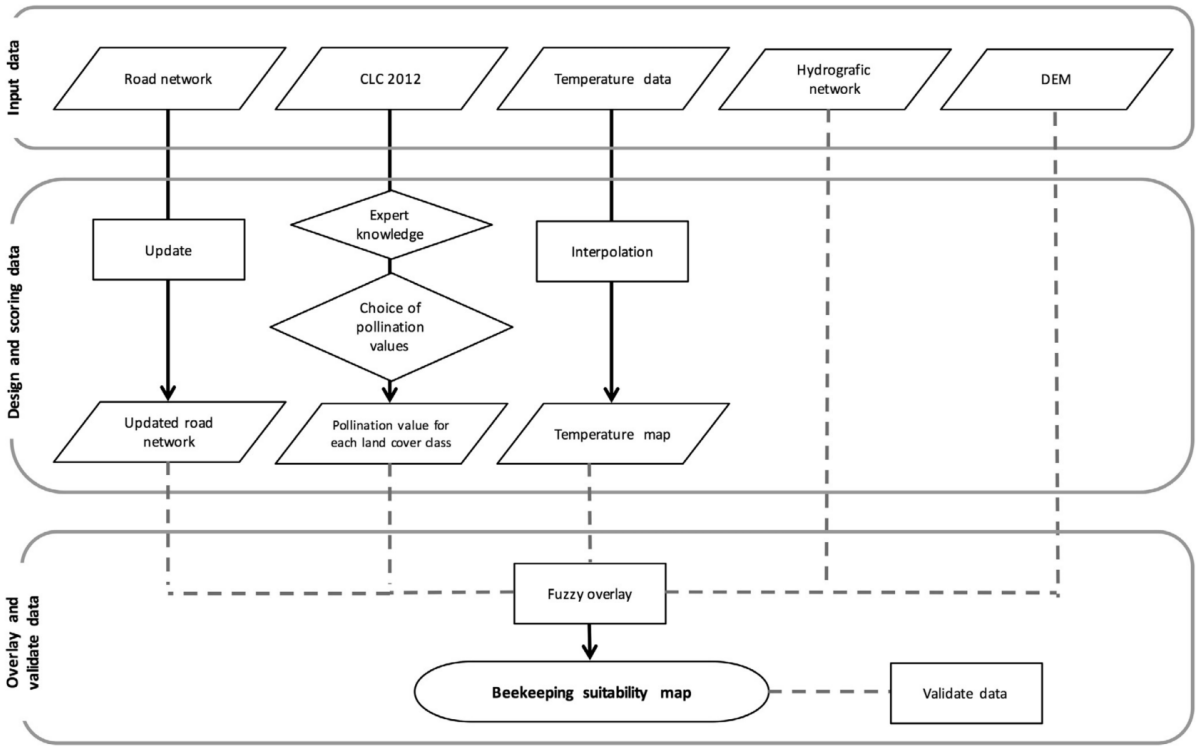


Figure 3.7: Suitability analysis mapping procedure flow chart (Zoccali et al., 2017)

In general, the workflow involves the selection of criteria, the collection of data, the development of the suitability model in GIS, the production of the final suitability map and the validation of the analysis.

The selection of criteria and the collection of data is the first and most important feature of the study because it will determine the final outcome. The authors of this research selected temperature, road, water needs, altitude and land use as criteria of the analysis. Then, having already decided on the criteria, they gathered the selected data. In the following table, criteria, data and their sources are presented (table 3.4).

Factors	Data	Source	URL
Temperature	Temperature data	ARSAC	http://arsac.calabria.it/ (available upon request)
Road	Road network	CISIS DBPrior 10 k project	http://www.centrointerregionale-gis.it/
Water needs	Hydrographic network	CISIS DBPrior 10 k project	http://www.centrointerregionale-gis.it/
Altitude	Digital elevation model	ISPRA	http://www.isprambiente.gov.it
Land use	CLC IV level 2012		

Table 3.4: Selected criteria and relative data source (Zoccali et al., 2017)

All data that are presented in the table above were sourced from online and free sources. The temperature records were derived from a very extended dataset (30 years) and were selected as a criterion because high temperatures (not extreme conditions) tend to enhance beekeeping activity. In addition, the proximity to the road network is considered very important as beekeeping nowadays is mainly moving and the need for transportation is constant. Furthermore, proximity to water (especially rivers and lakes) is also crucial because it is proportional to the optimisation of the beekeeping activity. In order to perform the beekeeping activity seamlessly, lower altitudes are favored because altitude defines the density and the

variety of vegetation (the higher the altitude, the less vegetation). Finally, the last criterion was land use, which was very important in order to assess the vegetation cover of the area.

Several software were used in this specific analysis, such as ArcGIS, Microsoft Excel, IBM SPSS and XTools. All the criteria were normalized by using the fuzzy function, scaled between 0 and 1 and they were combined by using a fuzzy overlay (gamma function). The combination of the analysis using the software led to the creation of the final suitability map (figure 3.8). The model's accuracy was assessed through stratified sampling, generating 600 random points and comparing their suitability values to those assigned by a panel of five experts.

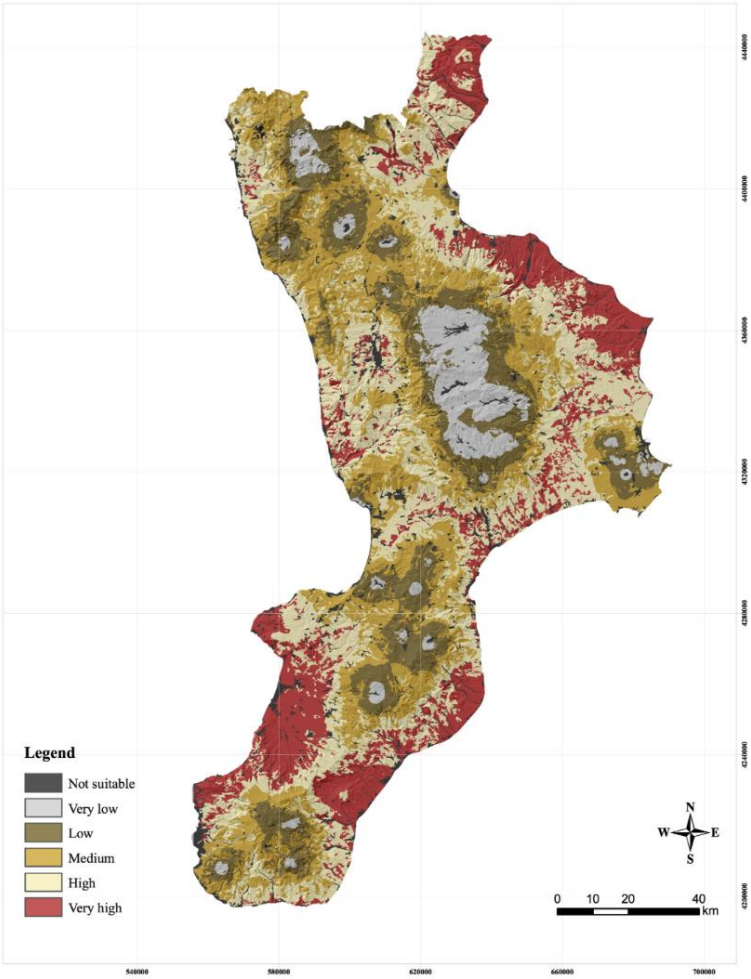


Figure 3.8: Final Suitability Map (Zoccali et al., 2017)

The authors argue that this study is innovative as it combines expertise and high-quality data to provide certainty and to ensure that the results are accurate. In addition, the importance of beekeeping is highlighted as it is a growing sector driven by the demand for food products such as honey, propolis, pollen and royal jelly. In Europe there are an estimated 620.000 beekeepers producing around 220.000 tons of honey per year. Despite this growth, the sector is characterised by a high proportion of non-professional beekeepers and a low number of colonies per beekeeper.

4. Methodology and Tools

4.1 Overview

The suitability assessment for apiculture activities demands the inclusion of environmental, climatic and infrastructural aspects, which are evaluated by means of a well-structured and scientifically substantiated methodology. In this study, a multi-criteria decision making framework (MCDM) in a Geographic Information System (GIS) environment was implemented to assess spatial suitability across the study area.

The Analytic Hierarchy Process (AHP), developed by Saaty (1980), acted as the basic MCDM method, allowing systematic identification of the relative importance of each factor influencing beekeeping site selection. By structuring complex decision-making problems into a hierarchical model, AHP facilitates the integration of both qualitative and quantitative criteria in a consistent manner (Saaty, 2008).

Spatial analysis and data processing were conducted using QGIS, an open source GIS software platform that supports raster and vector data processing, spatial analysis and cartographic generation. Data from satellite imagery, digital elevation models (DEMs) and geospatial crowd-sourced databases were used to extrapolate key biophysical and accessibility criteria. These criteria were reclassified into discrete suitability categories based on thresholds defined by the scientific literature and expert recommendations.

The methodological workflow can be outlined below:

1. Data acquisition and preprocessing

2. Generation of thematic layers representing each criterion (Temperature, Vegetation, Slope, Proximity to roads, Distance from settlements)

3. Pairwise comparison and weight assignment using AHP

4. Consistency checks (Consistency Index and Consistency Ratio)

5. Reclassification of the raster products for each criterion

6. Weighted overlay analysis in order to produce the final suitability map

7. Web cartographic application

This comprehensive approach provides a thorough and transparent assessment, which is aligned with best practices in spatial multi-criteria decision analysis (Malczewski, 2006).

4.2 Data Collection

The accurate and consistent data collection is the core of spatial suitability analysis. For this study, the datasets were obtained from a combination of remote sensing platforms, open access geospatial databases and official (governmental) databases to ensure the credibility, integrity and adequacy of the spatial analysis. The following table presents the criteria of this study and their data source (table 4.1).

Criterion	**Description**	**Data Source**
Vegetation (NDVI-Normalized Difference Vegetation Index)	Indicates floral resource availability, higher NDVI = more forage.	Sentinel 2 Imagery
Temperature (LST-Land Surface Temperature)	Influences bee activity and hive survival, moderate range preferred.	MODIS Imagery
Slope	Affects hive placement feasibility, flat terrain is ideal.	DEM (Shuttle Radar Topography Mission)
Road (Proximity to Road Network)	Ensures transport and hive access, closer = better logistics.	Open Street Map
Settlements (Distance from Settlements)	Provides access to services but too close may increase risks.	Helenic Data Service (Greek government open-source database)

Table 4.1: Criteria of the study and their data sources

4.2.1 Satellite Imagery

Two types of satellite imagery were used in this study. MODIS data for calculating Land Surface Temperature (LST), and Sentinel 2 imagery for computing the Normalized Difference Vegetation Index (NDVI). Specifically, LST was derived from MODIS daily thermal products

(MOD11A1), which provide surface temperature estimates at a spatial resolution of 1 km. This imagery was processed in Google Earth Engine and then resampled to 10-meter resolution using bilinear interpolation to align with the spatial detail of the other layers. MODIS was selected due to its consistent thermal coverage and validated LST products, which are suitable for large-area temperature assessments (Wan et al., 2004).

NDVI, on the other hand, was calculated using Sentinel 2 surface reflectance bands, specifically Band 8 (NIR) and Band 4 (Red). Sentinel-2 offers 10-meter spatial resolution for both bands, making it especially suitable for detailed land cover and vegetation assessments (Drusch et al., 2012). The use of Sentinel-2 ensures improved sensitivity to vegetation variation across complex landscapes like Aitoloakarnania. NDVI was first introduced by Rouse et al. (1974) and further developed by Tucker (1979), serves as a reliable index for vegetation health and floral resource availability, which are critical factors for the sustainability of apiculture.

4.2.2 Digital Elevation Model (DEM)

The DEM was used to obtain slope information, which influences beekeeping accessibility and hive stability. Slope information from DEM is widely used in agricultural and environmental applications (Wilson & Gallant, 2000). The Shuttle Radar Topography Mission (SRTM) DEM with 30-meter resolution was selected because of the balance between spatial resolution and availability (Farr et al., 2007).

4.2.3 Road Network Data

The road network data were derived from OpenStreetMap (OSM), a collaborative work providing freely available and regularly updated geospatial data (Haklay & Weber, 2008). The proximity to roads is necessary for the operational logistics of beekeeping activities such as transporting hives, maintaining and harvesting honey (Gupta, Rey, & Dobson, 2016).

4.2.4 Urban and Settlement Data

The urban areas and the vector data for the settlements in the study area were obtained from an official and open-source database of the Greek government in the context of digital governance and the sharing of data on the internet between expert users.

4.2.5 Data Preprocessing

All datasets were subjected to strict preprocessing procedures to ensure spatial coherence and analytical robustness. The steps of data preprocessing include, first of all, the reprojection into a common coordinate system between all the data needed. Secondly, by clipping to the study area boundaries, the computational load is being minimized. Thirdly, in order to have common spatial resolution among the raster data the procedure of resampling is being performed. Lastly, when all the raster data are finalized, a masking is performed, in order to exclude the water bodies and non-relevant land cover types from the study area. The afore-mentioned steps are

necessary in order to minimize spatial errors and ensure the robustness of the results in both visual and statistical aspects.

4.3 Data Processing in QGIS

The data were obtained from different sources, so it was necessary for them to be systematically transformed in order to be compatible between them. The software which was used in order to perform all these transformations was QGIS as discussed earlier. The preparation of the geospatial data is fundamental and ensures that the final datasets will be properly aligned, ready for analysis and comparable. The steps that are about the data processing are following:

4.3.1 Reprojection and Harmonization

All input datasets were reprojected into a common coordinate reference system (CRS), specifically the Greek Geodetic Reference System 1987 (GGRS87 - EPSG:2100), to minimize spatial errors due to differing projections. Spatial reprojection is an important and initial step in every geospatial analysis in order to ensure that overlay operations and spatial measurements are accurate and consistent (Bolstad, 2016).

Vector layers (road network, settlements) were transformed into raster layers through QGIS algorithms in order to fit in with the other raster layers (Slope, LST, NDVI). Where needed, these raster layers were transformed using the nearest neighbor method for categorical data and bilinear interpolation.

4.3.2 Clipping and Study Area Extraction

To minimize the computational load and to focus on the area of interest, all datasets were clipped to the Regional Unit of Aitoloakarnania, which was the study area. The clipping operation reduces data load, focusing the analysis only on the area of interest. (Burrough & McDonnell, 1998).

The administrative boundary shapefile of Aitoloakarnania was used as the mask layer for clipping, ensuring that all layers shared a common extent.

4.3.3 Resampling and Spatial Resolution Standardization

Considering the varying spatial resolutions of the data, a resampling procedure was performed to align all raster datasets at 10-meter resolution. This combined analysis enables consistent operations during raster overlay analysis. Standardizing spatial resolution is vital to prevent errors including incorrectly aligned pixels and interference artifacts during multicriteria analysis. (Jensen & Jensen, 2013).

4.3.4 Raster Calculations and Index Derivation

Raster-based calculations formed an integral part of the data processing phase. The following key indices were derived:

Land Surface Temperature (LST)

Land Surface Temperature (LST) was obtained from the MODIS MOD11A1 product, which provides daily surface temperature estimates derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA's Terra satellite. This dataset offers LST values at a 1-kilometer resolution, already atmospherically corrected and validated (Wan et al., 2004).

To ensure compatibility with the spatial resolution of other layers, the MODIS LST raster was reprojected to the Greek grid (ETRS89 / GGRS87) and resampled to 10 meters using bilinear interpolation. The result was a continuous temperature surface representing the average annual LST for 2024.The use of MODIS LST products is particularly appropriate for broad-scale environmental suitability analysis, as they offer high temporal coverage and have been widely used in ecological and agricultural modeling (Neteler, 2010). These LST values are critical for evaluating regions where temperature regimes align with optimal bee activity thresholds (Abou-Shaara, 2014).

Normalized Difference Vegetation Index (NDVI)

NDVI was computed using the classic formula:

$$\text{NDVI} = \frac{NIR + RED}{NIR - RED}$$

where NIR and RED represent the reflectance in the near-infrared and red bands, respectively (Tucker, 1979). The areas where NDVI values are significantly high are those that include dense and healthy vegetation. On the contrary, lower values of NDVI indicate sparse vegetation. This index (NDVI) is commonly used as a surrogate index for the availability of floral resources, which is a key factor in beekeeping sustainability (Pettorelli, 2013).

Slope Calculation

Slope was derived from the DEM using specific algorithms from the processing toolbox within QGIS. Slope values were expressed in percentage and provide an indication of terrain steepness, which affects both accessibility and hive stability (Wilson & Gallant, 2000).

Proximity Analysis - Distance from Settlements

Proximity to the road network and distance from the settlements were calculated using the raster distance (proximity) tool inside the QGIS environment, generating continuous raster surfaces that represent the shortest distance from each pixel to the nearest feature (roads or urban centers). Raster distance analysis is standard in suitability modeling where accessibility and disturbance gradients are considered (Store & Kangas, 2001).

The distance rasters dataset were subsequently reclassified into discrete suitability classes based on literature-derived thresholds (e.g., preferred distances less than 2 kilometers for optimal accessibility).

4.3.5 Data Validation and Error Checking

Before proceeding to multi-criteria analysis, all layers underwent a quality control procedure, including the visual inspection for misalignments and projection errors, the histogram analysis to verify value ranges and the cross-comparison against ancillary datasets (e.g., OpenStreetMap validation). This kind of validation ensure that subsequent analytical results are based on robust and reliable data (Goodchild, 2007).

4.4 Analytic Hierarchy Process (AHP)

Thomas L. Saaty, in the 1970s developed a well-structured technique based on mathematics in order to organize and analyse complex decisions. This technique is called the Analytic Hierarchy Process (AHP) and provides an integrated and streamlined framework for decision-making. This can be done with the decomposition of a particular problem into a hierarchy of more easily understood subproblems, each of which can be separately analysed (Saaty, 1980). The ability to incorporate both qualitative and quantitative factors and criteria as well as its transparency and capacity to model complex decision structures, makes AHP the proper choice in every spatial multi-criteria decision analysis (Feizizadeh & Blaschke, 2013).

In this study, AHP was employed to determine the relative weights of five key factors influencing the suitability for beekeeping: Temperature (Land Surface Temperature), Vegetation (Normalized Difference Vegetation Index), Digital Elevation Model (Slope), Road Network (Proximity to Road Network), and Urban Areas (Distance from Settlements).

4.4.1 Theoretical Background

In order to perform AHP, three main steps must be followed. First, the hierarchy construction is about structuring the problem into the criteria of choice. Secondly, the pairwise comparisons are about the comparisons between the criteria of the main problem (e.g. their interaction and the importance of one over the other). Thirdly, the priority calculation, which is mainly about the derivation of weights for the criteria.

As discussed, the core of AHP is the pairwise comparison matrix, where each criterion is compared to every other criterion based on its relative importance. Saaty (1980) proposed a standardized fundamental scale for pairwise comparisons (Table 4.1).

Importance Value	Definition
1	Equal importance

3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between two adjacent judgments

Table 4.2: Saaty's Fundamental Scale for Pairwise Comparisons (Source: Saaty, 1980)

Let a_{ij} represent the importance of criterion *i* compared to criterion *j*. The pairwise comparison matrix *A* is thus a square, positive reciprocal matrix, where:

$$a_{ij} = \frac{1}{aji} \text{ and } a_{ii} = 1$$

Once the matrix is filled, the priority vector *w* (i.e., the weights of each criterion) is obtained by calculating the principal eigenvector associated with the maximum eigenvalue ($\boldsymbol{\lambda_{max}}$) of the matrix.

Mathematically:

$$A \times w = \lambda_{max} \times w$$

where *A* is the pairwise comparison matrix, *w* is the weight vector, λ_{max} is the maximum eigenvalue of *A*.

A common approximation method to derive *w* involves normalizing each column of the matrix and averaging across rows (Vargas, 1990).

