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Modelling Ancient Pathways of Cretan Landscapes: Building Networks and Social Dynamics

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Abstract

Mapping human–environment interactions involves understanding complex systems based on continuous material and non-material flows. These interactions are linked to the ecological context and involve both physical and social dynamics. This study explores such interactions within ancient Crete from a long-term and multi-scalar perspective, with a specific focus on the entanglements that contributed to the formation of patterned landscapes. Methodologically, this research employs digital tools such as site mapping, GIS-based analysis and network science techniques to shed light on emerging spatial patterns and historical mobility arising from the interconnectedness of specific factors within Cretan landscapes. The results contribute to a deeper understanding of the spatial network configuration of complex social landscapes in this region, which holds strategic historical connections within the broader Mediterranean context.

Keywords: landscape archaeology; site mapping; Focal Mobility Network (FMN); Spatial Design Network Analysis (sDNA); Crete; Eastern Mediterranean

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1. Introduction

The Mediterranean world experienced profound transformations in the constitution and characterisation of societies inhabiting its shores in antiquity. These communities were interconnected through complex networks operating across multiple scales, from local and regional to far-reaching Mediterranean dynamics [1–3]. Focusing on these networks, this study examines ancient Crete—an essential link between the Near East, the Aegean and the Central and Western Mediterranean during the Minoan/Mycenaean, Protohistoric, Classical/Hellenistic and Roman periods—to investigate how such connections shaped the island's historical and ecological trajectories.

This timeframe, which spans from the Late Bronze Age to the Late Roman period (*ca.* 1400 BCE–565 CE), witnessed significant transformations in social, economic, cultural and political structures. Bureaucratic systems flourished and subsequently collapsed, leading to societal reorganisations at the end of the Bronze Age and the Early Iron Age. These transitions were characterised by technological innovations, such as the progressive replacement of bronze with iron, and shifts in material culture, including evolving pottery styles and ritual practices, along with the emergence of city-states (*poleis*) that redefined sociopolitical structures, giving rise to dynamic urban centres that became hubs of trade, governance and cultural innovation. A striking example of these transformations is the monumental inscription of the Gortyn Law Code (mid-fifth century BCE, though most probably reflect an earlier period), which illustrates the codification of legal practices and the public display of civic authority in the evolving Greek polis [2–7]. These processes, continuing into the later periods, were accompanied by increasing urban nucleation, monumental architecture, and regional and interregional connectivity, which played a crucial role in shaping sociocultural and sociopolitical dynamics [8–11].

The study of these societies, however, has long grappled and, in certain cases, continues to do so with the fragmented and incomplete nature of the archaeological record and of the limited testimonies during the Early Iron Age. Nevertheless, in recent years, advanced technologies and analytical frameworks have emerged; notably, integrating mapping techniques, spatial analysis and network science have proven effective in characterising the spatial and temporal complexities inherent in archaeological data. By leveraging these approaches, the present paper explores how the applied methodology interconnects with the archaeological record and examines what their spatial positioning reveals about long-term human–environment interactions that shaped the historical trajectories of ancient Cretan societies, with a specific focus on sociopolitical structures, regional mobility, patterns of connectivity and their entanglements with the biophysical world.

2. Study Area

2.1. Boundaries and Landscapes

Crete, the largest and southernmost Greek island—excluding the islets of Gavdos, Khrisi and Koufonisi—spans approximately 245 km in length and up to 50 km in width [12]. Its diverse landscapes, shaped by both natural and human-induced changes, have undergone significant transformations over millennia. Located at the southern edge of the Aegean Sea, Crete holds a strategic position at the crossroads of major maritime routes, connecting the Greek mainland with the broader Eastern Mediterranean, historically linking regions such as Asia Minor/Anatolia, the Cyclades and North Africa, including Cyrenaica, Marmarica and the Nile Valley via the Libyan Sea. These natural waypoints, combined with the island's ecological diversity, have established Crete as a crucial hub for trade and cultural exchanges within interconnected Mediterranean networks (Figure 1).

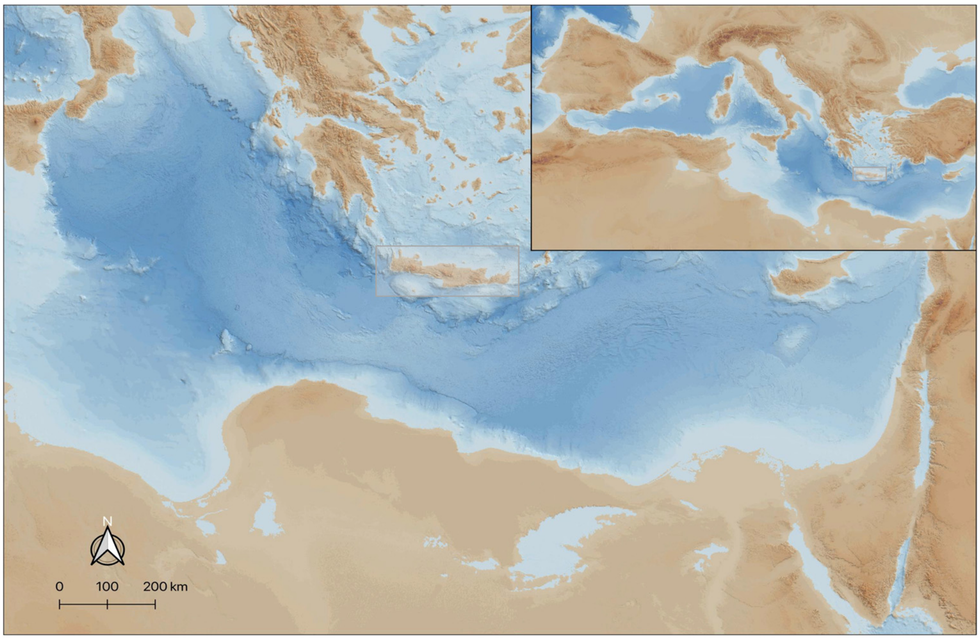


Figure 1. Map of the Mediterranean illustrating the location of Crete (Basemap© CNIG).

2.2. Physical Geography and Ecological Context

The island's varied topography is defined by prominent mountain ranges, the White Mountains (Lefka Ori), Mount Ida (Psiloritis) and the Dikti Mountains, which serve as both natural barriers and landmarks. These ranges, interspersed with deep, prominent valleys and narrow coastal plains, significantly shape settlement patterns and resource distribution [13]. The geological cores of the island's mountain massifs are composed of stacked limestone and dolomite tectonic nappes, i.e., large-scale sheets of rock squashed together by tectonic forces. These nappes, exposed through uplift and erosion, reflect Crete's dynamic geomorphological history at the southern edge of the Aegean Plate, near the Hellenic Arc, a prominent tectonic feature resulting from the subduction of the African beneath the Eurasian Plate. In contrast, the lowlands and plains, formed by younger sediments deposited during the Neogene and Quaternary periods, have long served as focal points for human habitation and agricultural activity [14–19].

These geological and topographical features of Crete significantly influenced land-use patterns, shaping diverse agricultural practices such as terrace farming in the uplands and the extensive cultivation in the plains. Consequently, settlements often cluster near alluvial plains or natural harbours, where fertile soils and accessible trade routes support dense populations. Archaeological sites like Phaistos exemplify such assumptions, being located on fertile alluvial plains with access to land and maritime routes [12]. These patterns underscore the centrality of fertile lands for agriculture as well as for trade and sociocultural exchanges. This relationship between upland and lowland, mountain and plain, reflects Crete's inherent duality as a landscape of contrasts shaped by both human (e.g., agriculture and urban development) and non-human factors (e.g., tectonic movements and climatic variations) over time.

3. Materials and Methods

3.1. Site Mapping

To reconstruct long-term historical and ecological trajectories in the study area, we first assembled a georeferenced corpus of complementary sources: published archaeological surveys and excavations, archival documents, historical aerial photographs (1945–) and open-source multispectral satellite imagery (e.g., Sentinel-2, Landsat). Integrating this set of data into a common GIS environment provided in-depth insights of several facets of the regional Cretan landscapes, ranging from socioeconomic conditions (e.g., settlement dynamics, subsistence strategies) to environmental characteristics (e.g., topography, hydrography). However, these sources carry inherent uncertainties. For instance, the accuracy of historical cartography varies, reflecting technological and conceptual limitations of the time, while sources provide uneven levels of detail. This situation posed a significant challenge, prompting the development of a formal validation strategy—based on cross-checking and comparing multiple sources of information—and the design of a validation scale considering the 'accuracy' and 'validation' provided by the sources [20].

A systematic remote-sensing survey was then undertaken. Potential archaeological features were flagged whenever their spectral signature or microtopographic expression contrasted, for example, as vegetation stress, differential soil moisture, or subtle relief. Each potential site was digitised as a point feature, irrespective of its real extent, so that every observation shares the same geometry and attribute structure (Figure 2). This standardisation guarantees methodological consistency, facilitates the integration of legacy data, and permits robust spatial statistics. By superimposing sociocultural and environmental variables within a single analytic framework, the mapping process not only facilitated a detailed archaeological assessment but also supported the analysis and interpretation of diverse landscapes.