4.4.2 Application in the Current Study

In this study, the hierarchy consisted of three levels. Firstly, the goal is the identification of the suitable areas for beekeeping. Secondly, the criteria of the analysis which are based on personal preference and thirdly, **the alternatives which is a different spatial distribution due to different approach between the same criteria each time.**

A pairwise comparison matrix was constructed based on expert knowledge and literature regarding the relative influence of each factor on beekeeping success. For instance, suitable temperature and vegetation availability were considered more critical compared to accessibility factors.

An illustrative fragment of the matrix is shown in table 4.2 below (In order to demonstrate how to fill a matrix of AHP the following hypothetical values were used):

Criteria	Temperature	Vegetation	Slope	Road Proximity	Settlement Proximity
Temperature	1	3	5	7	9
Vegetation	1/3	1	3	5	7
Slope	1/5	1/3	1	3	5
Road Proximity	1/7	1/5	1/3	1	3
Settlement Distance	1/9	1/7	1/5	1/3	1

Table 4.3: Hypothetical filling of the table

After completing the matrix, the weight vector was computed, representing the relative importance of each criterion. These weights were later used in the weighted overlay analysis in GIS.

4.4.3 Strengths and Limitations of AHP

AHP offers several advantages, including a structured and transparent decision-making process, the ability to handle both tangible and intangible factors, and integration with GIS for spatially explicit decision-making (Vargas, 1990).

However, AHP is not without limitations. It is sensitive to inconsistencies in judgment, especially when the number of criteria is large (Forman & Gass, 2001). Furthermore, the pairwise comparison process can introduce subjectivity, which, although partially mitigated by consistency checks, may still influence the final results.

Despite these challenges, AHP remains one of the most widely used and validated methodologies for spatial decision problems, particularly when integrated with GIS (Malczewski, 1999).

4.5 Consistency Checks: Consistency Index (CI) and Consistency Ratio (CR)

In the Analytic Hierarchy Process (AHP), the consistency of the pairwise comparison matrix is a critical quality control step. Because human judgments may not always be perfectly

consistent, especially when dealing with multiple criteria, it is essential to evaluate the logical coherence of the comparisons (Saaty, 1980).

AHP offers two standard indices for consistency verification: the Consistency Index (CI) and the Consistency Ratio (CR). These measures assess whether the set of comparisons approximates a perfectly consistent matrix or whether inconsistencies exist at unacceptable levels.

Ensuring a high degree of consistency enhances the credibility and reliability of the resulting weights and, consequently, of the final decision-making outcomes (Forman & Gass, 2001).

4.5.1 Consistency Index (CI)

The Consistency Index (CI) quantifies the degree of consistency in the pairwise comparison matrix relative to a perfectly consistent matrix of the same size.

The CI is calculated as follows:

$$\text{CI} = \frac{\lambda max - n}{n-1}$$

where λ_{max} is the maximum eigenvalue of the comparison matrix and n is the number of criteria being compared.

In a perfectly consistent matrix, the maximum eigenvalue (λ_{max}) equals the number of criteria (n). In practice, slight deviations are expected due to minor inconsistencies in human judgment (Saaty, 1990). The closer the CI is to zero, the more consistent the judgments are.

4.5.2 Random Index (RI)

To evaluate whether a given CI is acceptable, it must be compared against a Random Index (RI). The RI represents the average CI of randomly generated pairwise comparison matrices of the same order nnn (Saaty, 1980).

The standard RI values are provided in Table 4.3:

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 4.4: Random Index (RI) Values for Different Matrix Sizes (Source: Saaty, 1980)

4.5.3 Consistency Ratio (CR)

The Consistency Ratio (CR) provides a normalized measure of consistency by comparing the CI to the RI. It is calculated as:

$$CR = \frac{CI}{RI}$$

A CR value of 0.10 (10%) or less is generally considered acceptable, indicating that the level of inconsistency is sufficiently low, and that the judgment matrix is reliable for decision-making purposes (Saaty, 1990)

If the CR exceeds 0.10, it is recommended to review and revise the pairwise comparisons to improve consistency.

4.5.4 Application in the Current Study

In this study, the pairwise comparison matrix for the five beekeeping suitability criteria was subjected to consistency analysis. The steps followed included:

1. Calculation of λ_{max} from the comparison matrix.
2. Derivation of the Consistency Index (CI) using the formula provided.
3. Selection of the appropriate Random Index (RI = 1.12 for n=5).
4. Calculation of the Consistency Ratio (CR).

The calculated CR was found to be below the 0.10 threshold, indicating acceptable consistency in the judgments made. Therefore, the derived criteria weights were deemed robust for use in the weighted overlay analysis.

Incorporating CI and CR evaluations in AHP ensures methodological rigor, reducing potential biases and subjectivity that may arise in complex decision environments (Forman & Gass, 2001).

4.6 Criteria Reclassification

In multi-criteria spatial analysis, especially within the framework of suitability modeling, the transformation of raw environmental variables into standardized suitability classes is a critical step. This process, referred to as criteria reclassification, involves categorizing continuous or discrete variables into ordinal classes reflecting their relative favorability for the intended application (Eastman, 1999).

In this study, the reclassification of the thematic layers derived from satellite imagery, terrain analysis, and proximity analyses into four discrete suitability classes was essential to harmonize heterogeneous data into a common evaluation framework for subsequent weighted overlay analysis.

4.6.1 Conceptual Basis for Reclassification

Reclassification transforms raw values (e.g., temperature in °C, NDVI values between -1 and +1, slope in degrees) into a smaller set of qualitative classes (e.g., Highly Suitable, Suitable, Moderately Suitable and Not Suitable). This standardization allows the integration of various criteria with different measurement units into a single suitability model (Malczewski, 2006). The reclassification thresholds were determined based on the literature review of beekeeping environmental requirements, expert judgment and of course statistical distribution of the data within the study area. Adopting literature-based thresholds ensures that the classification aligns with ecological realities, while local adaptations allow for contextual refinements (Store & Kangas, 2001).

4.6.2 Temperature Suitability

Land Surface Temperature (LST) plays a pivotal role in apiculture, as bees are highly sensitive to ambient temperatures, which influence foraging behavior, hive metabolism, and brood development (Abou-Shaara, 2014). Based on empirical studies, optimal conditions for beekeeping generally occur between 14°C and 24°C (Abou-Shaara, 2014; Le Conte & Navajas, 2008). Temperatures below 12°C or above 30°C were considered less favorable due to increased hive stress and mortality risks. Thus, the following classification was suggested: (Table 4.4)

LST (°C) Range	Suitability Class
< 12	Not Suitable
12 – 17	Moderately Suitable
17 – 24	Highly Suitable
> 24	Suitable

Table 4.5: Temperature thresholds (based on literature)

This schema reflects the temperature range favorability for colony productivity and survival.

4.6.3 Vegetation Suitability

Vegetation cover, as indicated by the Normalized Difference Vegetation Index (NDVI), serves as a proxy for floral resource availability, crucial for nectar and pollen collection (Pettorelli, 2013; Tucker, 1979). The following classification was suggested (Table 4.5):

NDVI Range	Suitability Class
< 0.2	Not Suitable
0.2 – 0.4	Moderately Suitable
0.4 – 0.6	Suitable
> 0.6	Highly Suitable

Table 4.6: Vegetation thresholds (based on literature)

Areas with NDVI above 0.6 were considered highly suitable, representing dense and healthy vegetation communities conducive to apiculture.

4.6.4 Slope Suitability

Slope affects site accessibility, hive stability, and microclimatic conditions. Steep slopes pose operational challenges and increase the risk of hive overturn or damage (Wilson & Gallant, 2000). The following classification was suggested (Table 4.6):

Slope (Degrees)	Suitability Class
> 20	Not Suitable
10 – 20	Moderately Suitable
5 – 10	Suitable
0 – 5	Highly Suitable

Table 4.7: Slope thresholds (based on literature)

Gentle slopes (0–5°) were prioritized for their ease of access and stability.

4.6.5 Road Network Proximity Suitability

Proximity to road networks influences logistical efficiency, hive maintenance, and honey harvesting (Gupta, Rey, & Dobson, 2016). The following classification was suggested (Table 4.7):

Distance to Road (m)	Suitability Class
> 5000	Not Suitable
3000 – 5000	Moderately Suitable
1000 – 3000	Suitable
< 1000	Highly Suitable

Table 4.8: Proximity to road network thresholds (based on literature)

Closer proximity to roads was considered favorable, reducing operational costs and enhancing emergency access.

4.6.6 Settlement Proximity Suitability

While proximity to settlements can facilitate access to markets, very close proximity may expose hives to pollution, pesticide application, and human disturbance. The following classification was suggested (Table 4.8):

Distance to Settlement (m)	Suitability Class
< 500	Not Suitable
500 – 1500	Moderately Suitable
1500 – 3000	Suitable
> 3000	Highly Suitable

Table 4.9: Distance from settlements thresholds (based on literature)

Maintaining a buffer zone (>3000 meters) from densely populated areas was prioritized for optimal hive health.

4.6.7 Reclassification in QGIS

The reclassification process was implemented in QGIS using the “Raster Calculator” and “Reclassify by Table” tool. Each raster layer was transformed from continuous values to integer-coded classes (e.g., 1: Not Suitable, 2: Moderately Suitable, etc.). This approach ensures compatibility with the subsequent weighted overlay analysis, where categorical integer

rasters are multiplied by respective weights and summed to derive the final suitability surface (Longley et al., 2015). All reclassified rasters were carefully checked through visual inspection and histogram analysis to ensure the correctness of class assignments.

4.7 Weighted Overlay Analysis

The weighted overlay method is one of the most widely used techniques in GIS-based multi-criteria decision analysis (GIS-MCDA) for combining multiple layers of spatial information into a single composite index (Malczewski, 1999). It enables the integration of diverse datasets by assigning a relative importance (weight) to each criterion based on decision-makers' preferences or objective analyses, such as the Analytic Hierarchy Process (AHP). In the context of beekeeping suitability modeling, the weighted overlay approach was utilized to synthesize the standardized thematic layers—each representing a different environmental or infrastructural criterion—into a final suitability map.

4.7.1 Conceptual Framework

Weighted overlay analysis is grounded on the principle of linear combination, where each input raster layer is multiplied by its assigned weight, and the results are summed to produce a final composite raster (Eastman, 1999; Malczewski, 2006).

Mathematically, the weighted overlay formula can be expressed as:

$$S = \sum_{i=1}^{n} (wi \times ri)$$

where S is the final suitability score, n is the number of criteria, w_i is the weight assigned to criterion i (derived from AHP) and r_i is the reclassified raster value for criterion i. This approach assumes a compensatory model, meaning that a lower score in one criterion can be compensated by a higher score in another, reflecting the trade-offs inherent in many real-world decisions (Store & Kangas, 2001).

4.7.2 Implementation in the Current Study

Following the reclassification of the individual criteria into four standardized classes (1: Not Suitable, 2: Moderately Suitable, 3: Suitable, 4: Highly Suitable), and the determination of criterion weights via AHP, the weighted overlay was conducted in QGIS.

There were three basic steps that were followed. Firstly, the multiplication of each criterion raster by its AHP-derived weight. Each pixel value (corresponding to a suitability class) was multiplied by the weight assigned to that particular criterion. Secondly, the summation of the weighted layers. The resulting rasters were summed on a pixel-by-pixel basis to generate a continuous surface of composite suitability scores. Finally, the normalization of the final suitability map. To facilitate interpretation, the resulting composite scores were normalized on a scale (e.g., 0–1 or 1–4) using linear transformation techniques. The process was performed using the Raster Calculator tool in QGIS, allowing the specification of complex mathematical

expressions and the direct combination of raster layers. The general raster calculator expression was structured as:

$$\text{Suitability} = (w_{\text{Temp}} \times \text{Temperature Raster}) + (w_{\text{Veg}} \times \text{NDVI Raster}) + (w_{\text{Slope}} \times \text{Slope Raster}) + (w_{\text{Roads}} \times \text{Road Network Raster}) + (w_{\text{Settlements}} \times \text{Settlements Raster})$$

where each variable represents the respective weighted thematic raster layer.

4.7.3 Advantages of Weighted Overlay

Weighted overlay analysis offers several advantages in suitability modeling. First, the flexibility which allows different types of data (continuous, categorical) to be harmonized within a common decision-making framework (Jankowski, 1995). Moreover, the transparency where weights and classifications are explicitly defined, allowing reproducibility and sensitivity analysis. Simplicity, which is about the linear combination method, is computationally straightforward and easily implemented in most GIS platforms. Because of these advantages, weighted overlay remains a staple method for land suitability assessments, environmental planning, and resource management studies (Feizizadeh & Blaschke, 2013).

4.7.4 Limitations

However, weighted overlay is not without limitations. Some several compensatory assumptions are needed. Extremely poor performance in one criterion can be masked by good performance in others, potentially leading to unrealistic conclusions in some contexts (Eastman, 1999). Furthermore, subjectivity is about the determination of weights, even when using AHP, involves a degree of expert judgment, which may introduce bias. However, subjects that refer to the real world may not always behave linearly. This may cause some complex interactions among factors. To mitigate these limitations, it is recommended to conduct sensitivity analyses by varying weights and assessing the stability of the final results (Feizizadeh & Blaschke, 2013).

5. Case Study: Aitoloakarnania

5.1 Introduction

This chapter presents the application of the methodology described in Chapter 4 within the Regional Unit of Aitoloakarnania, Greece. The aim is to identify and map the most suitable areas for beekeeping using a GIS-based multi-criteria evaluation framework.

Aitoloakarnania was selected as the case study due to its diverse landscape, significant agricultural activity, and long-standing beekeeping tradition. Through the integration of remote sensing, spatial analysis, and decision-support techniques, this case study illustrates the effectiveness of geospatial technologies in supporting sustainable apiculture planning.

This case study applies AHP to determine the most suitable areas for beekeeping in the Regional Unit of Aitoloakarnania, Greece. It also integrates multiple criteria, including vegetation, slope, temperature, proximity to road network, and distance from settlements, to generate suitability maps that facilitate decision-making. The outcome of the study is a composite beekeeping suitability map, derived from the weighted overlay of individual criteria layers in a Geographic Information System (GIS).

5.2 Study Area

Aitoloakarnania is the largest (in area) Regional Unit in Greece, located in the western part of the country, covering approximately 5.461 km² (546.100 ha). It is characterized by diverse topography, including mountains, valleys, wetlands, and coastal areas. The climate of Aitoloakarnania is Mediterranean, with hot, dry summers and mild, wet winters—a climatic pattern that significantly influences beekeeping potential.

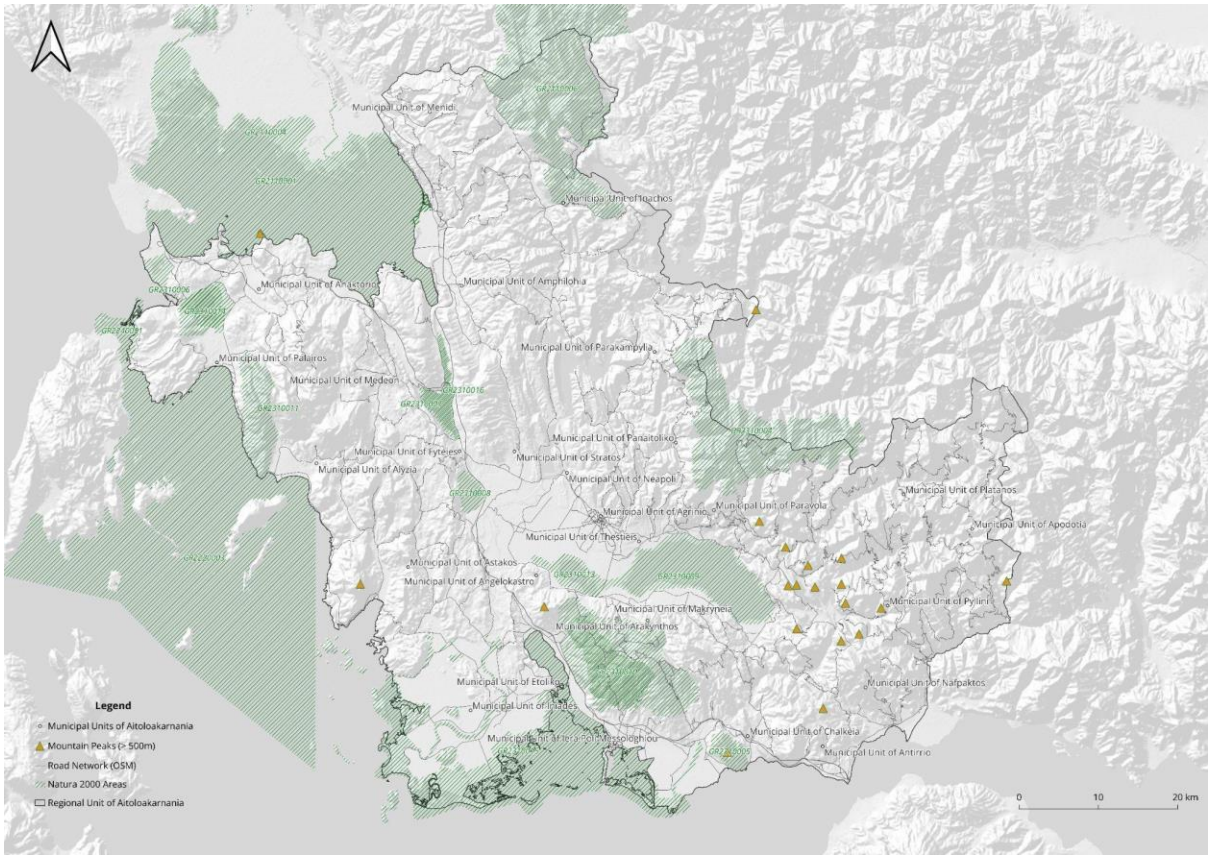


Figure 5.1: Study area map

Beekeeping is an integral part of the local economy, with abundant floral resources supporting honeybee populations. Key plant species include thyme (Thymus capitatus), oak (Quercus spp.), chestnut (Castanea sativa), and citrus trees, all of which are highly beneficial for honey production (Kasiotis, 2017). However, land use changes, urban expansion, and climate variability pose challenges to sustainable beekeeping. Thus, a systematic approach is necessary to identify optimal locations for apiary sites, ensuring both productivity and sustainability.

5.3 Objectives and Purpose

The core objective of this case study is to evaluate and map the spatial suitability for beekeeping across the Regional Unit of Aetoloakarnania using a geospatial multi-criteria decision-making framework and finally to create a modern and friendly tool with official data for crucial criteria that affect apiculture. Hence, each beekeeper would be able to select an area for beekeeping depending on the criteria analysis. Specifically, the analysis seeks to:

1. **Integrate diverse geospatial datasets**—including satellite imagery, elevation models, and infrastructure networks—within a unified GIS environment;

2. **Quantify and spatially represent** key environmental and infrastructural factors that influence apiculture suitability;

3. **Apply the Analytic Hierarchy Process (AHP)** to derive relative weights for each criterion based on expert-informed pairwise comparisons;

4. **Perform a consistency check (CI and CR)** to validate the AHP-derived weights;

5. **Generate thematic raster layers** for each criterion, reclassified into suitability classes;

6. **Execute a weighted overlay analysis** to produce a final composite suitability map;

7. **Visualize the results in both static and web-based formats**, providing a useful decision-support tool for apiculture stakeholders, including land planners, local authorities, and beekeepers.

This tool will be a web-based cartographic application that will include various basemaps, the boundaries of the study area, important data such as road network and settlements as well as five (5) different scenarios. These five scenarios will constitute equal different weight distributions for the AHP, which will result in five different suitability maps. Each of them will be based on statistical standards and will be complied with the mandatory statistical tests that will confirm the validity of the weights (e.g. CR, CI).

Through this application, the study aims to demonstrate the practical relevance of geoinformatics tools in sustainable rural planning, and to support the strategic siting of new apiaries in a scientifically defensible and spatially explicit manner.

5.4 Application of the Methodology

This section details the step-by-step implementation of the methodology developed in Chapter 4, specifically as applied to the region of Aitoloakarnania. All processes were carried out within QGIS 3.34, complemented by relevant plugins and processing tools.