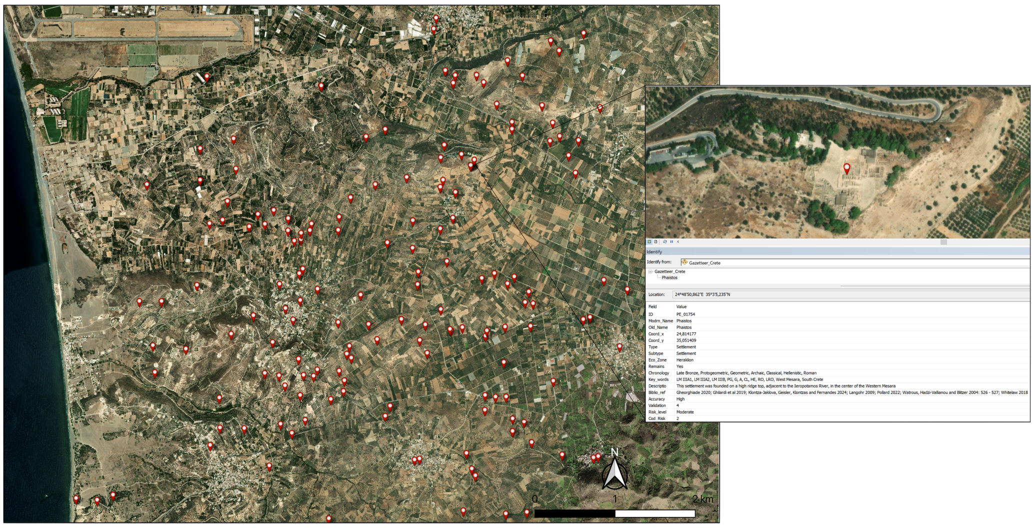


Figure 2. (**Left**) Archaeological sites identified in the Messara Plain (south-central Crete). (**Right**) The archaeological site of Phaistos, with its associated information in the dataset.

3.2. Cost, Effort and Mobility

The site mapping established a baseline for understanding long-term socio-spatial dynamics across Crete spanning from the Late Bronze Age to the Late Roman Period. Nonetheless, as John Pendlebury noted in the 1930s, "It is most important when considering the distribution of sites at certain periods to look at the means of communication each had with its neighbours; whether easy access from one quarter has caused a site to favour in this style of pottery the technique of another which may lie at a considerable distance from it; through what sections would pass the traffic, influencing perhaps one group of sites..." [12]. Consequently, modelling potential ancient pathways and interaction networks is an effective way of approaching the dynamics of past Cretan communities. In this context, several methods can simulate past mobility based on specific factors, though most rely extensively on the Accumulated Cost Surface (ACS) analysis [21–33]. In practice, this approach entails generating a continuous raster-based surface from a Digital Elevation Model (DEM) of the study area, where each cell (or pixel) in the DEM contains a friction or cost value, measured in a particular unit or impedance, that indicates the difficulty of movement (Figure 3).

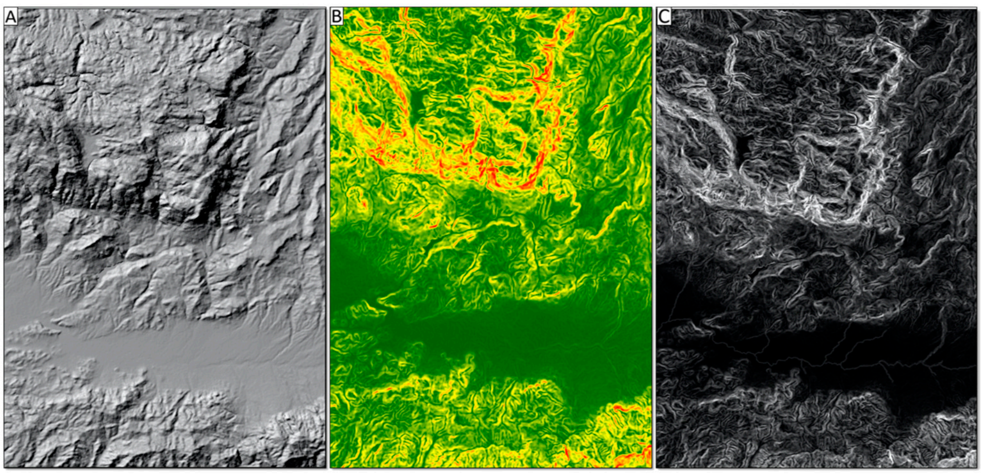


Figure 3. Stages for generating a friction map. (**A**) Digital elevation model (DEM) of the Messara plain. (**B**) Slope representation for the same area, rendered using distinct colour categories. (**C**) Friction map integrating the costs associated with different variables considered; darker colours indicate lower resistance to movement, while lighter colours signify higher resistance.

Now consider a scenario in which the friction surface lacks a defined point of origin but includes designated destination points. If, for example, water was split at any location on the surface, it would flow along the paths of least resistance until it reached these destination points, effectively 'capturing' the flow. This process would naturally result in the emergence of a network, illustrating the distribution of pathways across the landscape and revealing areas of highest accessibility, as well as the preferential movement corridors towards specific locations, without necessitating the definition of a specific origin. In other words, this approach identifies all the cells that must be traversed to reach a destination. This serves as a conceptual introduction to the generation of routes using the Focal Mobility Network methodology, also referred to as the Cumulative Focal Mobility Network (FMN, hereafter) [27–29].

It is worth noting that this method has also been published under the name *Modelo de Acumulación de Desplazamiento Óptimo* (MADO) [22–26]. This terminology originates from its initial development and publication by Fábrega-Álvarez in 2006, with the main objective of analysing the location of known archaeological sites in relation to optimal travel routes, defining it as a method for delineating routes without a specific destination [23]. A few years later, this procedure was reconceptualised by Llobera, Pacero-Oubiña and Fábrega-Álvarez in the publication *Order in Movement: A GIS Approach to Accessibility* [22], where the authors redefined it as an approach for analysing movement towards a destination without a predefined origin, thereby offering new possibilities for exploring the accessibility of specific areas [27–29].

The approach's strength lies in the sequential yet conceptually straightforward coupling of cost distance and hydrological analyses in a GIS environment. This workflow highlights natural corridors that channel movement and predicts the directions a traveller is most likely to follow when moving from any point in the landscape towards a location of interest. Moreover, as will be detailed later, this method produces accumulation values that are fundamental for applying network-based analytical approaches.

Reconstructing mobility networks with this approach, therefore, requires a clear understanding of its operational logic and data needs. Regarding this, after identifying the factors that condition movement, each must be quantified and weighted in proportion to its spatial relevance, producing a friction surface that integrates all variables into a unified cost raster. In this case, the friction surface was constructed exclusively from topographic variables derived from the DEM, namely the slope and the hydrographic network. No additional environmental parameters (e.g., vegetation, land use, soils) were incorporated, as the aim of the model is to evaluate potential mobility patterns determined solely by the island's orography. This surface is then transformed by a displacement function; in the present study, we adopt Naismith's rule, which estimates travel time at 12 min per km on level ground, plus an additional 10 min for every 100 m of ascent [30,31].

Once the friction or final cost surface is obtained, an orthogonal lattice of evenly spaced points is created to serve as simulated destinations. This grid is draped over the friction surface so that every point inherits the cost values of the cells beneath it. The analysis then proceeds in three sequential steps: (i) compute the least cost–distance from every cell to each destination (*cost distance*); (ii) generate a flow direction raster that assigns to every cell the downslope path of minimum cumulative cost (*flow direction*); and (iii) accumulate cost along those paths, producing a raster in which each cell records the number of upstream cells that would channel movement through it (*flow accumulation*). Borrowed from hydrological modelling, this sequence identifies corridors where potential mobility converges and thus delineates the most likely routes across the landscape (Figure 4).