5.4.1 Data Preparation

a. Overview of Data Requirements

The dataset preparation focused on acquiring spatial layers corresponding to five core criteria that influence beekeeping suitability:

- **Temperature** (as Land Surface Temperature),

- **Vegetation** (as NDVI),

- **Slope** (derived from a DEM),

- **Proximity to road network**,
- **Distance from Settlements**

Each layer would eventually be processed, standardized, and integrated into the overall weighted overlay model.

b. Data Sources and Acquisition

All datasets were sourced from credible national or international platforms that provide open-access geospatial information. The datasets and their respective sources are summarized below:

Sentinel 2 and MODIS. Sentinel-2 Level-2A imagery was used to compute the Normalized Difference Vegetation Index (NDVI) by utilizing Bands 8 (NIR) and 4 (Red) at a 10-meter resolution. This dataset was accessed through the Copernicus Open Access Hub and processed in QGIS. For Land Surface Temperature (LST), data from MODIS MOD11A1 daily products were used, offering surface temperature estimates at 1 km spatial resolution. The LST layer was reprojected to ETRS89 / GGRS87 and resampled to 10 meters using bilinear interpolation, in order to match the spatial resolution of other criteria layers. Both indices were harmonized into the project's spatial framework and exported as GeoTIFF files for reclassification and analysis (figure 5.2).

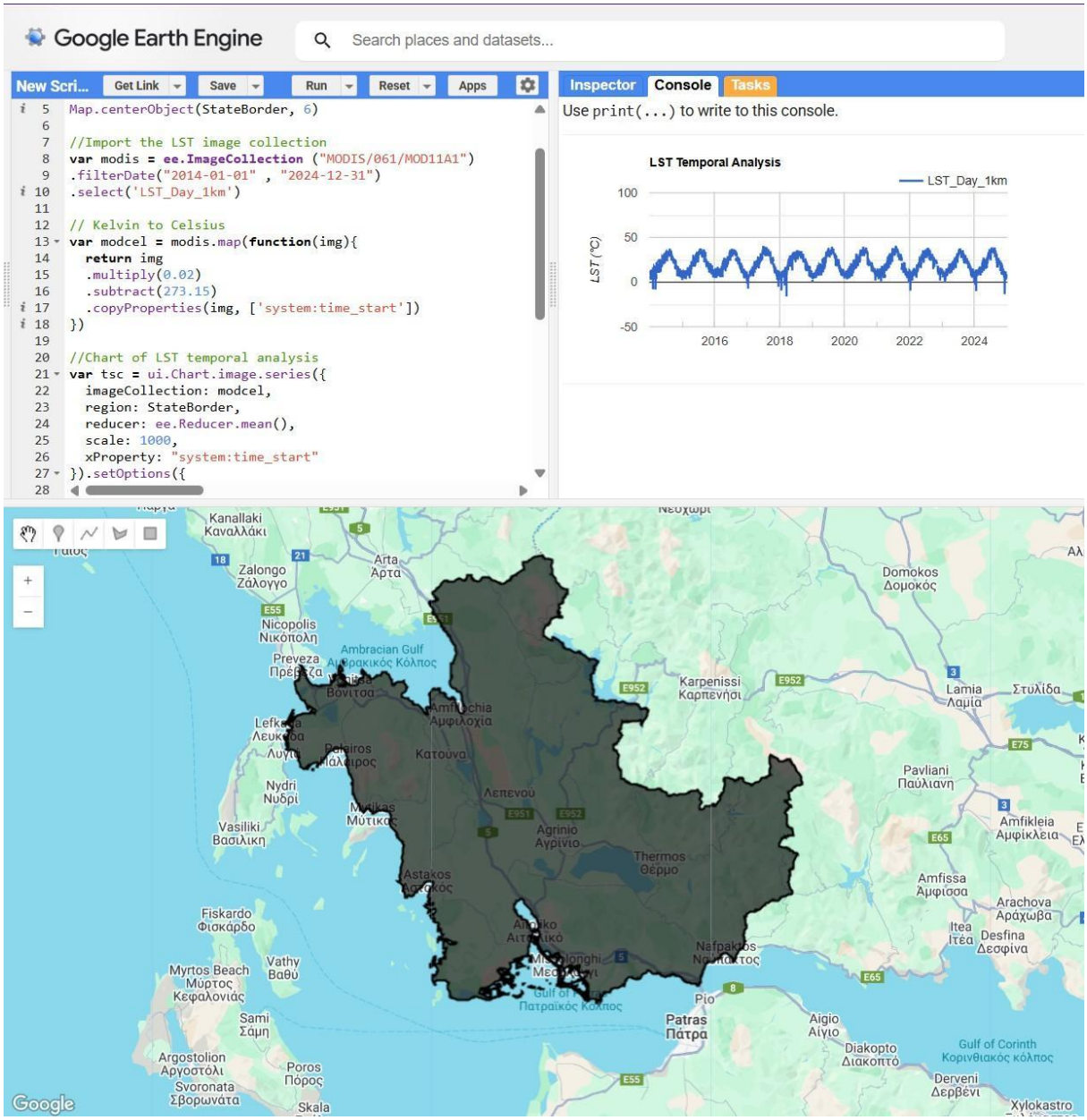


Figure 5.2: LST script inside the Google Earth Engine (GEE) environment

Digital Elevation Model (DEM). A 30-meter resolution elevation dataset was downloaded from the SRTM (Shuttle Radar Topography Mission). This DEM was used to derive the slope of the terrain using terrain analysis tools in QGIS (figure 5.3).

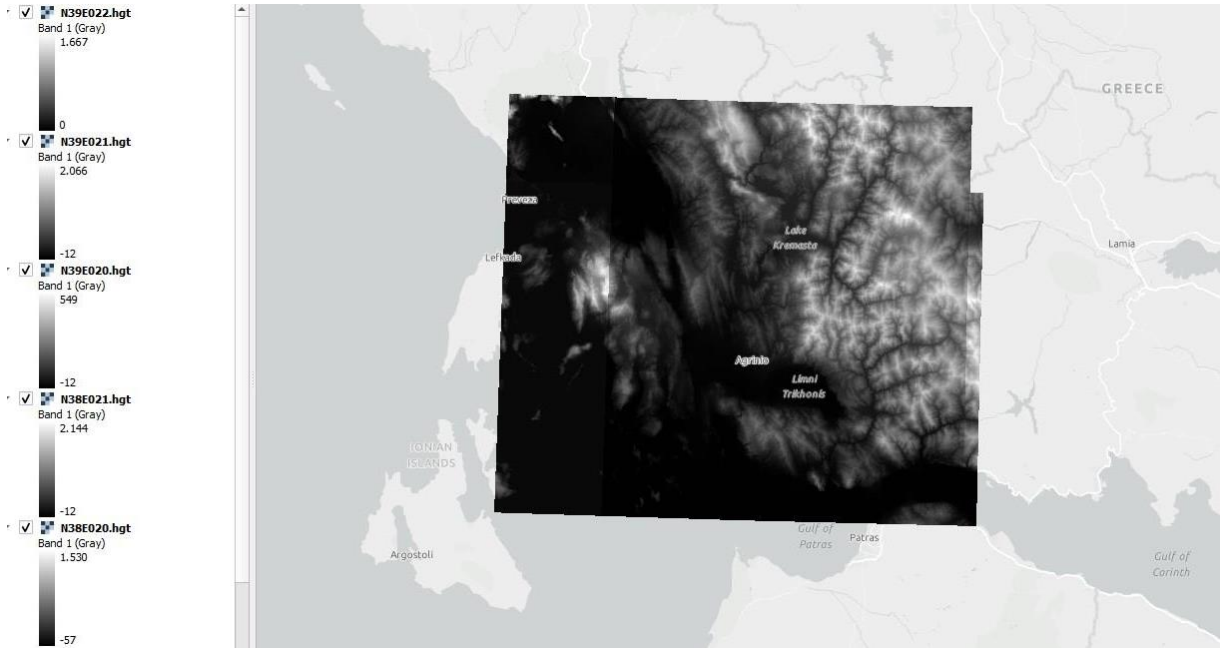


Figure 5.3: Satellite images inside QGIS environment

Road Network (Vector). Road network data was acquired from OpenStreetMap (OSM) through the QuickOSM plugin in QGIS. The final data was about only major road types relevant to beekeeping access. The network was filtered to retain only major road types relevant to beekeeping access. These types were: motorways, primary, secondary, tertiary, and service roads (figure 5.4).



Figure 5.4: Road network shapefile inside QGIS environment

Settlements (Vector). Settlement data was retrieved from the Hellenic National Geospatial Infrastructure (HELIX) portal (https://geodata.gov.gr/), the official open data platform for Greek public sector geospatial information. The specific dataset used was published by the Hellenic Statistical Authority (ELSTAT) and includes geometries and names of populated areas in vector format (shapefiles) (figure 5.5).

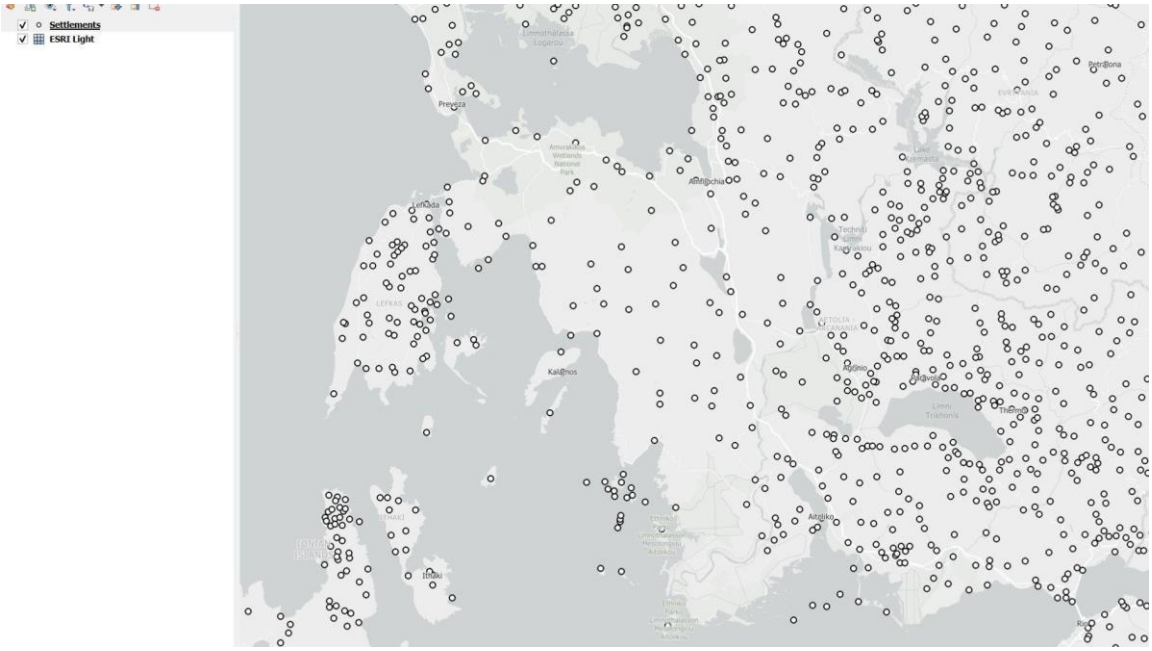


Figure 5.5: Greek settlements shapefile inside QGIS environment

Administrative Boundaries. The regional boundary of Aitoloakarnania was obtained from official Greek open data sources and was used to clip and standardize the spatial extent of all analysis layers (figure 5.6).



Figure 5.6: Aitoloakarnania boundary inside QGIS environment

c. Projection and Coordinate System Alignment

To ensure spatial consistency and compatibility in calculations, all layers were reprojected into the **Greek national coordinate system (ETRS89 / GGRS87 - EPSG:2100)**. This projection is commonly used in Greek geospatial analysis and supports accurate distance and area computations. The reprojection was performed using QGIS's **"Reproject Layer"** tool, ensuring all subsequent analyses occurred within a unified reference frame (figure 5.7).

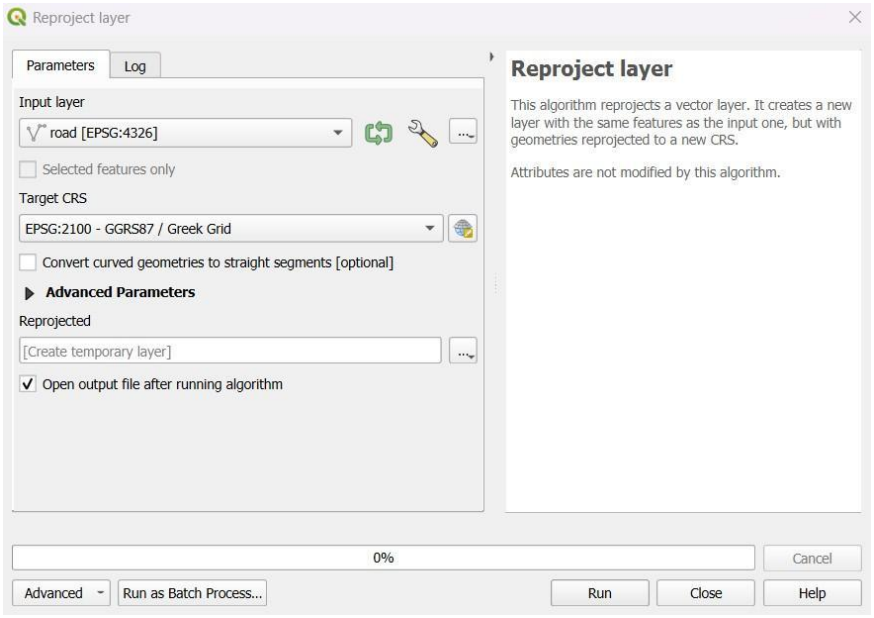


Figure 5.7: Raster reprojection from WGS84 to GGRS87 (Reproject Layer)

d. Spatial Clipping to Study Area

Following projection, all raster and vector layers were clipped to the boundary of Aetoloakarnania using the **"Clip Raster by Mask Layer"** and **"Clip Vector by Polygon"** tools in QGIS. This ensured that no irrelevant data outside the study area would affect calculations or increase processing time (figure 5.8).

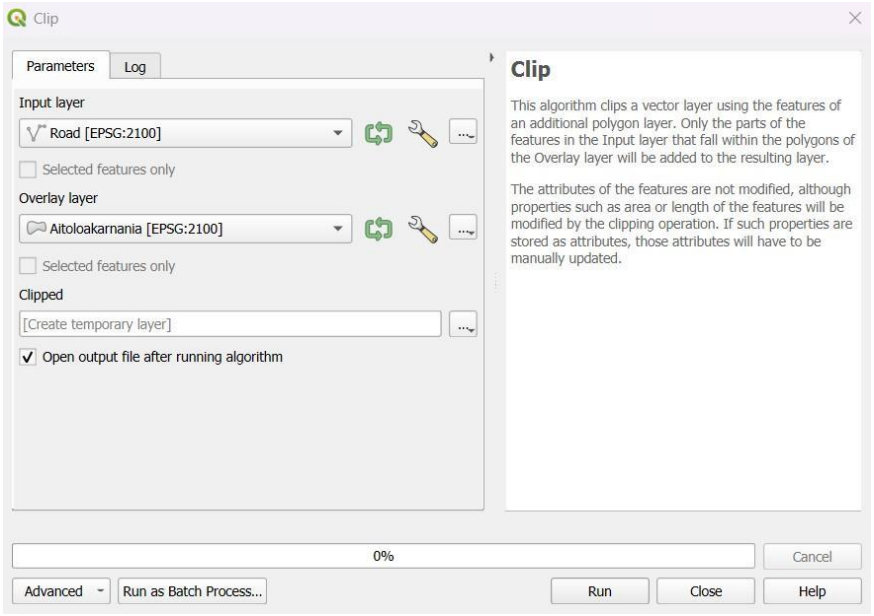


Figure 5.8: Aitoloakarnania road network (Clip)

e. Resampling and Raster Alignment

As datasets were originally at different spatial resolutions (e.g., DEM at 30 m, vector data at varying scales), all raster layers were resampled to a **uniform spatial resolution of 10 meters**. The **"Align Rasters"** tool was used to ensure identical extent, resolution, and pixel alignment across all raster layers (figure 5.9).

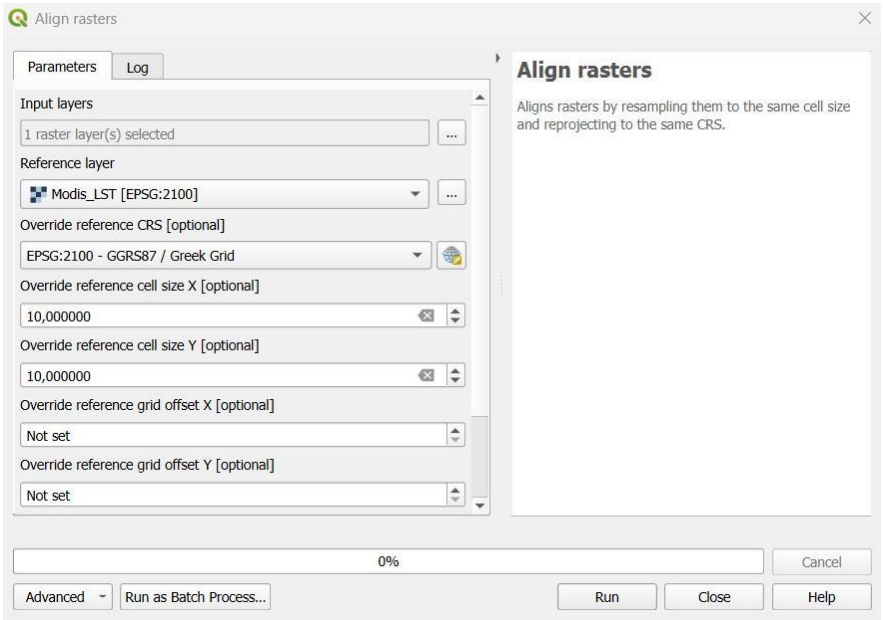


Figure 5.9: Layer Resampling

For continuous data such as LST, NDVI, and slope, **bilinear interpolation** was selected during resampling to preserve value gradients. For categorical data such as the proximity rasters (road

and settlements), **nearest neighbor** interpolation was applied to preserve discrete class boundaries.

f. Preliminary Quality Control

Before moving to the analytical stages, each dataset was visually inspected for anomalies (e.g., data gaps, cloud cover, extreme values) and validated statistically. The **"Layer Properties" → "Histogram"** panel in QGIS was used to verify data distributions, while the **"Identify Features"** tool was used for spot-checking pixel values. Problematic areas (e.g., NoData zones or cloud-covered pixels) were masked or excluded using conditional logic in the Raster Calculator.

5.4.2 Raster Reclassification

Following the pre-processing in QGIS had been carried out and the data was ready to a first level, the rasters for each criterion were created based on the thresholds defined by the literature and empirical studies.

Each raster was reclassified into four **ordinal suitability classes**, based on literature-informed thresholds and expert knowledge from beekeepers. The classes (table 5.1) were:

Suitability Class	Description	Raster Value
Highly Suitable	Ideal conditions	4
Suitable	Favorable conditions	3
Moderately Suitable	Acceptable conditions	2
Not Suitable	Unsuitable conditions	1

Table 5.1: Beekeeping suitability classes

Vegetation Index (Vegetation)

NDVI was derived from Sentinel bands using the standard formula as it was discussed in the previous subchapters. The result was a continuous raster indicating vegetation density. Then based on specific thresholds that were sourced from scientific studies literature and empirical knowledge, the NDVI raster had been reclassified into suitability classes using the following syntax in the raster calculator in QGIS:

("NDVI@1" < 0.2) * 1 +

(("NDVI@1" >= 0.2) AND ("NDVI@1" < 0.4)) * 2 +

(("NDVI@1" >= 0.4) AND ("NDVI@1" < 0.6)) * 3 +

("NDVI@1" >= 0.6) * 4

Thus, the reclassified NDVI raster file was divided into 4 suitability classes as illustrated below (figure 5.10).