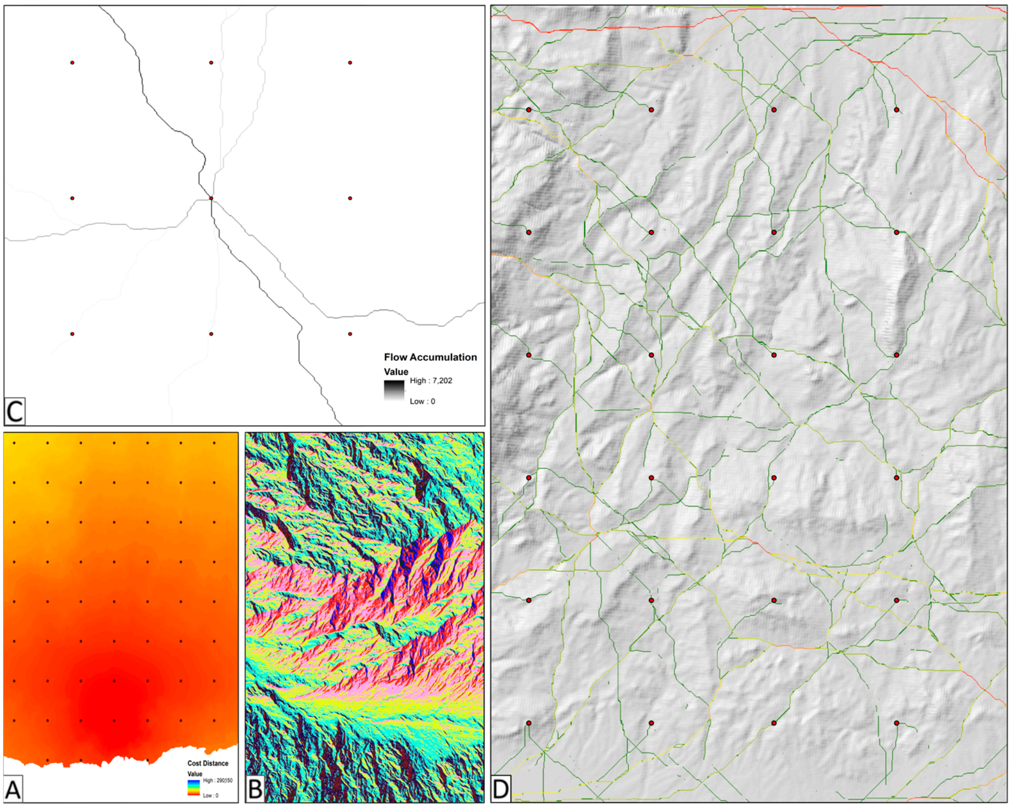


Figure 4. The application of the FMN sequence of operations. (**A**) Cost–distance analysis; (**B**) flow direction; (**C**) flow accumulation and (**D**) final output showing the generated routes or mobility corridors. These corridors connect destination points by following paths of least resistance, as determined by the FMN process.

As a result, a raster layer is generated for each destination point, in which each cell contains a value representing the accumulated cost of travelling from any location within the study area to that specific point. Finally, the average or sum of all resulting layers is computed to produce a final raster that integrates the accumulated travel cost values. In this way, a flow value is assigned to each cell across the raster layers representing the analysed landscapes. Nonetheless, the reliability of the outcome obtained chiefly depends on the density of destination points and on the spatial resolution of the Digital Elevation Model (DEM); both parameters must be calibrated to the study area, data quality and—most importantly—the research questions addressed. The strength of this method lies in the fact that, because it does not require a predefined origin and incorporates all cells (pixels) within the study area; it generates an accumulation value that can consistently be interpreted in relation to the overall distribution of values produced by the analysis. Furthermore, insofar as the characteristics of the landscape can be reconstructed, these routes acquire a diachronic quality, as they are not contingent upon archaeological sites assigned to a specific period. Rather, they represent the ways in which mobility is structured and configured within a given landscape over time. As such, this FMN application provides a simplified representation of potential terrestrial mobility. It does not account for maritime routes or past shoreline changes and is constrained by the resolution of the DEM and its exclusive focus on topographical and hydrographic features.

3.3. Spatial Design Network Analysis (sDNA)

Although the procedure described above isolates the most plausible movement corridors, the objective extends further: to model the historical connectivity of ancient Crete. Accordingly, the raster outputs are converted into graph structures and examined with network-analytic techniques [34]. Additionally, a set of accumulation values has been obtained, which allows for the quantification of the strength of connections between different locations based on their potential for circulation. This is of critical importance, as the study is grounded in the concept of spatial networks, where connectivity is defined not only by the number of links between places but also by the strength—or intensity—of those connections.

However, before applying these network-based approaches to the data, it is essential to undertake a series of preliminary steps. These include the review and correction of potential topological errors that may have emerged during the network generation process, such as fragmented segments or discontinuous intersections. This step is crucial to ensure that the analysed network introduces the least possible amount of distortion. Once the network has been revised and corrected, the next phase involves integrating the accumulation values (raster) with each segment or section of the route (vector). To ensure a high degree of precision, a line density analysis was first conducted, enabling the gradual visual identification of areas with the highest flow accumulation values associated with each route segment. Subsequently, a buffer zone was created in vector format, with linear distance parameters of 1 km on either side of each segment. The buffer was generated using the default 'planar' method, which ensures that, when working within a projected coordinate system, as in this case, the resulting areas of influence are calculated using Euclidean distance (Figure 5).

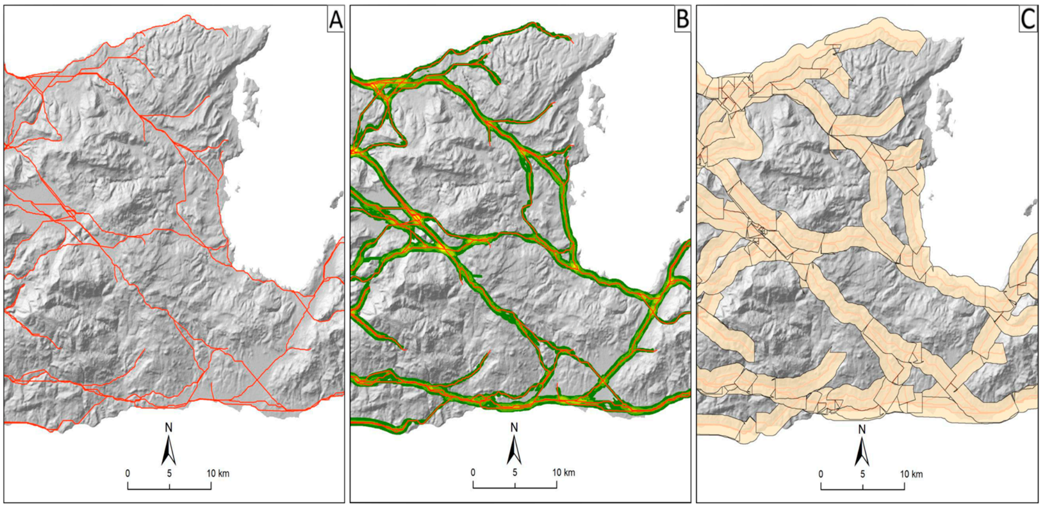


Figure 5. Illustration of the process used to capture flow accumulation values within the area of influence surrounding each network segment, rather than limiting the analysis to pixels directly intersected by the vectorized network. (**A**) Vectorized network of Crete; (**B**) line density analysis displayed as a heat map, highlighting cells with the highest flow accumulation values (indicating potential mobility); (**C**) a 1 km buffer applied on each side of each network segment to encompass relevant accumulation values.

To enhance the analytical capacity of the study, a series of metrics were also derived from these values. These measurements include the area, number of cells, sum, average, standard deviation, range and length for each network segment. Finally, to complete the structure of the network data, it was necessary to define nodes at the start and end of each segment, assigning a unique identifier (ID) to each. These fields represent the intersections where each segment begins and ends. Upon completion of these steps, the result is a layer that not only represents the integrated network for each study region but also includes all the essential data required to conduct an exploratory network analysis.

Given that the research questions focus on identifying the roles played by ancient settlements, key connection points and transit routes as structuring elements within the communication and exchange networks shaping these landscapes, one of the primary objectives was to independently analyse the roles of both nodes (e.g., settlements, connection points) and edges (e.g., routes, mobility corridors). But how can we determine which elements are most critical within these networks, and what specific roles do they play? To address these questions, various metrics are available that assess the contribution of these entities in terms of accessibility and connectivity—metrics that fall under the broader concept of 'centrality.' Broadly defined, centrality encompasses a set of measures designed to identify strategic nodes and edges, thereby facilitating an understanding of the overall structure and functionality of a network [34].

The structure of the mobility routes was examined using the Spatial Design Network Analysis (sDNA) (v.4.1.1) application package, developed by the Cardiff School of Planning and Geography in collaboration with the Sustainable Places Research Institute [35]. Originally designed to adapt network science metrics to the analysis of spatial networks, particularly within urban environments, sDNA has also been successfully applied to the study of historical transport networks across various analytical scales [36,37]. This tool enables the extraction of key metrics that facilitate an understanding of the overall structure and functioning of a network, based on parameters such as the centrality of its component segments [35–37].

Using this approach, it has been possible to evaluate which segments and nodes were more central and better connected, as well as to identify those that played a critical role in facilitating the flow of communication and exchange within these networks. Specifically, the metrics analysed—discussed in greater detail in the following section—include the degree centrality, closeness centrality and betweenness centrality. At this level of analysis, degree centrality reflects the level of immediate connectivity of each segment, determined by the number and strength (intensity) of its potential circulation. Closeness centrality indicates how close a given connection is to all other components in the network, while betweenness centrality measures the frequency with which a segment functions as a 'bridge' or intermediary between different parts of the system [34].

4. Results and Discussion

The first part of this paper details the process of the archaeological mapping. Once the survey was completed, a total of 1665 archaeological sites were identified, spanning from the Late Bronze Age to the Late Roman occupation (Figure 6, above). Their distribution underscores the island's archaeological density and diversity, covering all four regional units: Chania (western Crete) with 347 sites; Rethymno and Heraklion (central Crete) with 119 and 663 sites, respectively; and Lasithi (eastern Crete) with 535 documented sites. This regional breakdown enabled a detailed and comparable analysis of each area, facilitating the detection of recurrent patterns and occupation dynamics across the island.

In addition, the systematic classification applied to each record—supported by a validation scale—served two main purposes. First, it established a rigorous framework of systematisation, ensuring consistency and normalisation in the treatment of sources and data. More importantly, it improved the overall precision of site location and enabled a critical appraisal of the confidence associated with each dataset. This was crucial, since locational accuracy directly affects the contextualisation of archaeological evidence and, consequently, the interpretation of results (Figure 6, below).

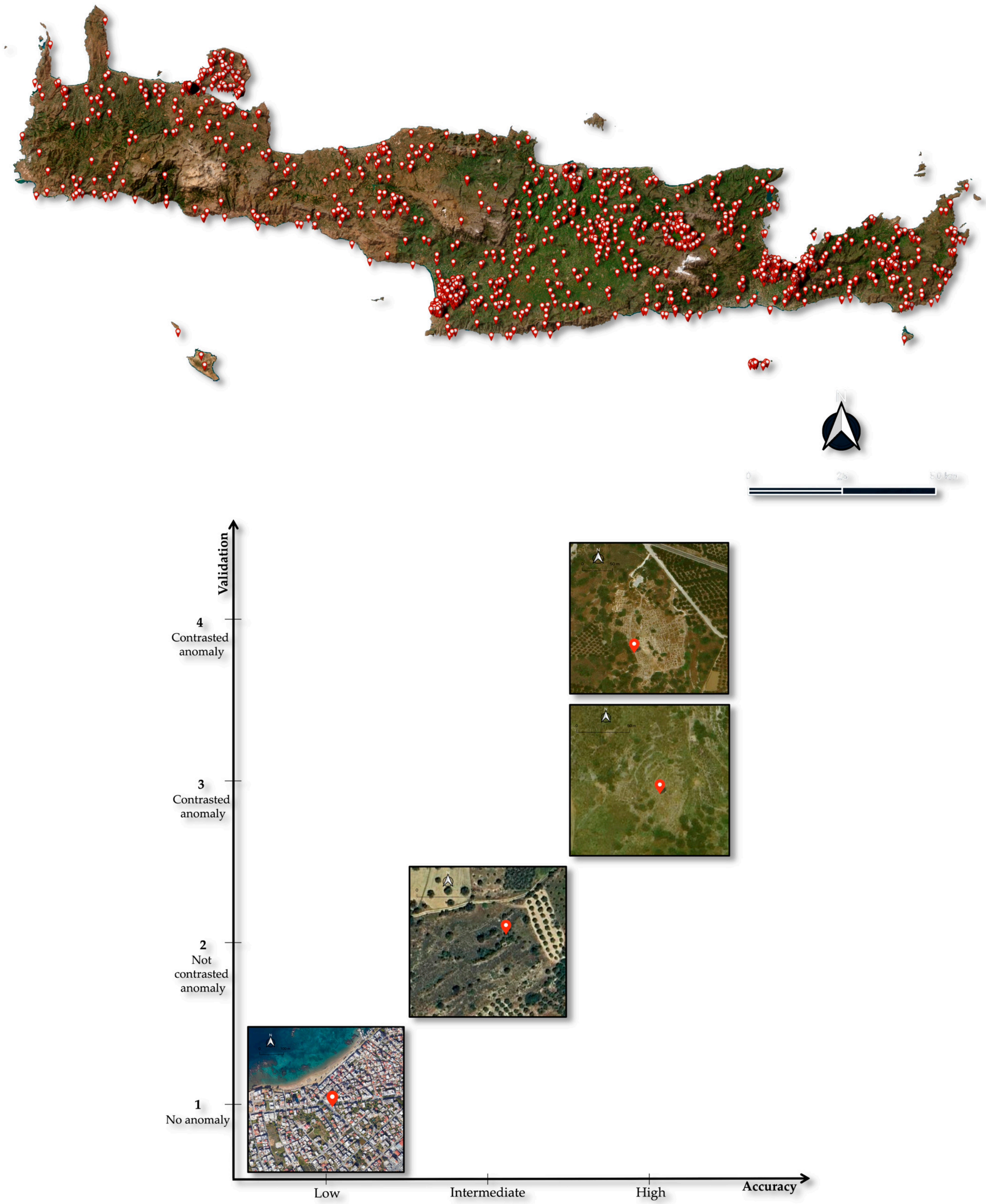


Figure 6. (**Above**) Map of Crete illustrating the locations of ancient sites from the Late Bronze Age to the Late Roman period documented in the study. (**Below**) Examples of archaeological sites categorised according to the level of source accuracy and validation.

The second part of this paper presents, in detail, the procedures for mobility and network reconstruction, which are organised in two distinct phases: (i) an initial (re)constructive phase and (ii) a subsequent analytical phase. Although the workflow comprises conceptually discrete steps, it was implemented using Python 2.7 integrated with ArcGIS (v.10.5). This approach enabled the optimisation of data management and the automation of the entire workflow.

First, the working environment was established and configured based on the delimitation of the study area—i.e., the entire island of Crete—using a Digital Elevation Model (EU-DEM, Copernicus) with a spatial resolution of 25 m and the hydrographic network encompassing the region. Regarding the latter, extensive work was carried out using hydrological tools and remote sensing data integrated within the GIS platform. The objective of this approach was to model these systems and produce an accurate representation of areas with the highest potential for flow accumulation and flood risk, taking into account the characteristic seasonality of Mediterranean environments (Figure 7).

Figure 7. (**Above**) Setup of the working environment through code. (**Below**) Digital Elevation Model (25 m resolution) of the island of Crete, overlaid with the hydrographic network. Areas of highest flow accumulation, as identified in this study, are highlighted.

To generate an Accumulated Cost Surface (ACS) that explicitly incorporates movement friction, we first quantified the influence of the main environmental drivers on regional mobility, which are the topography and the hydrographic network. Slope values were calculated as percentages instead of degrees, recognising that steeper gradients impose higher travel costs. Concurrently, the hydrographic network was assigned a specific resistance by buffering the channels by 100 m on either side (Euclidean distance) and applying a graded cost that rose to a maximum of 15% through a conditional expression (Figure 8). The 100 m buffer represents an average riparian zone where movement may be broken by unstable banks or seasonal flooding. As the model is based entirely on the DEM, it already incorporates steep slopes, fault scarps and fractured terrain.

Figure 8. Procedure for calculating slope (expressed as a percentage) and assigning a graduated cost to areas intersecting the hydrographic network.

The resulting layer was then transformed with Naismith's rule to approximate human walking speed. On level ground, an adult can cover ~5 km h^{-1}, or 12 min km^{-1}, but for every 10 m of ascent (≈1% gradient), an extra minute is added—an 8.33% increase in cost. Thus, at a 12% gradient, the cost effectively doubles relative to flat terrain. Operationally, the friction factor X was computed with $X = 0.0833 \times P + 1$, where P is the slope (%) and X is the resulting cost, yielding a more realistic portrayal of how environmental conditions shaped human mobility.

Once the final cost surface layer or friction map (ACS) was generated, a grid of points was placed within an orthogonal mesh, and 5 km spacing was chosen as an optimal balance between spatial resolution and computational manageability. This resolution provides a sufficient sample size to produce coherent and spatially representative results while remaining within the processing capabilities of standard GIS software. In total, 331 simulated points were established to represent destination sites (Figure 9). By deliberately excluding previously documented archaeological sites, the objective was to minimize potential biases in the model, thereby enabling an exploratory approach in which patterns and areas of interest could emerge organically from the model itself, rather than being influenced by known site locations. With both the point grid and the friction map integrated, the sequence of operations associated with the FMN methodology was then executed.