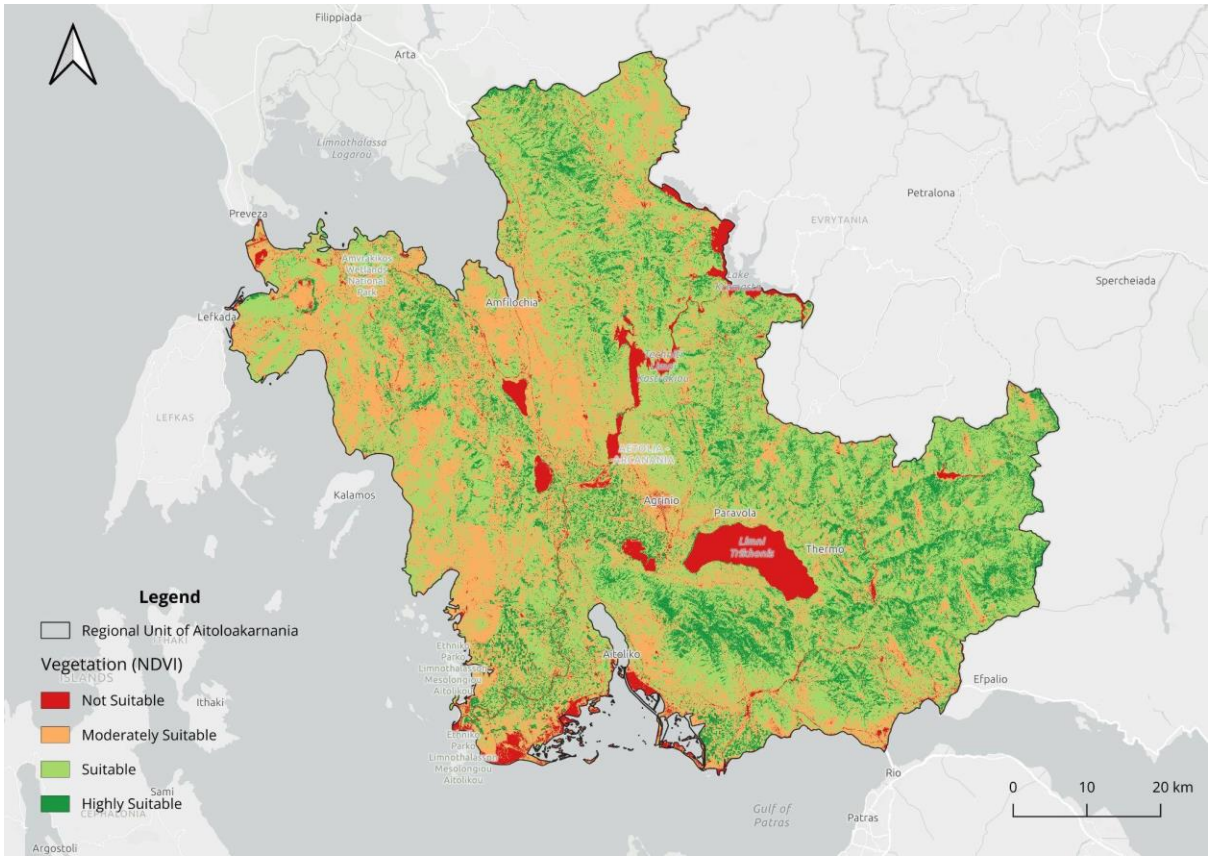


Figure 5.10: *Study area reclassified into suitability classes based on NDVI thresholds*

Slope

Slope was derived from the Digital Elevation Model. Thresholds were set in order to reclassify the entire raster into 4 suitability classes based on the degrees of the slope. In order to reclassify the original slope raster, the following syntax was implemented through raster calculator:

("slope@1" <= 5) * 4 +

(("slope@1" > 5) AND ("slope@1" <= 10)) * 3 +

(("slope@1" > 10) AND ("slope@1" <= 20)) * 2 +

("slope@1" > 20) * 1

The new reclassified raster for the slope criterion is being illustrated below (figure 5.11)

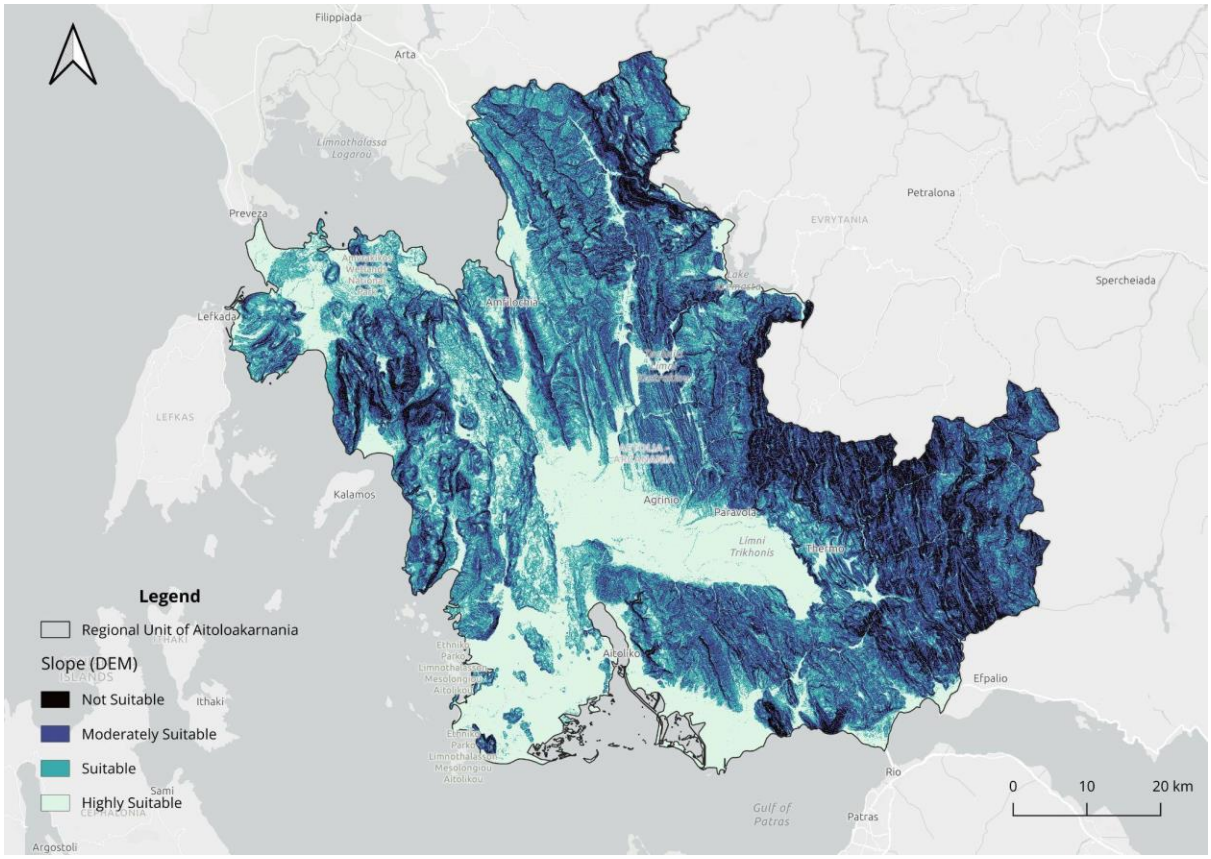


Figure 5.11: *S*tudy area reclassified into suitability classes based on Slope thresholds

Land Surface Temperature (Temperature)

Land Surface Temperature (LST) was derived from the MODIS satellite imagery. The final product was reprojected to the Greek grid and resampled from its original 1 km resolution to **10 meters** using bilinear interpolation to match the resolution of the other layers. This raster was loaded into QGIS and visualized to assess temperature ranges. The raster was classified into four temperature suitability classes using the "Raster Calculator", based on thresholds from literature and empirical knowledge:

("LST@1" < 18) AND ("LST@1" > 29,7) * 1 +

(("LST@1" >= 18) AND ("LST@1" < 22)) * 2 +

(("LST@1" >= 22) AND ("LST@1" <= 25)) * 4 +

("LST@1" > 25) AND ("LST@1" < 29,7) * 3

The figure 5.12 is presenting the result of the raster calculator procedure.

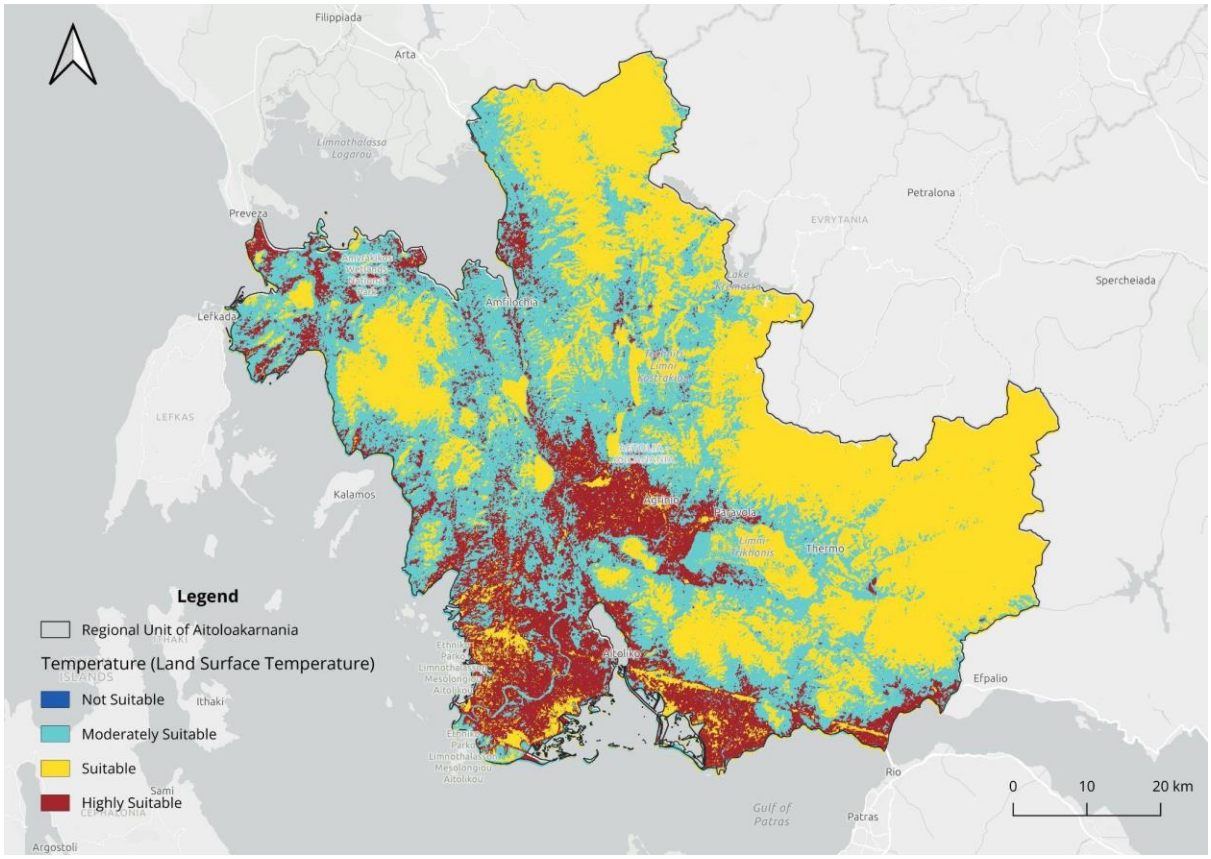


Figure 5.12: *S*tudy area reclassified into suitability classes based on LST thresholds

Proximity to Road Network (Road Network)

Road Network data were obtained from OpenStreetMap and were converted to raster using the "Rasterize (Vector to Raster)" tool. The "Proximity (Raster Distance)" tool then generated a continuous raster of distances to the nearest road. The reclassification was based on practical access considerations, which were applied in the raster calculator with the following syntax:

("dist_roads@1" < 1000) * 4 +

(("dist_roads@1" >= 1000) AND ("dist_roads@1" < 3000)) * 3 +

(("dist_roads@1" >= 3000) AND ("dist_roads@1" < 5000)) * 2 +

("dist_roads@1" >= 5000) * 1

The final reclassified raster for the proximity to road network is being presented below (figure 5.13)

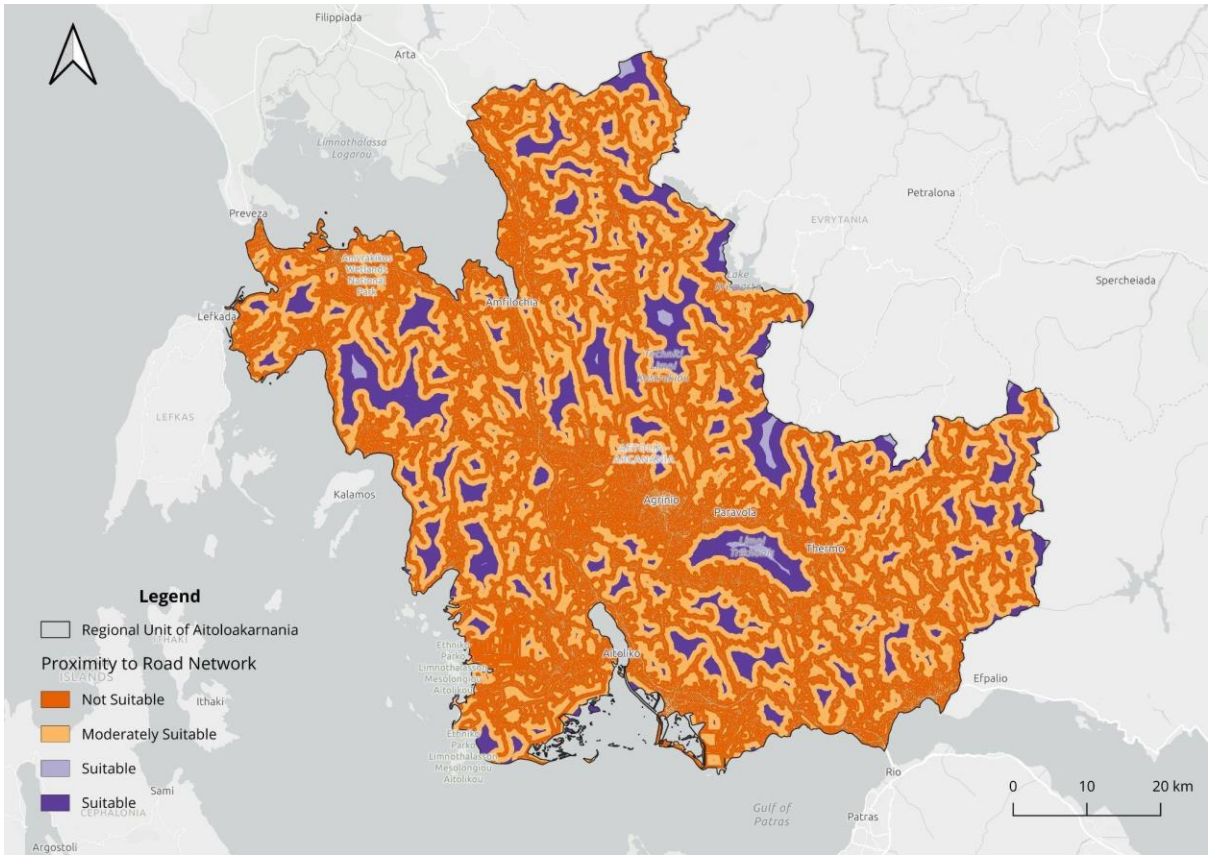


Figure 5.13: *Study area reclassified into suitability classes based on proximity to road network thresholds*

Distance from Settlements (Settlements)

The vector data for the settlements of Aitoloakarnania were obtained from the Hellenic Data Service Infrastructure (HELIX) and were rasterized in order to be subjected to raster analysis. Following the rasterization, thresholds were set in order to reclassify the produced raster from settlements:

("dist_settlements@1" < 500) * 1 +

(("dist_settlements@1" >= 500) AND ("dist_settlements@1" < 1500)) * 2 +

(("dist_settlements@1" >= 1500) AND ("dist_settlements@1" < 3000)) * 3 +

("dist_settlements@1" >= 3000) * 4

Finally, the new reclassified raster is being illustrated below (figure 5.14)

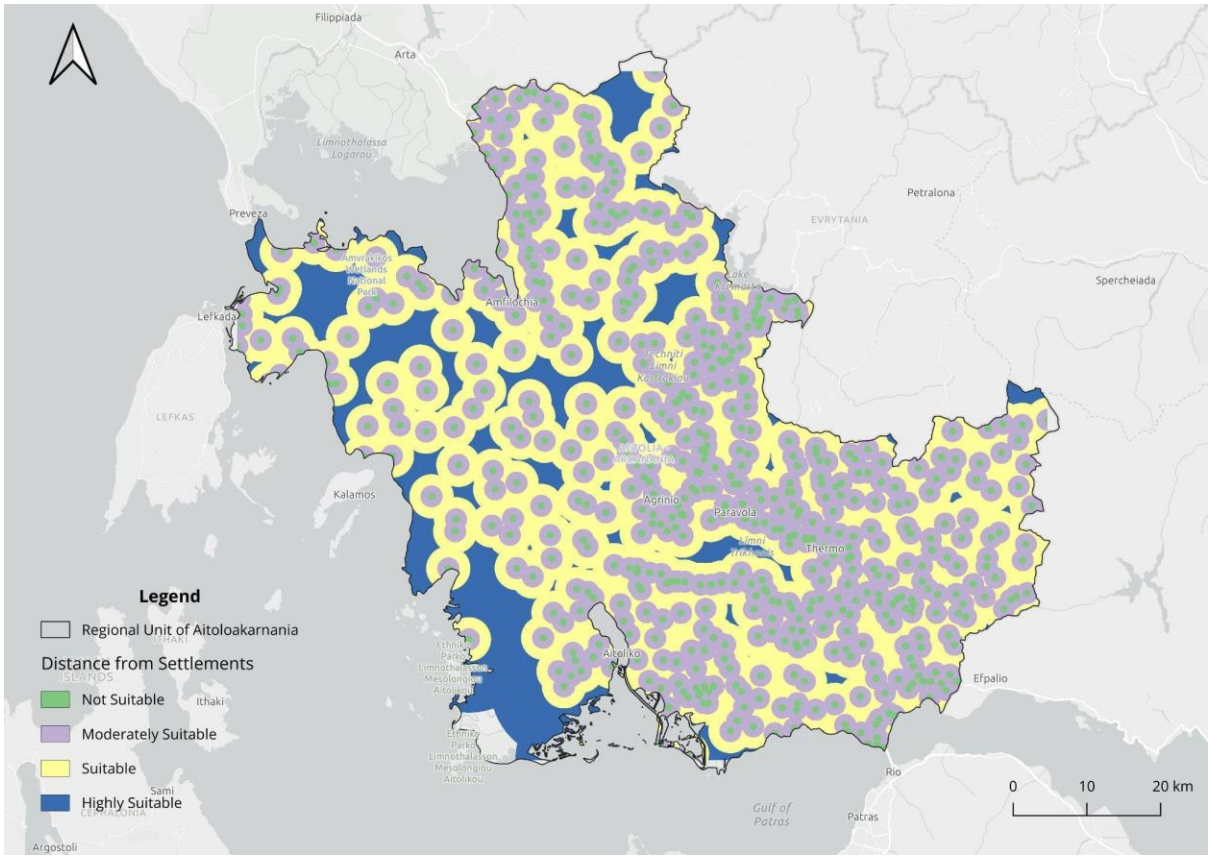


Figure 5.14: *S*tudy area reclassified into suitability classes based on distance from settlements thresholds

5.4.3 AHP Weight Calculation

5.4.3.1 Introduction to AHP

The process of combining multiple criteria in a weighted overlay model requires a clear, structured approach to assign relative importance to each factor. To achieve this, the Analytic Hierarchy Process (AHP) was applied, as it offers a systematic and mathematically sound method for deriving weights through pairwise comparisons (Saaty, 1980). The main advantage of AHP lies in its ability to transform qualitative expert judgment into quantitative weights that can be directly applied in GIS-based models.