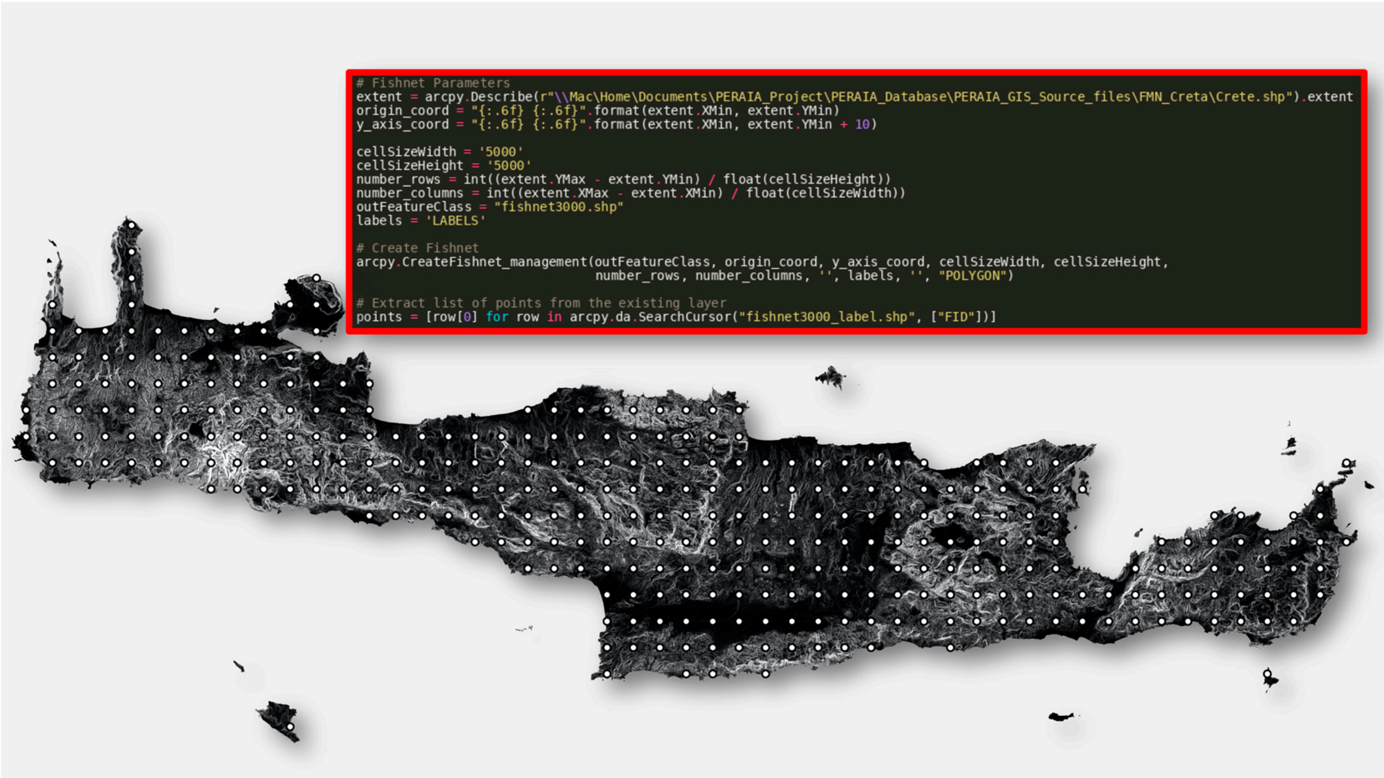


Figure 9. Point grid consisting of 301 target points uniformly distributed across the island of Crete, with a spacing of 5 km between them.

During analysis, the process was repeated for each of the destination points, generating multiple raster files per iteration—namely, cost distance, flow direction and flow accumulation. In this case study, with 301 destination points, a total of 903 raster layers were produced (3 per point). This has important logistical implications in terms of both processing time and storage capacity. Consequently, it is essential that archaeologists intending to apply this type of approach should be aware of the associated computational demands.

Finally, to generate the integrated network, the average of all the flow accumulation raster layers produced for each destination point was calculated. This resulted in a single raster file that visualises the network of potential routes or corridors structuring mobility across the island (Figure 10). In this raster layer, each cell contains a value representing the accumulated cost of travelling from any point within the study area to each of the destination points. By visualizing these potential routes, it becomes possible to identify the key corridors likely to have connected different regions, highlighting routes and areas characterised by the lowest cost and, consequently, the highest accessibility. This approach has not only facilitated the interpretation of mobility across Crete but also provides a foundational framework for reconstructing patterns and dynamics of interaction, communication and exchange throughout its landscapes.

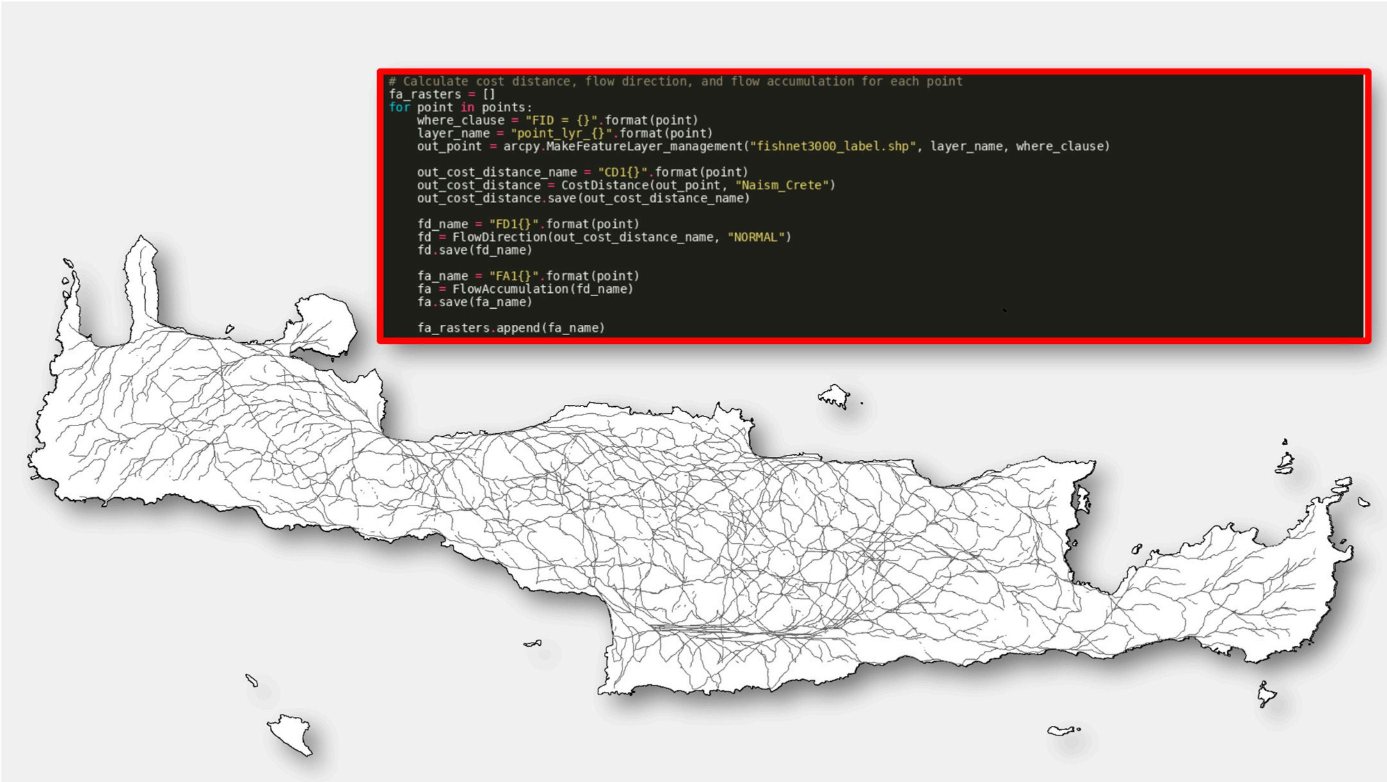


Figure 10. (**Above**) Sequence of operations comprising the FMN workflow. (**Below**) Preliminary results illustrating all potential routes and corridors identified throughout the study area.

As shown in Figure 10, the application of the FMN method produces a large number of routes due to the nature of this type of analysis. This high volume of data can complicate the interpretation of results. Therefore, it is necessary to conduct further processing to retain only the most significant routes—those that represent the greatest potential for mobility. To achieve this, the accumulation values were reclassified based on specific thresholds in the raster data to derive a vector-based network. In this regard, Llobera, Fábrega-Álvarez, and Parcero-Oubiña [22] emphasize that there is no strict rule for determining the appropriate threshold, as different thresholds reveal different hierarchical levels within the resulting network structures. Nonetheless, they propose a guideline based on factors such as the size of the study area, the pixel resolution and the desired density of the network for analysis.

In this study, to ensure methodological consistency with previous applications, we adopted parameters established in earlier works—particularly those of Sylviane Déderix [28,29]. Déderix applied this methodology to the Messara Plain in south-central Crete during the Early Bronze Age, using a reclassification based on 1/4 standard deviation. The same criterion was adopted here, resulting in the retention of only the primary routes or corridors with the highest potential for mobility (Figure 11). Additionally, to explore the strength of connections in terms of intensity, the values were further configured to emphasize corridors with the highest accumulation levels—that is, areas with the greatest potential circulation (Figure 12).