5.4.3.2 Original Scenario

The **original scenario** represents the baseline for evaluating beekeeping suitability in Aitoloakarnania and reflects a **balanced decision-making approach** based on ecological and operational criteria. In this model, **vegetation** and **slope** were judged to be the most influential factors, as they directly affect floral resources, hive placement, and terrain accessibility. **Temperature**, while still important, was ranked slightly lower, while **proximity to both roads and settlements** were considered less critical from an ecological standpoint.

Pairwise Comparison Matrix

To capture these priorities, a full **pairwise comparison matrix** was constructed (table 5.2) using the Saaty scale. Expert judgment and literature were used to guide each comparison, and the reciprocal rule was applied where applicable.

Criteria	Temperature	Vegetation	Slope	Roads	Settlements
Temperature	1	1/3	1/2	2	2
Vegetation	3	1	2	5	5
Slope	2	1/2	1	3	3
Road Network	1/2	1/5	1/3	1	1
Settlements	1/2	1/5	1/3	1	1

Table 5.2*:* Pairwise comparison matrix for the original scenario

Matrix Normalization and Weight Calculation

Then the table with the column sums for each criterion was generated (table 5.3)

Criteria	Temperature	Vegetation	Slope	Roads	Settlements
Column Sum	7.00	2.38	4.16	12.00	12.00

Table 5.3*:* Column Sums for each Criterion (Original Scenario)

Each element of the matrix was divided by the total of its column to create a normalized matrix. The **priority vector** (weight) was then calculated by averaging the values across each row (table 5.4).

Criteria	Temperature	Vegetation	Slope	Roads	Settlements	Row Average (Weight)
Temperature	0.143	0.140	0.120	0.167	0.167	**0.147**
Vegetation	0.429	0.420	0.481	0.417	0.417	**0.433**
Slope	0.286	0.210	0.240	0.250	0.250	**0.247**

Road Network	0.071	0.084	0.080	0.083	0.083	**0.080**
Settlements	0.071	0.084	0.080	0.083	0.083	**0.080**

Table 5.4*:* Normalized matrix and calculated weights (Original Scenario)

Consistency Validation

To ensure that the matrix is logically consistent, the **Consistency Index (CI)** and **Consistency Ratio (CR)** were computed.

a) Weighted Sum Vector

Each criterion row in the original matrix was multiplied by the priority vector, and the resulting values were summed. Then, each weighted sum was divided by its respective weight (table 5.5)

Criterion	Weighted Sum	WS / Weight
Temperature	0.744	0.744 / 0.147 ≈ **5.06**
Vegetation	2.198	2.198 / 0.433 ≈ **5.08**
Slope	1.252	1.252 / 0.247 ≈ **5.07**
Road Network	0.403	0.403 / 0.080 ≈ **5.04**
Settlements	0.403	0.403 / 0.080 ≈ **5.04**

Table 5.5: Weighted sum vector for each criterion (Original Scenario)

λ_{max} = (5.06+5.08+5.07+5.04+5.04) / 5=5.058

b) Consistency Index (CI)

CI = λ_{max}−n / n−1 = 5.058 - 5 / 4 = 0.0145

c) Consistency Ratio (CR)

Using the Random Index (RI) for n=5

RI = 1.12
CR = RI / CI = 0.0145 / 1.12 = 0.013

Since **CR < 0.10**, the matrix is considered **acceptably consistent**, and the derived weights are valid for decision-making purposes (Table 5.6).

Criterion	Final Weights	Final Weights (Rounded)
Vegetation	0.433	0.40
Slope	0.247	0.25
Temperature	0.147	0.15
Road Network	0.080	0.10
Settlements	0.080	0.10

Table 5.6*:* Final Weights for the Original Scenario

These weights were later used in the **weighted overlay operation** within QGIS to generate the primary suitability map for the original scenario, which aims to balance ecological quality and operational feasibility.

5.4.3.3 Alternative Scenario 1

The first alternative scenario was developed to represent beekeeping suitability with an emphasis on **climatic factors**, particularly **temperature**. This perspective is relevant in cases where apiaries operate at elevations or during periods when thermal comfort is critical for bee survival and honey production. To apply the AHP method consistently across all scenarios, a separate pairwise comparison matrix was created to reflect this thematic focus.

Pairwise Comparison Matrix

In this scenario, **temperature** was judged the most critical factor, rated more important than all others. **Vegetation** was considered moderately important. **Slope**, **road accessibility**, and **distance from settlements** were included but rated as less critical (table 5.7).

Criteria	Temperature	Vegetation	Slope	Roads	Settlements
Temperature	1	3	4	6	6
Vegetation	1/3	1	2	4	4
Slope	1/4	1/2	1	3	3
Roads	1/6	1/4	1/3	1	2

Settlements	1/6	1/4	1/3	1/2	1

Table 5.7*:* Pairwise comparison matrix for Alternative Scenario 1

Matrix Normalization and Weight Calculation

First, the column totals were calculated (Table 5.8).

Criteria	**Temperature**	**Vegetation**	**Slope**	**Roads**	**Settlements**
Column Sum	1.91	5.00	7.67	14.50	16.00

Table 5.8: Column Sums for each Criterion (Alternative Scenario 1)

Each element of the matrix was then divided by its column total to normalize it. Row averages were calculated to produce the **priority vector (weights)** (table 5.9).

Criteria	**Temperature**	**Vegetation**	**Slope**	**Roads**	**Settlements**	**Row Average (Weight)**
Temperature	0.524	0.600	0.521	0.414	0.375	**0.487**
Vegetation	0.175	0.200	0.261	0.276	0.250	**0.232**
Slope	0.131	0.100	0.130	0.207	0.188	**0.151**
Roads	0.087	0.050	0.043	0.069	0.125	**0.075**
Settlements	0.087	0.050	0.043	0.034	0.063	**0.055**

Table 5.9*:* Normalized matrix and derived weights (Alternative Scenario 1)

Consistency Validation

a) Weighted Sum Vector

Each original matrix row was multiplied by the final weights vector, then the row sum was divided by the corresponding weight (table 5.10)

Criteria	**Weighted Sum**	**WS / Weight**
Temperature	2.418	2.418 / 0.487 ≈ **4.97**

Vegetation	1.164	1.164 / 0.232 ≈ **5.02**
Slope	0.761	0.761 / 0.151 ≈ **5.04**
Roads	0.370	0.370 / 0.075 ≈ **4.93**
Settlements	0.274	0.274 / 0.055 ≈ **4.98**

Table 5.10: Weighted sum vector for each criterion (Alternative Scenario 1)

λ_{max} = 4.97 + 5.02 + 5.04 + 4.93 + 4.98 / 5 =4.988

b) Consistency Index (CI)

CI = λ_{max} −n / n−1 = 4.988−5 / 4= − 0.003

Since CI is slightly negative due to rounding (interpreted as 0), and:

c) Consistency Ratio (CR)

CR = CI / RI = 0 / 1.12 = 0

The matrix is considered **fully consistent**. Hence, the final weights following below (table 5.11).

Criterion	**Final Weights**	**Final Weights (Rounded)**
Temperature	0.487	0.45
Vegetation	0.232	0.25
Slope	0.151	0.15
Road Network	0.075	0.10
Settlements	0.055	0.05

Table 5.11: Final weights for Alternative Scenario 1

These weights were used in the raster overlay model within QGIS to generate a **temperature-prioritized suitability map**, suitable for guiding decisions in cooler microclimates or during thermally sensitive periods.

5.4.3.4 Alternative Scenario 2

The second alternative scenario was designed to reflect a beekeeping suitability perspective driven primarily by **infrastructure accessibility** and **logistical convenience**. This reflects situations where operational efficiency is prioritized — such as for commercial or migratory beekeeping — where ease of access to hives is essential for transportation, maintenance, or product collection.

In this scenario, **proximity to roads** and **distance from settlements** were considered the dominant criteria, while ecological characteristics like vegetation, slope, and temperature were rated with relatively less importance.

To maintain methodological consistency, a complete **pairwise comparison matrix** was developed and analyzed using the AHP approach (table 5.12).

Criteria	Temperature	Vegetation	Slope	Roads	Settlements
Temperature	1	1	1	1/4	1/4
Vegetation	1	1	1	1/4	1/4
Slope	1	1	1	1/4	1/4
Road Network	4	4	4	1	1
Settlements	4	4	4	1	1

Table 5.12: Pairwise comparison matrix for Alternative Scenario 2

Matrix Normalization and Weight Calculation

The column sums for each criterion were calculated below (table 5.13).

Criteria	Temperature	Vegetation	Slope	Roads	Settlements
Column Sum	11.0	11.0	11.0	2.75	2.75

Table 5.13: Column Sums for each criterion (Alternative Scenario 2)

Each value was divided by the corresponding column sum. The average of each row provided the final priority vector (table 5.14).

Criteria	Temperature	Vegetation	Slope	Roads	Settlements	Row Average (Weight)
Temperature	0.091	0.091	0.091	0.091	0.091	0.091
Vegetation	0.091	0.091	0.091	0.091	0.091	0.091
Slope	0.091	0.091	0.091	0.091	0.091	0.091
Road Network	0.364	0.364	0.364	0.364	0.364	0.364
Settlements	0.364	0.364	0.364	0.364	0.364	0.364

Table 5.14*:* Normalized matrix and calculated weights (Alternative Scenario 2)

Consistency Validation

a) Weighted Sum Vector

Each original matrix row was multiplied by the derived weight vector and summed (table 5.15).

Criterion	Weighted Sum	WS / Weight
Temperature	0.455	0.455 / 0.091 ≈ 5.00
Vegetation	0.455	0.455 / 0.091 ≈ 5.00
Slope	0.455	0.455 / 0.091 ≈ 5.00
Road Network	1.818	1.818 / 0.364 ≈ 5.00
Settlements	1.818	1.818 / 0.364 ≈ 5.00

Table 5.15: Weighted sum vector for each criterion (Alternative Scenario 2)

$\lambda_{max} = 5 + 5 + 5 + 5 + 5 / 5 = 5.00$

b) Consistency Index (CI)

$CI = 5-5 / 4 = 0 / 4 = 0$

c) Consistency Ratio (CR)

RI = 1.12 ⇒ CR= 0 /1.12 → CR = 0.00

Since **CR < 0.10**, the judgments are acceptably consistent. The final weights are following below (table 5.16)

Criterion	Final Weights (Rounded)
Vegetation	0.10
Slope	0.10
Temperature	0.10
Road Network	0.35
Settlements	0.35

Table 5.16: Final weights for Alternative Scenario 2

These weights were used in QGIS to produce a **suitability map prioritizing access** to infrastructure — ideal for professional beekeepers focused on transport logistics and routine hive access, particularly during periods of high activity.

5.4.3.5 Scenarios Comparison

Following the individual implementation of the Analytic Hierarchy Process (AHP) for each of the three suitability scenarios, a comparative summary is provided to highlight the differing strategic orientations and their influence on the final weight distributions. Each scenario refers to a different prioritization. The Original Scenario takes an ecologically balanced approach with an emphasis in vegetation and terrain slope. Alternative scenario 1 prioritizes climatic suitability, by giving much importance to temperature, which is crucial for bee survival and productivity. Alternative scenario 2 prioritizes logistics and transportation, giving the highest weight to accessibility — both in terms of road network proximity and distance from urban settlements based on the dangers involved. The following table summarizes the final weights assigned to each criterion across the three scenarios (table 5.17). Note that for purposes of convenience, the weights have been rounded off without affecting the quality of the results.

Criterion	Original Scenario	Alternative Scenario 1	Alternative Scenario 2

Vegetation	0.40	0.25	0.10
Slope	0.25	0.15	0.10
Temperature	0.15	0.45	0.10
Proximity to Road Network	0.10	0.10	0.35
Distance from Settlements	0.10	0.05	0.35

Table 5.17: Scenarios comparison table

Original Scenario: Ecological Suitability Prioritized

The original scenario reflects a balanced, ecology-centered perspective where vegetation (0.40) and terrain slope (0.25) are the most important factors. These criteria are related to the availability of floral resources and physical suitability for hive placement. These weights are ideal for locating beekeeping sites in areas like Aitoloakarnania, regardless of accessibility constraints. In terms of the planning perspective, it seems to be suitable for long-term, environmentally integrated beekeeping operations.

Alternative Scenario 1: Temperature-Focused Suitability

Alternative scenario 1 emphasizes thermal conditions by assigning half the total decision weight (0.45) to temperature (LST). Vegetation and slope remain important but are given reduced weights compared to the original scenario. The planning perspective seems suitable for climate-sensitive planning and aims at specific types of beekeeping.

Alternative Scenario 2: Accessibility-Focused Suitability

Alternative scenario 2 reverses the emphasis entirely, giving dominant weight to road proximity (0.35) and distance from settlements (0.35), while vegetation, slope, and temperature are all minimized to just 0.10 each. This scenario is ideal for commercial or mobile beekeeping operations where transport logistics and time is crucial. The planning perspective seems to prioritize ease of hive maintenance and proximity to service hubs.

5.4.4 Weighted Overlay Analysis

In 5.4.2, all five rasters of each criterion were reclassified into a standard scale from 1 to 4 based on their suitability for each criterion. Each final raster presented the suitability - as regards to each criterion - in Aitoloakarnania with 4 different colours based on their value (1 to 4). The final step in suitability analysis involved the combination of these 5 suitability maps-rasters. This process integrates the application of the weights (5.4.3) for each criterion and the

summary of all criteria together into one. This process concerns all the scenarios (Original and Alternative 1-2).

The weighted overlay was implemented in QGIS 3.34 using the "**Raster Calculator"**. The output for each scenario was a continuous raster surface where each pixel value represented a composite suitability score ranging from 1 (not suitable) to 4 (highly suitable), depending on the influence of each criterion.

For each one of the final three scenarios (Original and Alternative 1 & 2), a different set of weights was applied in order to produce the final suitability map in each occasion. The following figures (Figure 5.15-5.17) illustrate the expression that was used in QGIS Raster Calculator.

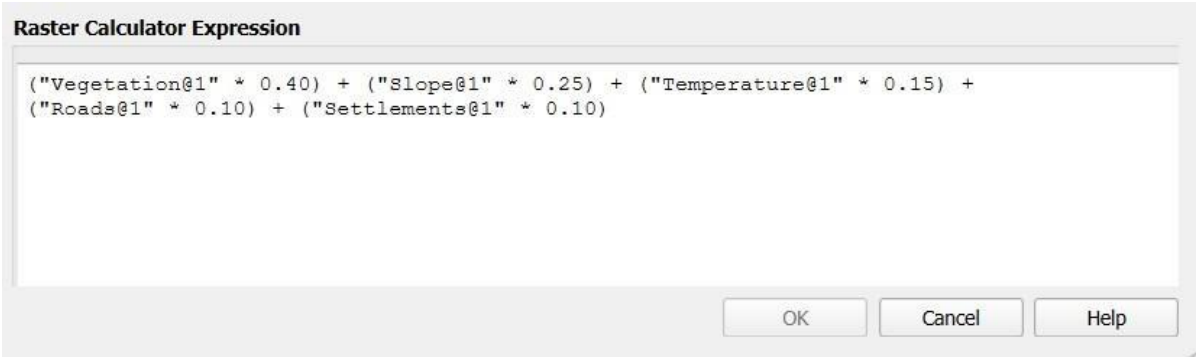


Figure 5.15: Raster Calculator Expression Original Scenario

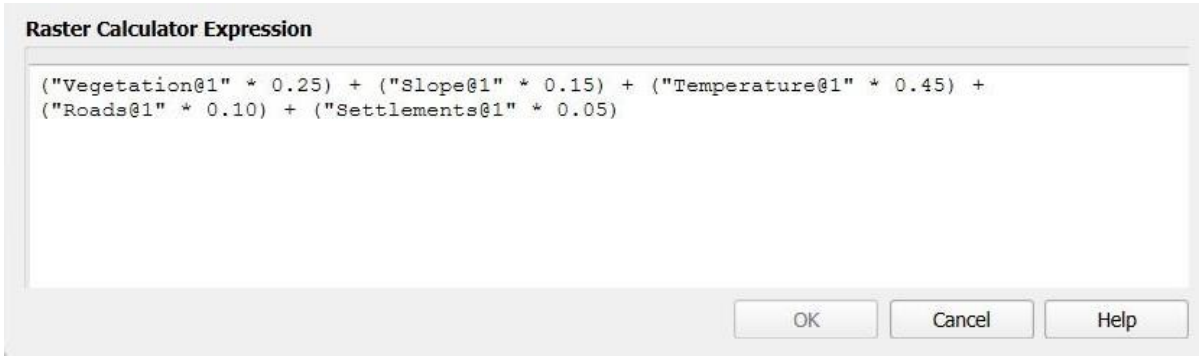


Figure 5.16: Raster Calculator Expression Alternative Scenario 1

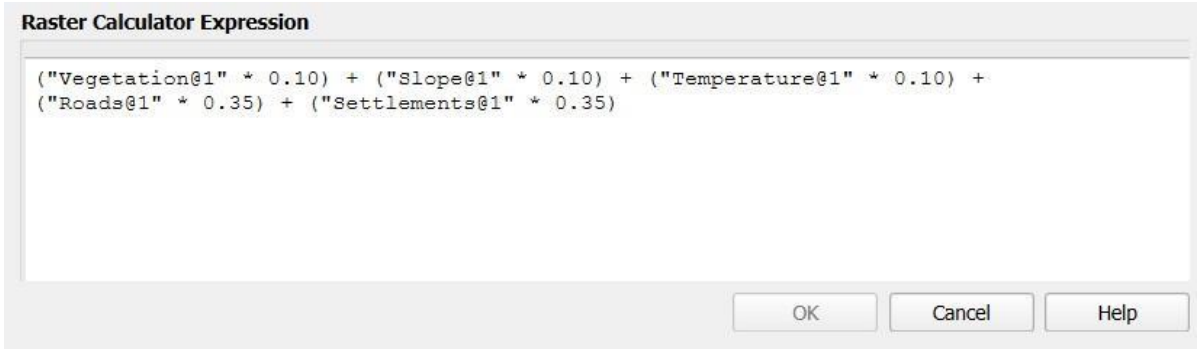


Figure 5.17: Raster Calculator Expression Alternative Scenario 2

A continuous raster was produced for each scenario, with decimal values ranging from 1 to 4, depending on how the scores and weights were combined. For visualisation purposes, a continuous symbol of the selected palette of ColorBrewer was chosen in order to gradually show the user the areas of suitability from the lowest to the highest and the prices in between. The produced final suitability rasters for each scenario are being illustrated below (figure 5.18-5.20).

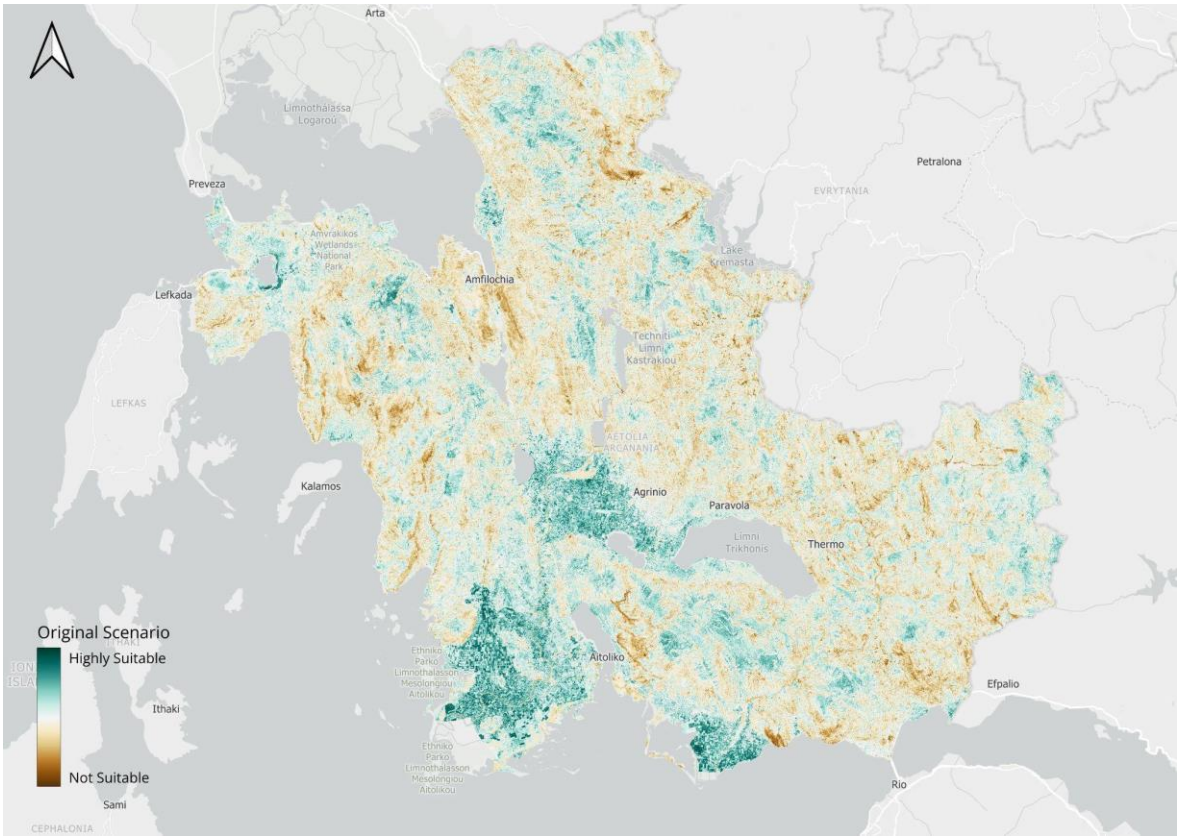


Figure 5.18: Original Scenario Final Map

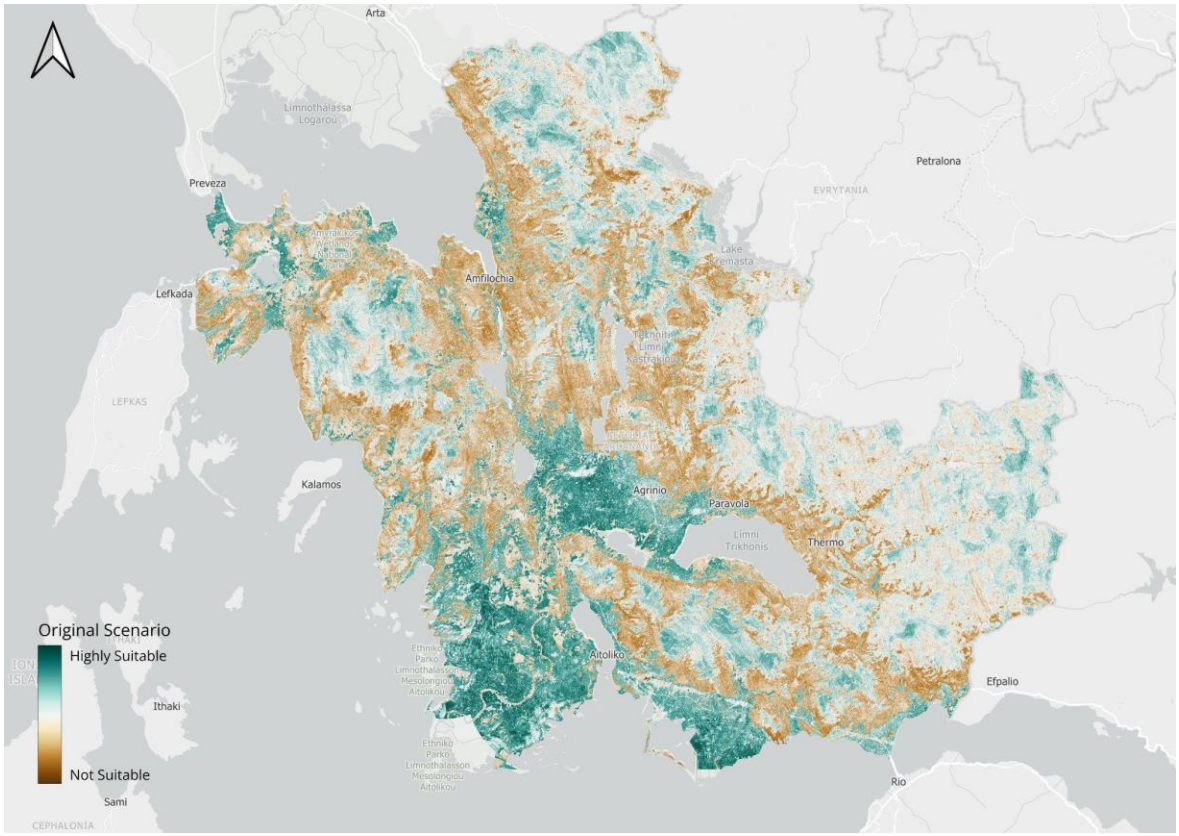


Figure 5.19: Alternative Scenario 1 Final Map

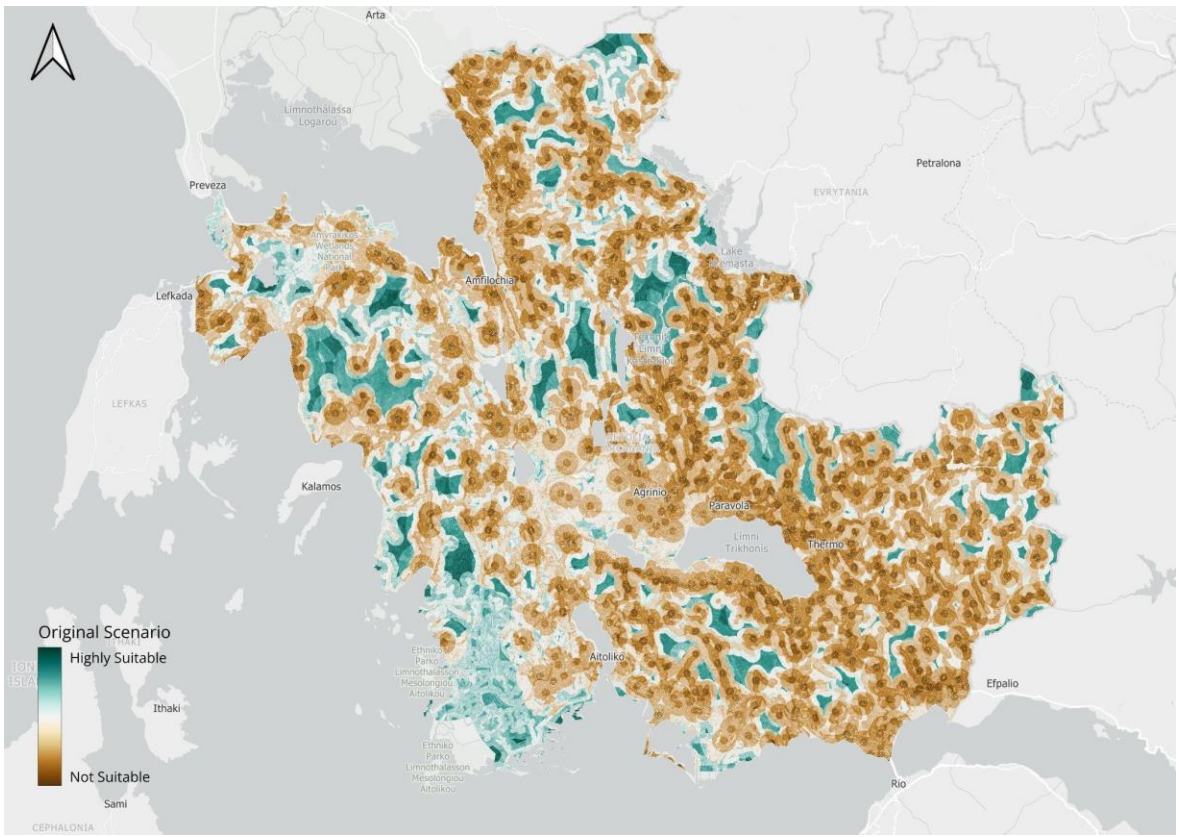


Figure 5.20: Alternative Scenario 2 Final Map

6. Web Map Development

6.1 Introduction to Web GIS

Geographic Information Systems on the web (Web GIS) represent an innovative technology that has emerged in recent years. More specifically, they have transformed the way spatial information is distributed, accessed, and interacted with by users. Unlike traditional GIS platforms that require software installation and operation, Web GIS integrates all necessary functions and features needed for users to engage with geospatial content. In real-time, users can view, analyze, and perform specific queries on spatial data through a web-based mapping application using a browser (Peng & Tsou, 2023). The incorporation of these technologies enhances user interaction with the application, leading to an increased sense of participation and accessibility to information.

Technology has permeated all aspects of daily life, production, and industry. Consequently, in the field of beekeeping (precision apiculture), the use of Web GIS applications can prove highly beneficial, as they offer a fast and user-friendly tool that provides a decision-making platform based on real and dynamically presented data. Scientists and beekeepers familiar with internet usage can explore potential hive installation areas. In conclusion, without requiring specialized knowledge or expertise in GIS software, users can observe the current situation, satellite imagery as background, and various scenarios that may have resulted from different types of spatial analyses.

In the context of this thesis, a web-based mapping application was developed using Leaflet (through a QGIS plugin), with the aim of visualizing the final suitability maps derived from each scenario, as analyzed in previous chapters. QGIS software enables the creation of a basic web mapping platform for simple data viewing. However, further code modifications were made to enhance the final output with visual improvements (such as an information bar, additional legend, title, etc.). Ultimately, this application allows the user to observe the visualized suitability results (original and alternative scenario 1 & 2) for the installation of beehives in the regional unit of Aitoloakarnania.

6.2 Web Map Design and Architecture

The web mapping application was developed using the QGIS plugin *qgis2web*. This plugin was chosen because it provides a ready-made backend framework and directly incorporates the necessary libraries without requiring a server or connected database. The final output is a folder containing the HTML code (the structural component), the JavaScript code (which includes all logic for connecting the map to layers and extensions), and the CSS code (handling appearance, layout, fonts, etc.).This results in a dynamic tool that can be re-edited at any time, as its structural components are open for use and modification by any user with the necessary technical knowledge.

6.2.1 Technology Stack

The basic technology stack of the QGIS Web Application is illustrated below (table 6.1).

Component	Technology	Purpose
Mapping Library	Leaflet.js	Map rendering and layer control
Export Tool	QGIS2Web	Export QGIS layers to Leaflet-compatible HTML
UI Enhancements	Custom HTML/CSS	Tabs, sidebars, layout customization
Base Map	Esri Imagery or else	Background reference layer
Overlays	Raster PNG	Final suitability maps for 3 scenarios
Vector Data	Polygons, Points and Lines	Selected vector data in order to assist in the interpretation of the result

Table 6.1: Basic technology stack of the QGIS Web Application

Noteworthy is the fact that the aforementioned components and technologies are the simplest, aiming for the maximum result with the least amount of code. The following figure presents the start screen of the qgis2web plugin inside the QGIS environment. It contains tabs such "Layers and Groups" where the user selects the layers in order to be previewed in the web app, "Appearance" where the user can select the zoom range and some little extensions, "Export" where the user selects the directory for the web app to be exported, "Settings" for some fundamental components and "WIKI" for documentation (figure 6.1).

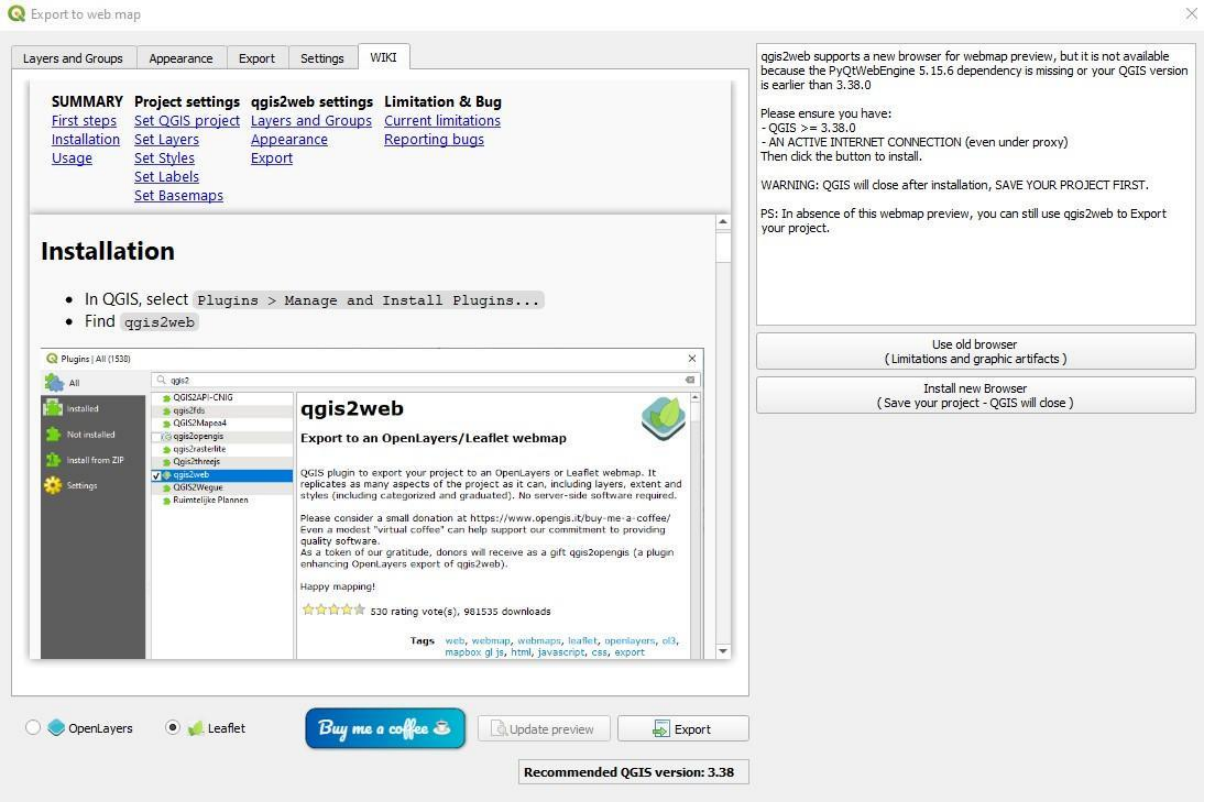


Figure 6.1: QGIS2Web plugin interface in QGIS 3.34

6.2.2 System Architecture Diagram

Regarding how the system functions, the map is initialized via the Leaflet library, which is embedded and automatically provided by the plugin. The raster files (exported from QGIS as TIFFs) corresponding to the scenarios are then automatically loaded and added as ***L.imageOverlay*** elements within the code. At the same time, all necessary vector data layers selected for this application are also incorporated.

6.3 Implementation Process

6.3.1 Exporting Data from QGIS

Following the processing of the initial data for each criterion (satellite imagery, road network in vector format, settlements in vector format), TIFF files were generated. These TIFFs incorporated the assigned weightings based on the analysis performed, and through raster operations, the final suitability raster files were produced. The first file created was the original scenario, followed by the two alternative scenarios (1 and 2).

The three final suitability raster files were exported via the qgis2web plugin as .png images and embedded into the generated output folder (figure 6.2), along with the corresponding code, to allow visualization in the web mapping application. The same process was applied to the vector files that were selected to complement and support the interpretation of the raster data.

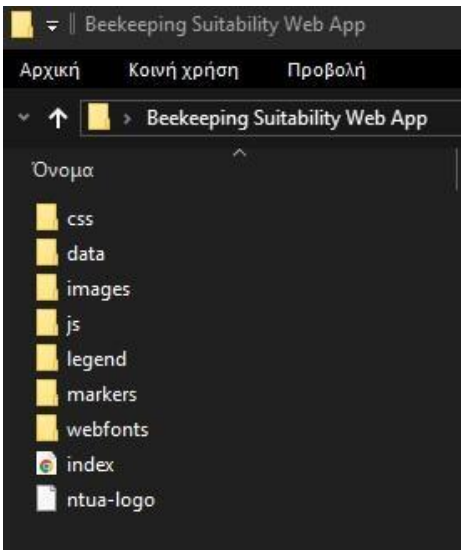


Figure 6.2: Final folder produced from QGIS2Web automatically by the end of the procedure

6.3.2 Initializing the Map

Map initialization was carried out in the main **"index.html"** file using the Leaflet API. The code snippet (Figure 6.3) below shows how the map setup was done:

```
var map = L.map('map', {
  zoomControl: false, minZoom:1, maxZoom:28
})
.fitBounds([[38.1280807,19.8692887],[39.1233794,22.9598826]])
.setZoom(10);
L.control.zoom({ position:'bottomright' }).addTo(map);
new L.Hash(map);
```

Figure 6.3: Map initialization in specific area and zoom

Then, the Esri World Imagery base map was added using the following code (figure 6.4)

```
var esriDark = L.tileLayer(
  'https://server.arcgisonline.com/ArcGIS/rest/services/Canvas/World_Dark_Gray_Base/MapServer/tile/{z}/{y}/{x}',
  { attribution:'Tiles © Esri — Esri Dark Gray' }
);
var esriImagery = L.tileLayer(
  'https://server.arcgisonline.com/arcgis/rest/services/World_Imagery/MapServer/tile/{z}/{y}/{x}',
  { attribution:'' }
).addTo(map);
```

Figure 6.4: Esri World Imagery base map addition

6.3.3 Adding Suitability Layers

Each of the three final raster files that were automatically exported by the plugin into the generated folder needed to be added to the code with their respective geographic bounds. This was done with the following code snippets (Figure 6.5 and Figure 6.6)

```
var orig = L.imageOverlay('data/OriginalScenario_4.png',
  [[38.2742591,20.7041906],[39.1873689,22.0378468]]
);
var alt1 = L.imageOverlay('data/AlternativeScenario1_3.png',
  [[38.2742125,20.7040937],[39.1874153,22.0378686]]
);
var alt2 = L.imageOverlay('data/AlternativeScenario2_2.png',
  [[38.2742125,20.7040937],[39.1874153,22.0378686]]
);
```

Figure 6.5: Final suitability layers addition

All scenarios were then added to a layer control panel:

```
var baseMaps = {
  "Esri Dark Gray": esriDark,
  "Esri Imagery":   esriImagery
};
var overlays = {
'<img src="legend/MunicipalUnitsPoint_5.png" width="30" height="30" style="vertical-align:middle; margin-top:-6px; margin-right:4px;" /> Settlements':      settlements,
'<img src="legend/BeehiveLocations_0.png" width="30" height="30" style="vertical-align:middle; margin-top:-6px; margin-right:4px;" /> Beehive Locations': beehives,
'<img src="legend/OriginalScenario_4.png"      width="16" height="16" style="vertical-align:middle; margin-right:4px;" /> Original Scenario':     orig,
'<img src="legend/AlternativeScenario1_3.png" width="16" height="16" style="vertical-align:middle; margin-right:4px;" /> Alternative Scenario 1': alt1,
'<img src="legend/AlternativeScenario2_2.png" width="16" height="16" style="vertical-align:middle; margin-right:4px;" /> Alternative Scenario 2': alt2
};
L.control.layers(baseMaps, overlays, { collapsed:true }).addTo(map);
```

Figure 6.6: Control layer panel addition

This setup allows users to switch between scenarios in real time, select which base map they prefer, and control which vector data layers they want active (Figure 6.7)

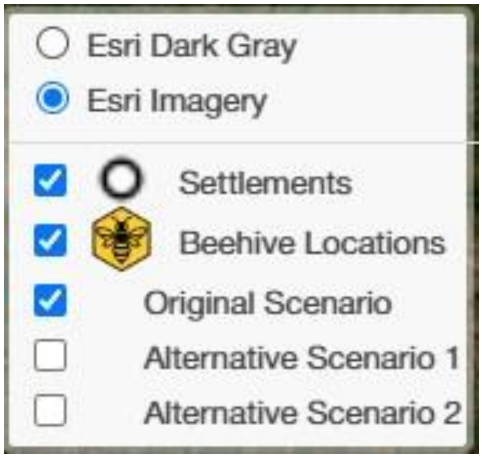


Figure 6.7: Layer panel inside the Web Application environment

6.3.4 User Interface Enhancements (UI Enhancements)

While the elements mentioned above are automatically generated through the QGIS plugin (which creates a ready-to-use directory with exported outputs and updated code), the goal was to take this a step further. Additional manual edits were made to the directory, code, and interface components to enhance the visual experience and provide a more user-friendly and informative Web GIS environment.