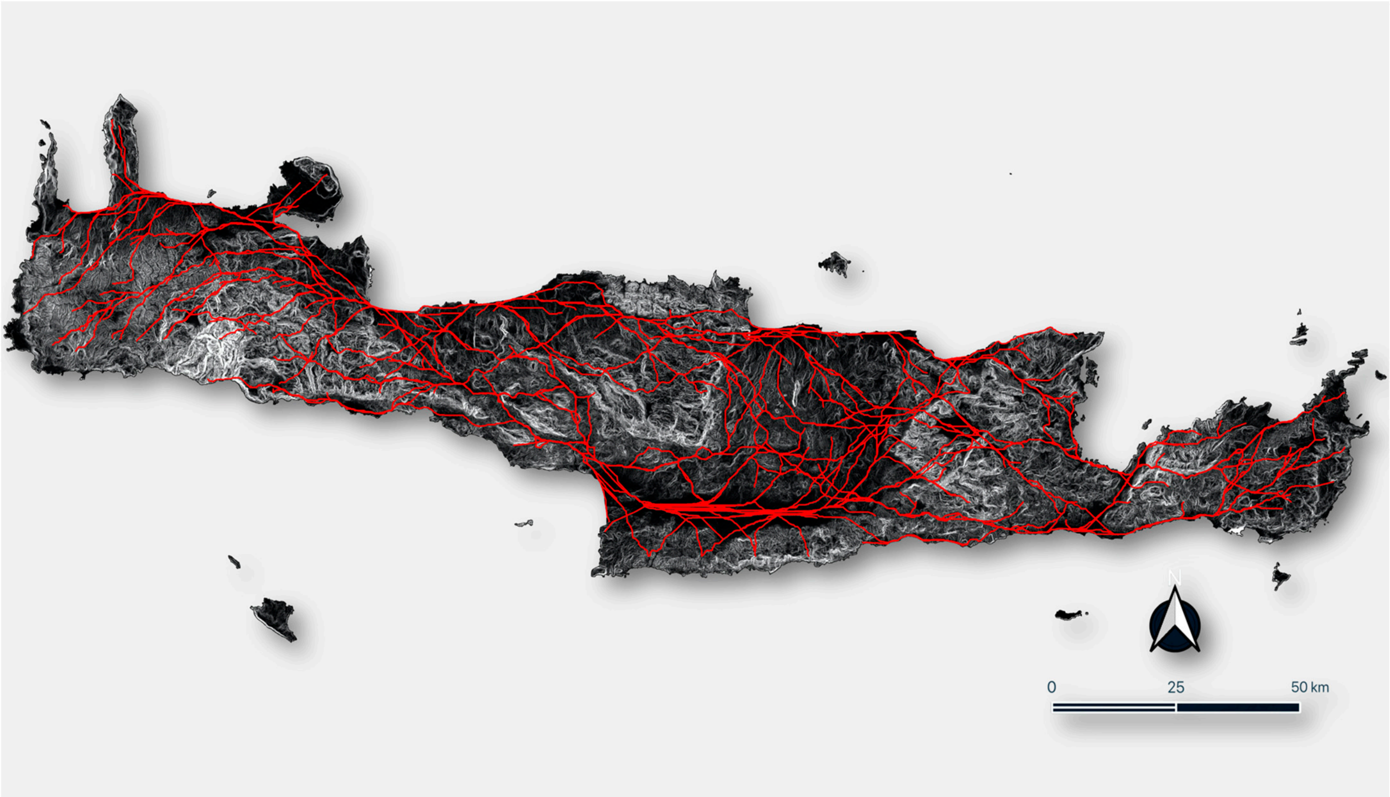


Figure 11. Final results after statistical reclassification (standard deviation 1/4), isolating only the routes or corridors (red) with the highest flow accumulation, representing areas with the greatest mobility potential.

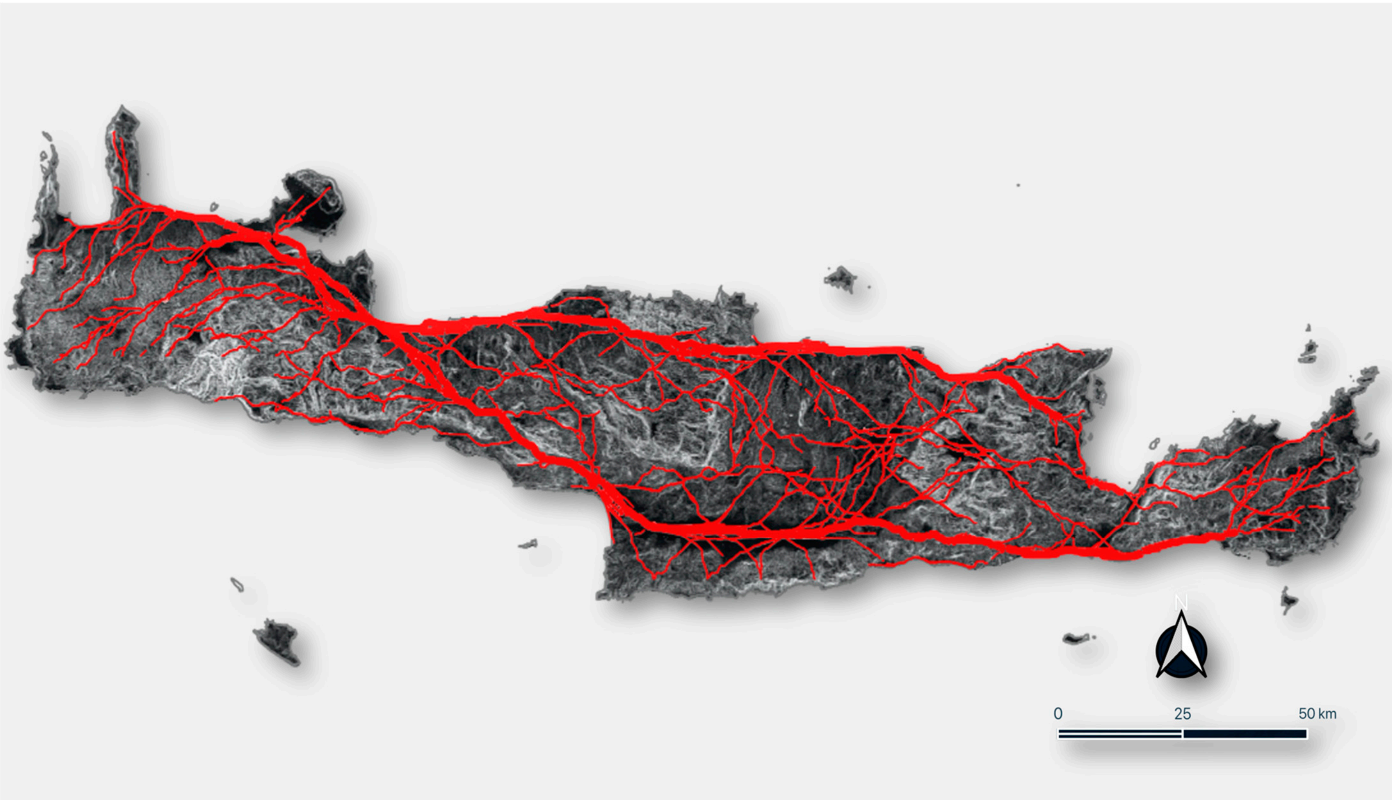


Figure 12. Gradual representation of corridors (red) with the highest flow accumulation values, highlighting areas with the greatest potential circulation.

Overall, the results indicate greater connectivity along coastal areas compared to inland regions. This pattern is generally consistent, with a few notable exceptions, such as the south-central coast, where the Asterousia Mountains serve as a natural barrier between the Libyan Sea and the island's interior. In this case, mobility corridors are redirected through adjacent areas, particularly the Messara Plain, which functions as a natural pass and emerges as a strategic transit point linking different parts of the island. The routes or corridors with the highest accumulation values—those with the greatest potential for circulation—converge along two main trajectories. The first follows a west–east axis along the northern coast, beginning in the Chania region and connecting key locations via natural passes such as the Selinari Gorge. This corridor links the north-central region with Agios Nikólaos and continues towards the Bay of Mirabello, where it branches out towards the easternmost parts of the island. The second main corridor follows a similar direction but diverges southward from Apokóronas, connecting with the Messara Plain. From there, it continues eastward along the southern coast towards Ierapetra and ultimately links with the easternmost regions of the island.

In terms of accessibility, the areas connected by these primary corridors exhibit a clear advantage over other regions. This is strongly evidenced by the strategic placement of key centres of occupation and human activity during the periods under consideration such as Kydonia, Knossos, Phaistos, Kommos, Gortyna, Mochlos or Palaikastro, which are all situated in close proximity to these main transit routes. This spatial advantage is reflected in the socioeconomic dynamics of these sites, where accessibility likely played a central role in facilitating the growth and development of local communities. Consequently, proximity to these routes appears to be directly correlated with the socioeconomic flourishing of the aforementioned areas. These results suggest that accessibility was a fundamental driver of economic growth and social complexity, enabling sustained flows of communication and exchange across the island.

These results offer clear responses to several of the research questions posed, providing a detailed understanding of historical patterns of mobility and settlement in Crete. First, the most probable corridors for reaching specific destinations are shaped by accessibility, which is notably higher in coastal zones and in the valleys that connect the northern regions with the central southern part of the island. Moreover, when comparing different areas, it becomes evident that the principal centres of human occupation and activity during the periods under study are strategically situated at key points along routes with the highest potential for movement. This spatial alignment underscores the importance of accessibility in shaping patterns of human settlement and interaction.