To enhance user experience, specific improvements were implemented. Firstly, a left sidebar was added, which can be toggled with a button to show or hide and contains all the general information about the creator, disclaimers and some information about the scenarios and

conclusion (Figure 6.8). Secondly, a custom legend panel was manually added, displaying the hues and their meaning (e.g., "not suitable", "highly suitable") for each scenario. Finally, a title banner was placed at the center of the page to clearly identify the Web GIS application to new users.

These formatting changes were implemented using custom CSS and targeted HTML edits, without altering the core structure of the application. All new interface elements were designed to be responsive and mobile-friendly using modern web design techniques.

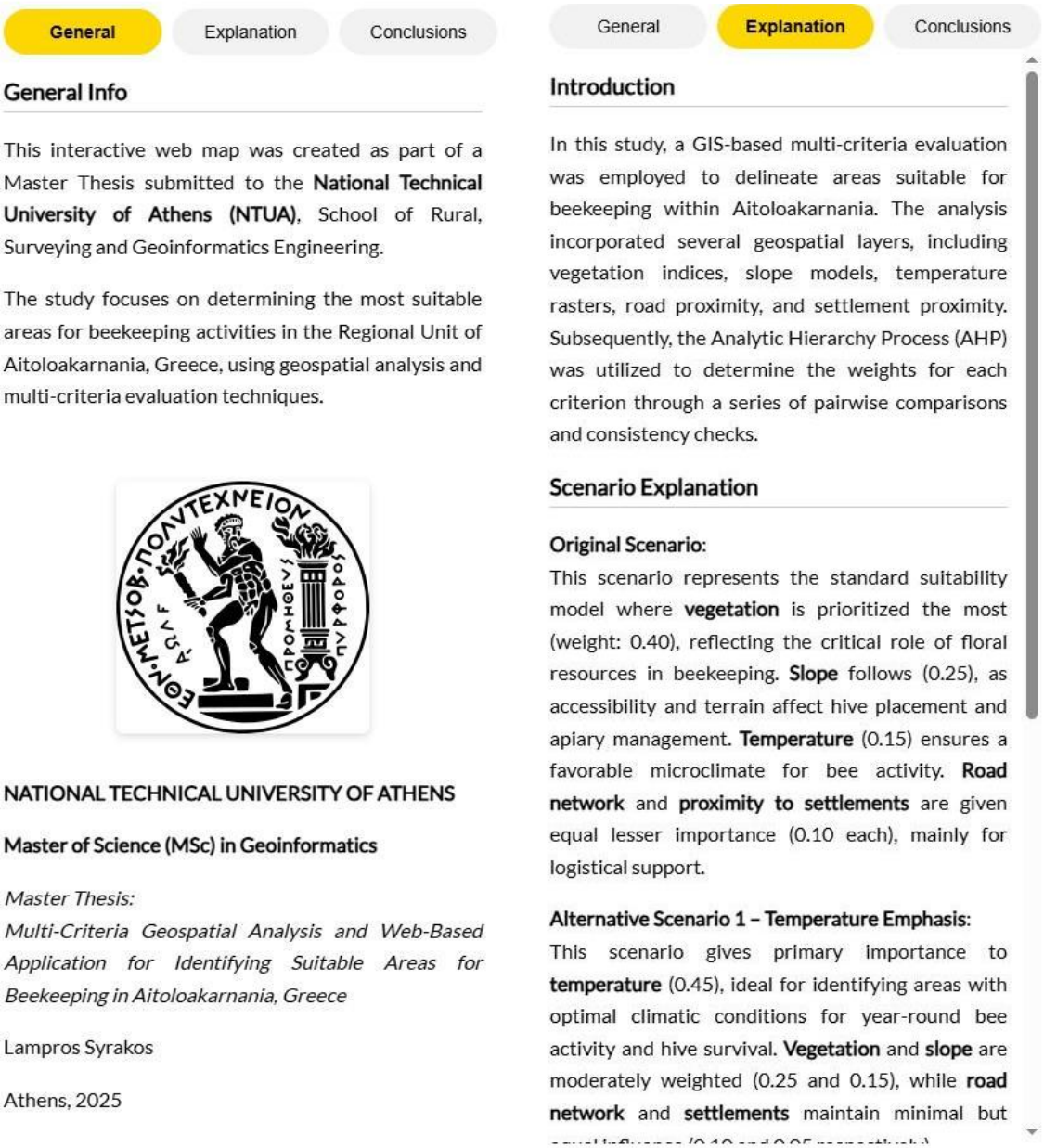


Figure 6.8: Abstract of the sidebar that was added manually via coding

6.4 Final Web Map

In conclusion, the essential elements of a functional web mapping application must include a smooth navigation and responsive interaction (zooming, panning), a clear legend to help users interpret what they see on the map (especially in the color-coded raster layers) and a functional layer control panel to toggle desired map elements.

By double-clicking the "**index.html"** file within the generated folder, the Web GIS application launches in the user's default browser directly from the local machine (Figure 6.9)

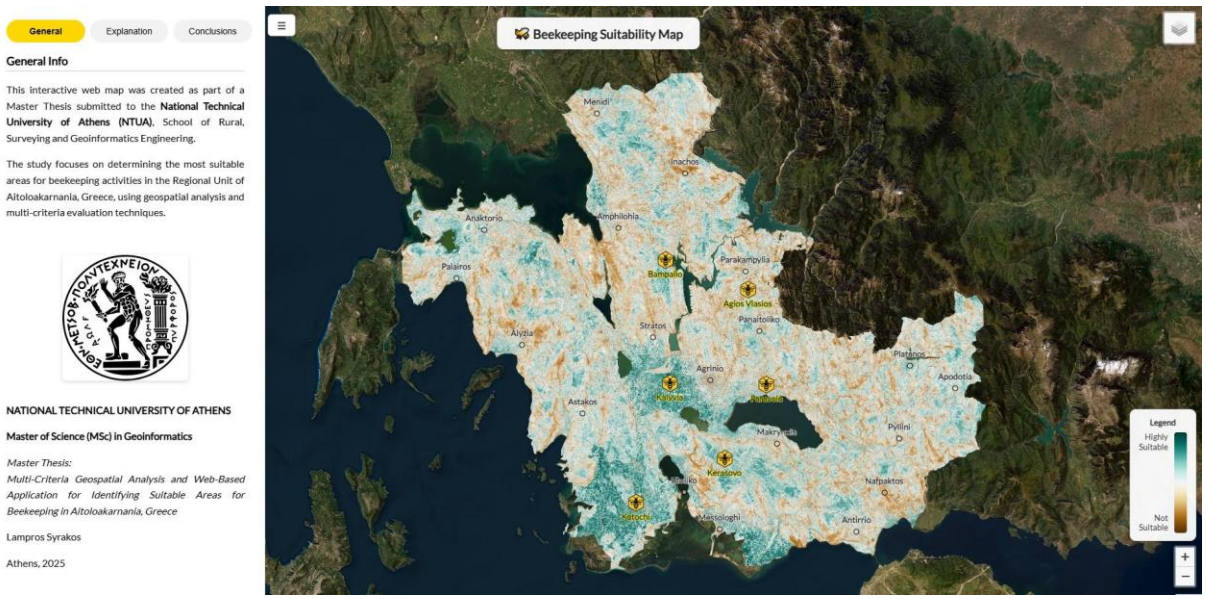


Figure 6.9: Final Web Application perspective

Since the application is hosted locally (localhost) and not on a web server, any external user must have access to the complete and up-to-date project directory in order to view it without issues.

The completed web mapping application, which visualizes suitability scenarios for beehive installation, is designed to be a simple tool for visualization and decision support. It aims to bridge the gap between technical scientific analysis and open, user-friendly access. The interface was intentionally designed to be accessible to non-specialist users such as local residents, beekeepers, farmers, and even students, allowing them to interact with the data and draw meaningful insights.

In order to make the final application accessible beyond multiple devices, the complete web map was published using GitHub Pages. After exporting the project through the qgis2web plugin in Leaflet format, the code was cleaned and customized — including edits to the index.html, map layers, sidebar controls, and user interface elements. The files were then uploaded to a GitHub repository which enables free static site hosting. The result is a fully interactive, open-access application available at: https://syrakosl.github.io/Beekeeping-Suitability/

7. Results and Discussion

7.1 Suitability Analysis Results

Original scenario and alternative scenarios 1 & 2 are the three final raster products that were produced by integrating the criteria weights that derived from the analysis in the previous chapters. Each pixel in these raster maps was calculated through the weighted overlay process and contains a score that combines the weights of all the criteria and ranges from 1 to 4. Then, each raster was classified into four discrete classes for beekeeping suitability. Value 1 represents "Not Suitable", value 2 represents "Moderately Suitable", value 3 represents "Suitable" and value 4 represents "Highly Suitable". Therefore, this means that one pixel in each raster covers a 100 m^2 (10m x 10m pixel size) and contains a value depending on the suitability score as discussed earlier.

Though, because of the different weights applied to each raster, the values that are being created range. So, in order to get some statistical results for each suitability class, thresholds based on literature and critical thinking were set:

- Not Suitable (< 1,75)
- Moderately Suitable (1,75 – 2,49):
- Suitable (2,5 – 3,24):
- Highly Suitable (≥ 3,25)

Area Distribution by Scenario

The total area of each suitability class was calculated by multiplying the count of classified pixels by their respective area. The following table represents the data (Table 7.1).

Suitability Class	Original Scenario (ha)	Scenario 1 (ha)	Scenario 2 (ha)
Highly Suitable	19.302,68	11.012,85	30.369,77
Suitable	263.325,24	269.852,04	115.657,11
Moderately Suitable	172.788,67	195.817,98	279.298,45
Not Suitable	2.776,76	367,82	38.269,80

Table 7.1: Area (in hectares) per suitability class and scenario

The figure below highlights the variation in suitability class area across scenarios as mentioned above. This provides an optimal representation to understand the spatial distribution of the

categorisation of the study area based on beekeeping suitability, as analysed in this study (figure 7.1).

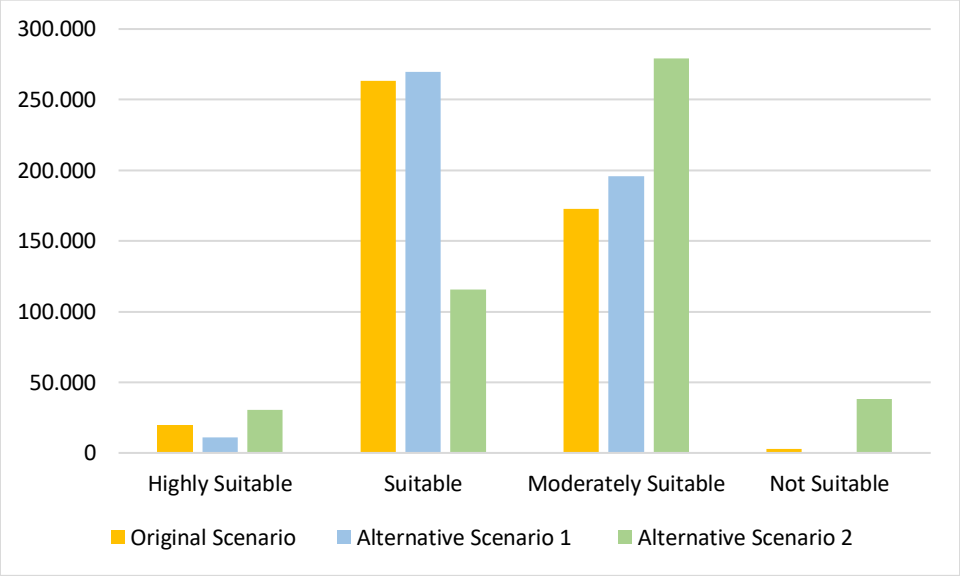


Figure 7.1: Suitability Class Area Comparison by Scenario

7.2 Interpretation of the Final Maps

Original Scenario

The original scenario indicates that vegetation and slope were the most important criteria. Mostly, the biggest part of the area is classified as “Suitable” (263.325 ha) and “Moderately Suitable” (172.789 ha). This reflects a balanced spatial distribution that favors areas with rich vegetation. Notably, the “Highly Suitable” category covers 19.303 ha, with most of these areas located in vegetated, mid-slope zones away from steep terrain and urban disturbance. The small extent of “Not Suitable” zones (2.777 ha) confirms that, ecologically and physically, much of Aitoloakarnania holds potential for beekeeping under natural land conditions.

Alternative Scenario 1

This scenario puts emphasis on land surface temperature (LST), aiming at warm conditions that are beneficial for the activity of bees and the growth of colonies. In comparison to the original scenario, Alternative Scenario 1 has slightly increased the total area classified as "Suitable" (269.852 ha) and "Moderately Suitable" (195.818 ha), while reducing the " Not Suitable" category significantly to only 368 ha. This change indicates that temperature is a less constraining factor in the region allowing for a greater distribution of favorable zones spatially. Nevertheless, the "Highly Suitable" class is the smallest across all scenarios at 11.013 hectares, implying that while more areas are generally acceptable, fewer areas simultaneously meet all of the criteria.

Alternative Scenario 2

By giving priority to proximity to roads and settlements, Alternative Scenario 2 resulted in a different pattern. While it created the largest "Highly Suitable" area (30.370 ha), it also led to a significant increase in the "Not Suitable" class to 38.270 ha - the highest among all scenarios. This indicates a model that promotes logistical ease over environmental optimization. Areas close to roads or urban areas scored higher, but rough, remote or heavily vegetated areas - which may be ecologically suitable - were often downgraded because of poor accessibility. The drop in "Suitable" area to 115.657 hectares suggests a focus shift in suitability towards areas with better facilities rather than environmental resources.

7.3 Statistical Evaluation of the Results

To validate the quality of the produced maps, several quantitative measures were calculated. Thus, the following statistical measures were computed for each scenario (Table 7.2).

- **Mean** (μ): Central tendency of suitability (suitability score)
- **Standard Deviation** (σ): Dispersion of suitability
- **Coefficient of Variation** (CV): $CV = (\frac{\sigma}{\mu}) \times 100$

Scenario	Mean	Std Dev	CV (%)
Original	2,62	0,44	16,86
Alternative Scenario 1	2,9	0,42	16,28
Alternative Scenario 2	2,35	0,52	22,34

Table 7.2: Quantitative measures by scenario

Based on the table above, the original scenario shows the highest average suitability value (2,62), suggesting a general trend towards moderate to very favourable environmental conditions when NDVI and Slope are favoured over ecological and physical factors. Scenario 1, which emphasizes temperature (LST), delivers a slightly lower mean value (2,59), while Scenario 2, which focuses on accessibility, results in a significantly lower mean value (2,35), reflecting the inclusion of less optimal locations from an environmental perspective but logistically feasible.

The standard deviation (STDV) and coefficient of variation (CV) reveal the internal variability of each scenario. Scenario 2 has the highest standard deviation (0,52) and the highest CV (22,34%), suggesting a greater dispersion of suitability scores - and hence a greater spatial dispersion. The result is in line with its design: the accessibility bias results in high suitability zones close to roads, but also excludes ecological areas, generating a contradiction. In contrast,

Scenario 1 shows the lowest variability (CV = 16,28%), indicating a more homogeneous distribution of the suitability classes.

Then in order to assess how even is the distribution of the suitability classification of the area, the Shannon Entropy (H) index was used:

$$H = - \sum_{i=1}^{n} pi * \log2(pi)$$

Where p_i is the proportion of area in each suitability class that was used in the analysis.

Entropy ranges from:

- **0**: Total dominance by one class
- **$\log_2(4) = 2$**: Perfectly equal distribution among 4 classes

The following table presents the calculations of Shannon entropy for each one scenario (table 7.3).

Scenario	Entropy (H)
Original	1,23
Scenario 1	1,13
Scenario 2	1,49

Table 7.3: Shannon entropy by scenario

Despite the fact that Scenario 2 has the most balanced class distribution (it favors logistical accessibility) over environmental criteria, the original scenario remains the most stable because the Shannon entropy index is just a statistical value that refers to only how the classes are distributed and it does not examine the background of the analysis.

7.4 Field-Based Validation Using Beekeeper Insights

Spatial models provide a robust tool for evaluating environmental suitability, but they also benefit strongly from alignment with real-world experience. Given this, this study integrated a qualitative field validation aspect to compare the results of the analysis with the practical knowledge of experienced beekeepers in Aitoloakarnania. Through informal conversations and field observations, the study investigated how practitioners rate suitable areas for hive placement and how their preferences compare with the model's suitability classes.

At the final stage of the analysis, several active beekeepers in the study area were interviewed informally. These interviews were conducted in person and by telephone during the spring of

2025 and were probing in nature, without structured questionnaires or recordings. Therefore, the objective was to understand how local beekeepers choose sites, what environmental characteristics they value, and if they agree with the overall logic and outcomes of the generated suitability maps. To assure ethical handling of the information, all contributions were anonymous. No personal data or identifiable information was registered. Responses were grouped thematically and summarized to extract common trends and preferences. In addition to the interviews, participants were asked to indicate generally or by reference to place names - where they usually place their beehives. These sites were geo-referenced and mapped and then spatially compared with the suitability categories for each scenario.

Hence, the following table illustrates all the necessary information gathered from the interaction with beekeepers. This information refers to criteria, characteristics, aspects between people who are practicing beekeeping for over 20 years (table 7.4).

Criterion	Priority Level (Based on Beekeepers)	Notes from Beekeepers
Type of Vegetation	Very High	The type of vegetation is crucial because it will give different types of honey products. Emphasis is being given in wildflowers, fir and pine.
Water Availability	Very High	From the most important factors that affect the life of bee colonies, especially when climate crisis has affected Earth so much
Accessibility (Roads)	High	Especially for seasonal or migratory hive movements. Moderate or flat terrain preferred for safety/access.
Microclimate/Temperature	High	Shaded areas in summer, mild conditions in spring
Distance from Settlements	Low	Slight preference for quieter, less disturbed areas

Table 7.4: Field-Based Criteria Review

While in this very study vegetation was a general criterion, most beekeepers went into it and said that it is quite important to see what type of vegetation because not all types of vegetation flourish everywhere.

Then, they mentioned that accessibility is way crucial and integrated slope inside accessibility manners in order to reach each suitable location while noting that moderate or flat terrain is preferred for safety reasons.

The microclimate conditions was also a criterion that was noted by beekeepers. As the climate crisis has affected our planet, vegetation which is the number one criterion is also being

affected. Also, it is quite hard for bees to survive, perform and produce honey in extremely high or low temperatures.
When beekeepers refer to distance from settlements, they do not think that it is dangerous or quite important. They do not see bees as a danger to humans, on the contrary they think that only humans can be harmful to bees.
Finally, water availability was mentioned as one of the most important criteria among others. Bees on extremely hot days store water and transfer it to the hive where they use it in order to cool the area. Hence, when water availability is low, bees prioritize this and spend more energy in order to access water areas near the hives.

For all the above-mentioned reasons, the location of the sites where local beekeepers install their hives was carried out. Then, an analysis was conducted in relation to the scenarios and how the results of these scenarios correlate with each other. The following figure illustrates the approximate location (for privacy reasons) that local beekeepers install their hives (figure 7.2).

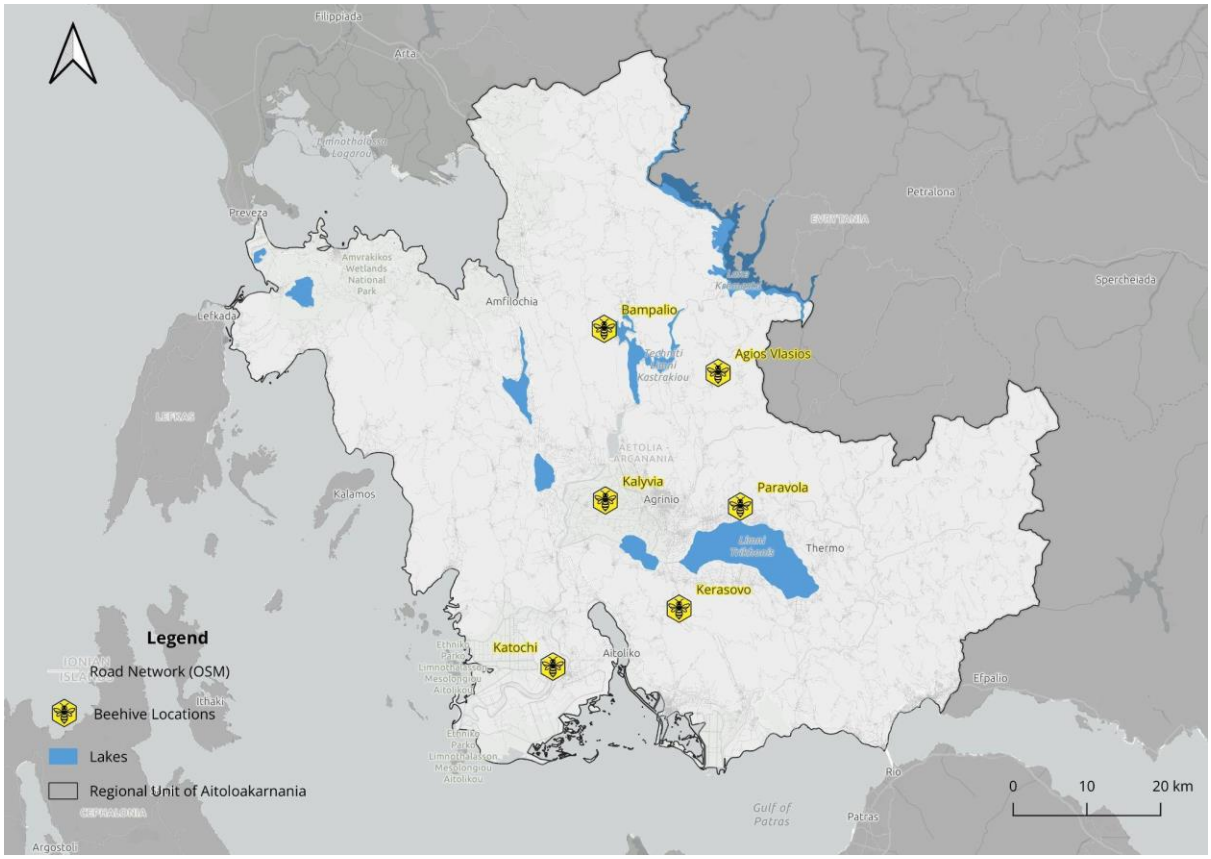


Figure 7.2: Local beekeepers approximate beehive locations illustration

Then these locations were integrated with the three scenarios of this study (Original Scenario, Alternative Scenario 1, Alternative Scenario 2) in order to extract useful information and validate the results of the analysis in an empirical way (Figure 7.3-7.5)

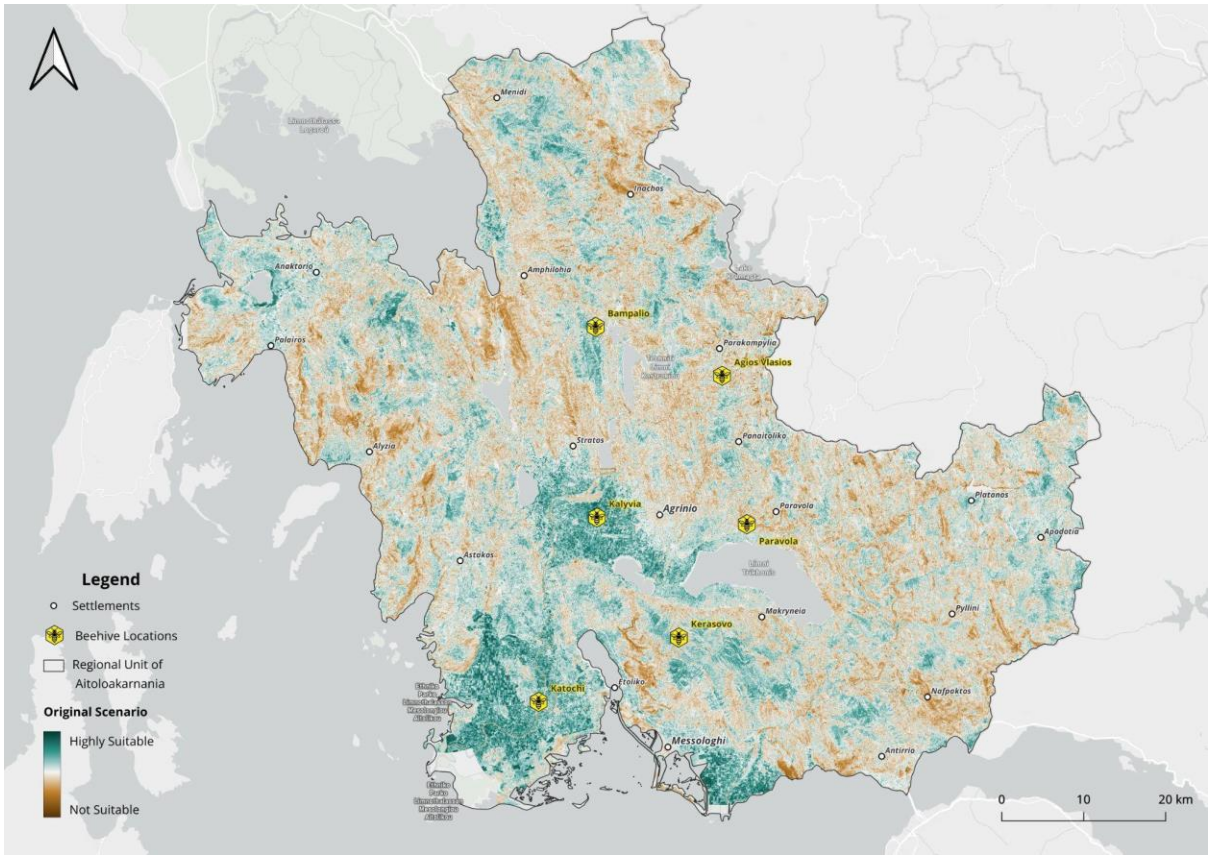


Figure 7.3: Association of the local beekeepers approximate beehive locations with the Original Scenario

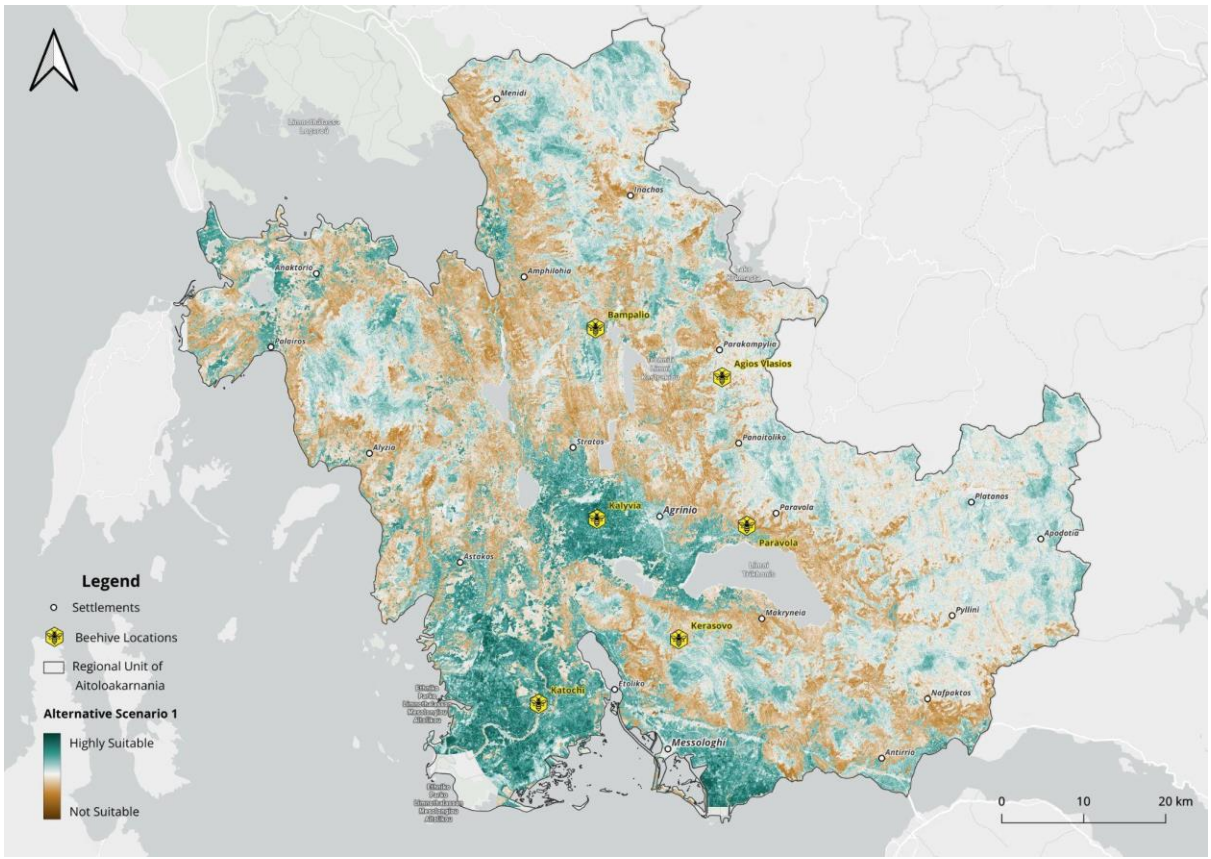


Figure 7.4: Association of the local beekeepers approximate beehive locations with Alternative Scenario 1

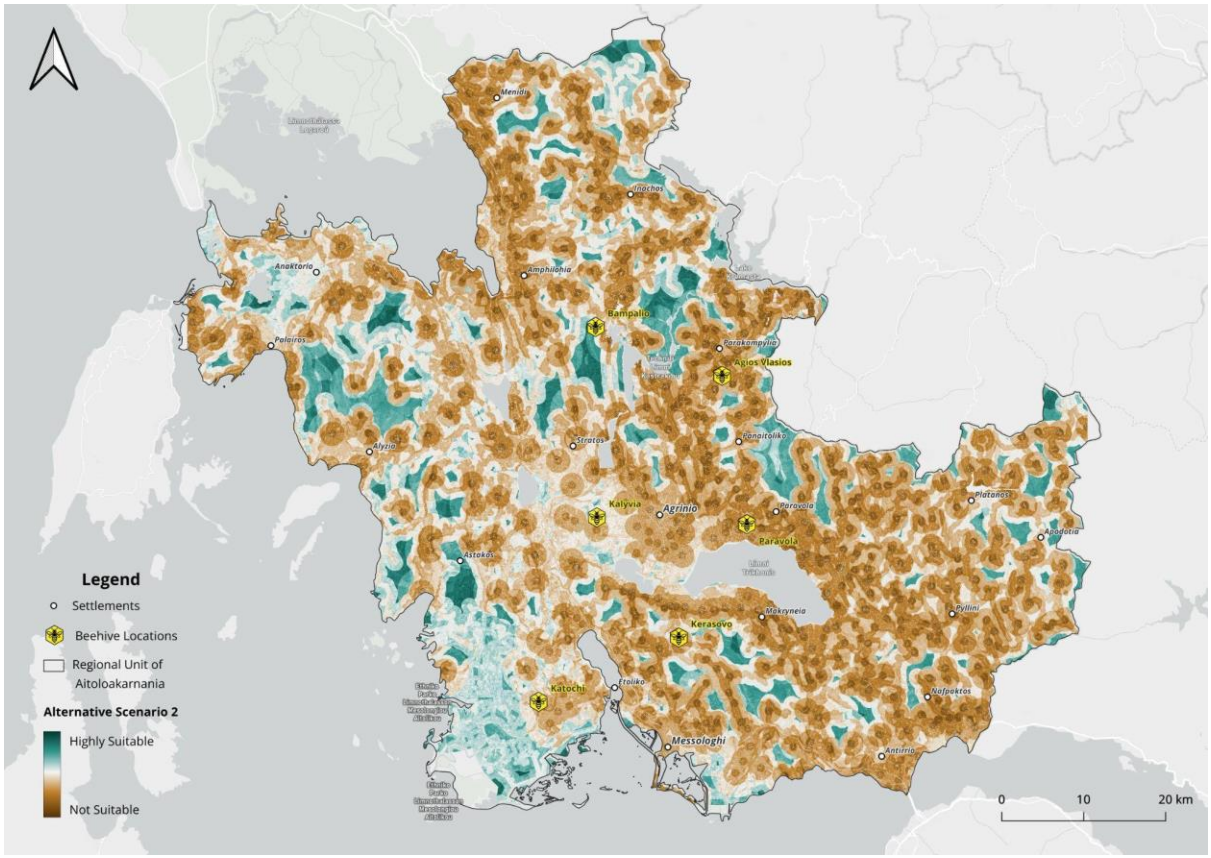


Figure 7.5: Association of the local beekeepers approximate beehive locations with Alternative Scenario 2

By using the approximate locations provided by the beekeepers that took part, a comparison of all three scenarios was generated to provide a comparative overview of the suitability maps. These were not precise coordinates, but general areas generated from field notes and beekeepers input on a basemap.

The results of the comparison indicated that:

- In the Original Scenario, about 90% of the beehive locations were found in "highly suitable" or "suitable" areas.

- In Alternative Scenario 1, this correlation was slightly lower (60%), especially in the mid-altitude zones.

- Alternative Scenario 2 aligned particularly for the beekeepers who prioritise logistics and maximization of productivity. From the 6 available beehive locations only 2 of them seem to match the “suitable” class.

The above results are subjective as they are based on the personal preferences of the beekeepers concerned. However, this suggests a strong level of agreement between the modeled spatial outputs and the empirical knowledge of local practitioners — especially in the central and eastern parts of Aitoloakarnania.

Overall, the field feedback strengthens the validity of the multi-criteria approach. While there are several characteristics of the human and natural environment (private areas, archaeological areas) that may restrict the suitability of the study area, the core decision-making logic used by beekeepers closely mirrors the structure of the suitability model.

7.5 Discussion of Limitations and Uncertainties

Despite the strengths of the methodology, several limitations must be noted. For instance, the MODIS-derived LST raster was resampled from 1 km to 10 m. This may lead to uncertainty through the interpolation that was implemented in the spatial analysis.

Furthermore, the suitability classes were determined using thresholds from the literature that were applied in multiple occasions and in different types of areas, which may not fully capture local microclimates or site-specific dynamics of Aitoloakarnania. In any case, the personal preferences and the empirical knowledge matters more than any case study that was employed somewhere else in the world.

The lack of official data on beekeeping from the Ministry of Rural Development and Food (which includes Agronomy-Agriculture and therefore Beekeeping) is a limitation in this specific study. In Greece, unlike the other European Countries, the open-source data is limited and concerns more general information for the whole country (and not for smaller spatial units like Regional Units and Municipalities). For example, possible future addition of beekeepers data like beehive locations, honey production, logistics data etc., could create a new approach to study and give a greater depth of specialisation. At the same time, it would lead to safer conclusions for the development of a firm strategic tailor-made policy for each regional unit on the basis of its geomorphological, economic and social characteristics.

As for the web platform, the plugin qgis2web, which is provided free of charge by QGIS, was used for the present thesis. However, there were some limitations with the size of the files it allows to view. At the same time, the interface of the generated page is very poor. For this reason, manual editing of the code had to be performed, and new objects had to be added to make the interface more friendly and easy to use.

8. Conclusions and Future Work

This study seeks to evaluate the study area and determine the most appropriate areas for apiculture in the Regional Unit of Aitoloakarnania by implementing geospatial analysis with multiple criteria decision-making methods (MCDM). The integration of remote sensing data, reclassification procedures, and spatial overlays presents the potential of GIS to aid environmental planning in terms of continuation of its evolution from static mapping to dynamic decision-support.

The importance of beekeeping in Greece supported the significance of the study. Beekeeping is both a tradition and a vital economic sector, which is vulnerable to climate change (crisis) and human activities. Scientific assessment of spatial suitability offers a way to support the robustness of this practice. Some international case studies offered a global perspective on beekeeping suitability models, from countries such as Turkey, Iran, and Italy. These examples used methodological tools and justified the use of AHP for weight assignment. By adapting best practices to the specific regional characteristics of Aitoloakarnania, the study created a methodologically grounded yet locally tailored model.

The use of weighted overlay techniques based on AHP allowed the incorporation of both environmental and infrastructure factors into a single suitability context. The model successfully distinguished sites into 'not suitable', 'moderately suitable', 'suitable' and 'very suitable' classes with strong internal consistency (CR < 0.1 in all AHP tables). The three scenarios showed how changing weights can be reflective of different real-world beekeeping preferences. While the original scenario balanced ecological and logistical factors, alternative scenario 1 placed as a priority the temperature conditions that affect the productivity and the life of bees, while alternative scenario 2 emphasized accessibility and logistics (transportation of beehives and efficiency). The spatial variation between these maps demonstrates the adaptability of the model to different user needs and preferences.

Informal interviews with local beekeepers indicated that most current hive sites coincide with areas identified as suitable or highly suitable by the model. Their preferences - particularly in terms of vegetation cover, slope, road access and microclimate - meet the model's criteria. This alignment enhances the applicability of the findings to the real world. Statistical measures and tools like mean, standard deviation, coefficient of variation and Shannon's entropy index detected internal structural differences between the scenarios, which is completely normal as the distribution of the scores for each criterion was based on literature and logic. Alternative scenario 2, for example, showed the highest entropy and spatial fragmentation, while the original scenario showed more stable suitability distributions.

Of course, beekeeping is an art, a way of life and not just a business for the majority of the beekeepers, since both the process and the result are beneficial to humans as it restores the relationship with nature and the environment. Hence, the utilization of geoinformatics in beekeeping is not only for maximizing productivity but also for the sustainability of the natural environment.

In terms of future work, integrating hydrological data and land ownerships would improve the suitability analysis because in a small scale it would be easier for each user-beekeeper to determine where exactly to place his hives. Moreover, a multi-year analysis as regards to vegetation would lead to more reliable results.

Furthermore, the interaction with beekeepers would be even better if there was a structured questionnaire or a workshop with all the beekeepers of the study area where with the main focus on strategic planning and fostering of sustainability, weights for each criterion would be recalculated or new criteria would be added in order to make the final suitability maps would be even more complete.

The web-based cartographic application created using the QGIS2web tool and re-editing the code to create and add more features is a good basis on which to build a standalone web-based cartographic application on a website without the use of QGIS tools. There the data will be stored in cloud geodatabases and there will be the possibility of real-time spatial queries. At the same time, the user experience will be developed as the user will be able to place the desired weight for each criterion in real time and observe changes in the final suitability map immediately. They will also be able to upload data to the platform that may relate to the boundaries of their land holdings in order to see which class he is in.

Finally, this approach is reproducible and can be adjusted to other regions of Greece or similar countries. The adjustment with local data and the collaboration with the involved parties in each new context will be crucial for the successful application of the approach.

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