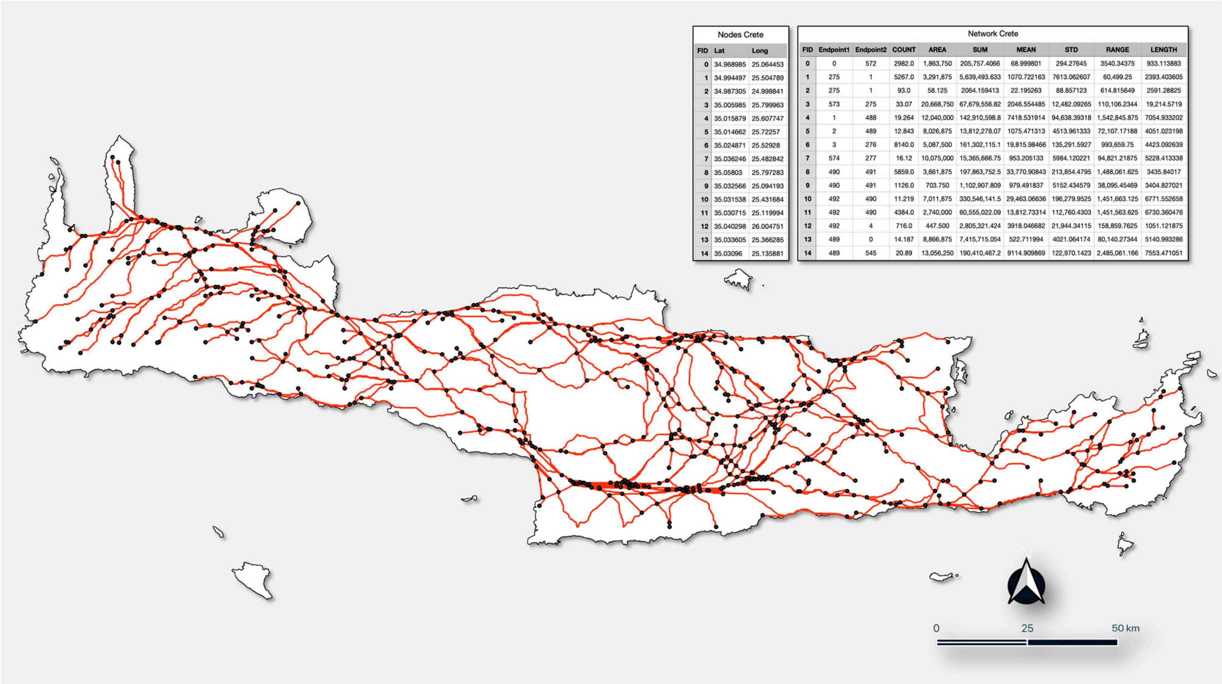
Thus, accessibility not only facilitated mobility between different areas, but may also have significantly influenced the location and distribution of settlements along these communication corridors. Indeed, the choice of where to establish major centres such as Knossos, Phaistos or Gortyna was likely not accidental but shaped by their strategic placement along natural transit routes. These corridors provided reliable lines of movement, resources and communication, making them decisive factors in the foundation and longevity of urban centres. Of course, accessibility was only one among several considerations—religious traditions, political authority and symbolic landscapes also played important roles—but it must be regarded as one of the principal determinants shaping settlement planning and civic organization. Crucially, accessibility also extended to maritime routes, ensuring connectivity not only within Crete but also across the wider Aegean and Eastern Mediterranean. In this respect, settlement patterns reveal both continuity with earlier Bronze Age traditions of seaborne interaction and moments of rupture, when shifting political, economic or cultural dynamics redefined how communities engaged with the sea. Furthermore, the mobility routes identified largely correspond to natural pathways that Cretan societies likely utilized to connect various parts of the island, thereby forming a historical network of routes that enabled sustained interaction among communities.

Although these results provide a comprehensive framework for understanding long-term settlement and interaction patterns across Crete, certain challenges persist. Future research could expand the scope by incorporating additional data and considering a broader range of variables to further refine the models. Additionally, the quality of the results is inherently tied to the resolution of the Digital Elevation Model (DEM), the density of destination points and the cost function employed. Moreover, while FMN routes provide a plausible reconstruction of ancient mobility on Crete, it is important to acknowledge that these models are hypothetical constructs rather than direct archaeological evidence. They do not fully account for potential changes in route utility over time or the influence of specific sociopolitical factors. Although the consistency between historically known and modelled routes is noteworthy, the results should be cross validated with field evidence wherever possible. Additionally, comparative studies with other Mediterranean regions could offer valuable context, situating the mobility patterns observed in Crete within a broader regional framework.

However, as emphasised throughout this study, the analysis has not been limited to the examination of sites and routes alone. In alignment with the theoretical framework underpinning this research, sites of human occupation and activity—along with the identified historical routes, roads and mobility corridors—are conceived as components of an interconnected network. This conceptualisation enables the integration of these elements into flexible trajectories within structures that can be navigated in any direction, not merely along the shortest or most efficient paths. Adopting a network-based perspective fundamentally transforms the analysis of these processes. While cost or friction surfaces consider the entirety of passable space, a network represents a set of structured elements that articulate flows of communication and exchange across multiple levels and scales. Although this approach may appear to entail certain theoretical limitations—such as the exclusion of interactions occurring outside the network—it also provides significant analytical advantages, as will be discussed in the following paragraphs.

The first consisted of a study of the network as a whole, focusing on the role played by each section, that is to say, the specific function performed by each route within the general dynamics of the network. To do this, we started from the flow accumulation values obtained, which allowed us to infer the potential circulation throughout the network, in combination with the Spatial Design Network Analysis (sDNA) application package. These types of tools allowed us to conceptualise and evaluate the routes as entities within the spatial network, facilitating the analysis of key metrics such as the degree of centrality, intermediation and proximity.

Degree centrality was employed to measure overall connectivity within a defined radius of the network at distinct spatial scales, in this case, 20 km and 50 km. This metric calculates the number of connections at each intersection or junction within the specified radius, weighting each one according to the sum of the accumulation values (i.e., traffic intensity). Betweenness centrality was particularly valuable for identifying key routes within the network, those functioning as critical axes of connectivity. This metric evaluates the frequency with which a route segment is used as an intermediate step in connecting different parts of the network, thereby highlighting the most frequently traversed corridors. These strategic routes are often vital to the overall stability and functionality of the network, as their disruption could fragment the flow of communication and exchange. Finally, closeness centrality offered a complementary perspective by emphasizing the accessibility of each route within the network. This metric measures the proximity of each segment relative to all others, thus identifying routes that facilitate fast and direct access across different areas (Figures 13–15).



Nodes Crete

FID	Lat	Long
0	34.968985	25.064453
1	34.994497	25.504789
2	34.987305	24.998841
3	35.005985	25.799963
4	35.015879	25.607747
5	35.014662	25.72257
6	35.024871	25.52928
7	35.036246	25.482842
8	35.05803	25.797283
9	35.032566	25.094193
10	35.031538	25.431684
11	35.030715	25.119994
12	35.040298	26.004751
13	35.033605	25.366285
14	35.03096	25.135881

Network Crete

FID	Endpoint1	Endpoint2	COUNT	AREA	SUM	MEAN	STD	RANGE	LENGTH
0	0	572	2982.0	1,863,750	205,757.4066	68.999801	294.27645	3540.34375	933.113883
1	275	1	5267.0	3,291,875	5,639,493.633	1070.722163	7613.062607	60,499.25	2393.403605
2	275	1	93.0	58.125	2064.159413	22.195263	88.857123	614.815649	2591.28825
3	573	275	33.07	20,668,750	67,679,556.82	2046.554485	12,482.09265	110,106.2344	19,214.5719
4	1	488	19.264	12,040,000	142,910,598.8	7418.531914	94,638.39318	1,542,845.875	7054.933202
5	2	489	12.843	8,026,875	13,812,278.07	1075.471313	4513.961333	72,107.17188	4051.023198
6	3	276	8140.0	5,087,500	161,302,115.1	19,815.98466	135,291.5927	993,659.75	4423.092639
7	574	277	16.12	10,075,000	15,365,666.75	953.205133	5984.120221	94,821.21875	5228.413338
8	490	491	5859.0	3,661,875	197,863,752.5	33,770.90843	213,854.4795	1,488,061.625	3435.84017
9	490	491	1126.0	703.750	1,102,907.809	979.491837	5152.434579	38,095.45469	3404.827021
10	492	490	11.219	7,011,875	330,546,141.5	29,463.06636	196,279.9525	1,451,663.125	6771.552658
11	492	490	4384.0	2,740,000	60,555,022.09	13,812.73314	112,760.4303	1,451,563.625	6730.360476
12	492	4	716.0	447.500	2,805,321.424	3918.046682	21,944.34115	158,859.7625	1051.121875
13	489	0	14.187	8,866,875	7,415,715.054	522.711994	4021.064174	80,140.27344	5140.993286
14	489	545	20.89	13,056,250	190,410,467.2	9114.909869	122,970.1423	2,485,061.166	7553.471051

Figure 13. Representation of mobility networks on the island of Crete, illustrating nodes that connecting endpoints of each route segment. Each segment integrates accumulation values as well as multiple attribute metrics, including area, length, sum, mean, standard deviation and range.

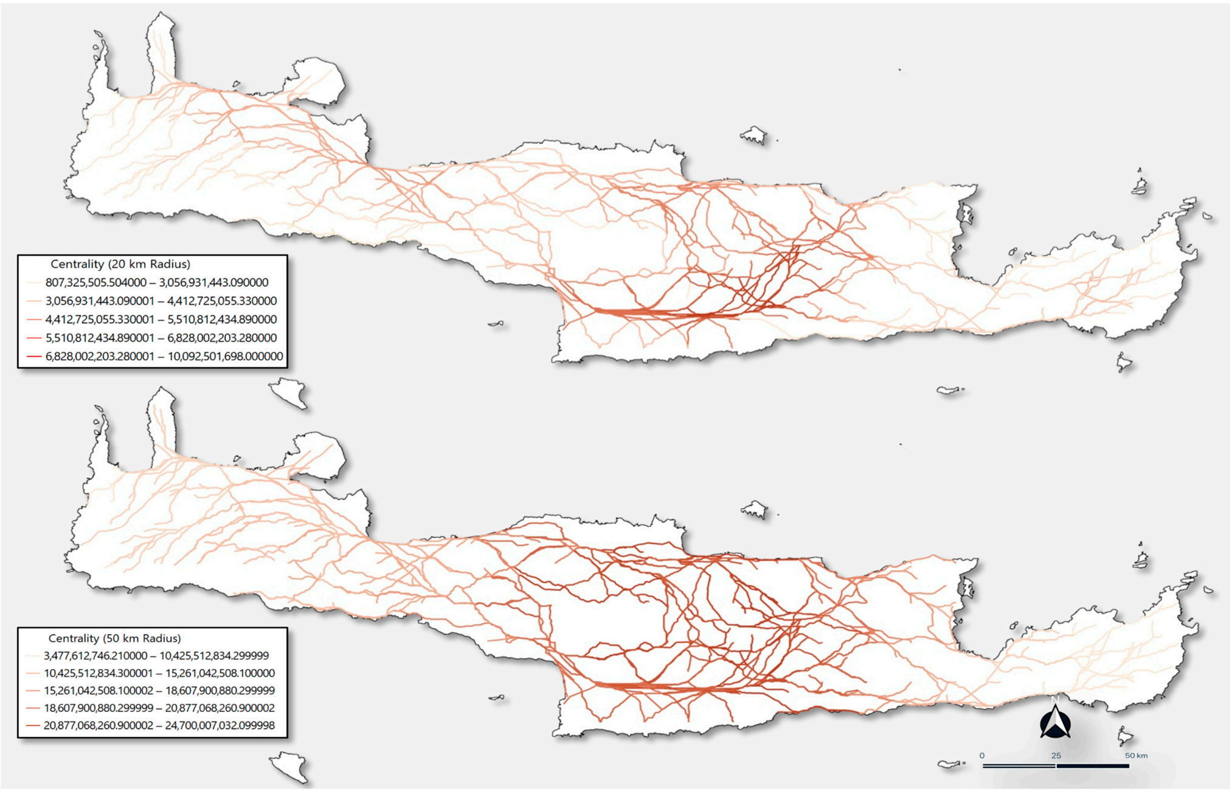


Figure 14. Degree centrality analysis using radii of 20 km (**above**) and 50 km (**below**). Centrality is assessed based on the strength of connections, weighted by circulation potential indicated by accumulation values.

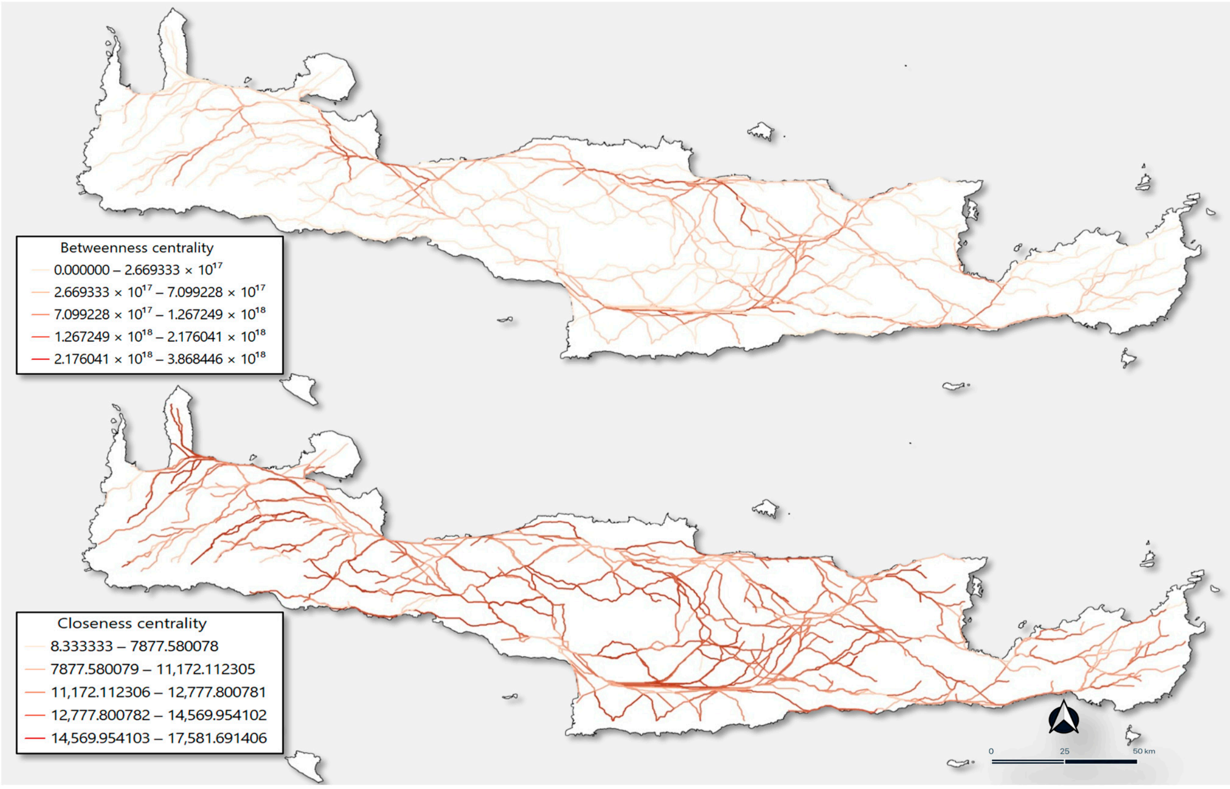


Figure 15. Betweenness centrality (**above**) and closeness centrality (**below**) analyses, both conducted using a 20 km radius. The complete mobility network of Crete is shown, emphasizing strategic corridors. High betweenness centrality values highlight key segments that serve as crucial intermediaries in connecting different parts of the network, whereas high closeness centrality values identify segments that provide optimal direct access across regions.

This exploratory analysis has enabled a comprehensive evaluation of the historical mobility networks in Crete, revealing both the overall connectivity of the network and the presence of strategic corridors, those characterized by high betweenness centrality and routes that facilitate direct access, as indicated by high closeness centrality. These metrics, calculated using values that reflect potential circulation, have been instrumental in deepening our understanding of how these networks shaped the socio-spatial dynamics and territorial organization of the island, as well as the historical mobility patterns that emerged and evolved over time.

The results highlight the pivotal roles played by specific routes and nodes in shaping patterns of mobility, communication and exchange. Notably, central Crete encompasses the majority of the strategic land corridors and accessible pathways identified through centrality measures, offering compelling evidence of a well-integrated system designed to support the island's socioeconomic and sociocultural functions. The fertile plains of central Crete, combined with their proximity to key urban centres, positioned this region as a natural nexus for trade and communication, effectively connecting the eastern and western parts of the island. However, it is essential to incorporate maritime connections (cabotage) into the analytical framework. These maritime networks facilitated the movement of goods and people between coastal settlements, effectively bridging otherwise isolated regions and enhancing the overall connectivity of the island. This analysis also underscores the resilience and adaptability of these historical networks. The relationship between highly connected nodes and strategic routes reveals a system optimised for both stability and efficiency. This aligns with the prominence of significant multi-period urban centres such as Knossos, Phaistos and later Gortyna and Ierapytna, which emerged within these interconnected areas. These centres functioned as hubs for governance, resource distribution and cultural exchange, leveraging strategic land corridors to maintain their influence over both nearby and distant settlements. From a cultural point of view, while all the important Cretan centres did not coexist throughout antiquity, there are clearly several important avenues for further investigation in future studies. One such example is the relationship between the strategic land corridors computed in the present research and the main Roman and Late Roman networks as depicted in the Tabula Peutingeriana. The main city centres shown on the Roman map are mostly located along the principal land corridors identified in this study. This will form the next step in the authors' research, where environmental factors will be analysed alongside cultural aspects in specific periods as part of a Research Programme [38,39].

5. Conclusions

Building on this methodology, the mapping process offered a long-term perspective on settlement patterns, while FMN modelling identified the natural corridors that likely channelled past movement across the ancient Cretan landscape. By integrating different variables, the models underscored the interplay among topography, hydrography and other factors in shaping patterns of settlement and interaction. The raster outputs depicted the spatial configuration of probable pathways, revealing high-potential routes that correspond with documented traditional tracks and pointing to new areas that warrant further investigation.

In this way, this study identified several primary mobility corridors with varying levels of accessibility. As outlined earlier, two major mobility axes were detected: (i) The first follows an east–west trajectory along the northern coastline, linking key areas including Chania, Heraklion, Sissi, Agios Nikolaos and Mirabello Bay, and extending to the easternmost regions of Sitia. (ii) The second connects the northwestern part of the island with the Messara Plain and extends along the southern coast to Ierapetra, and from there reaches the eastern zones. Overall, coastal pathways offered relatively lower friction and thus facilitated exchange, trade and communication. The exception is the south-central region, where the Asterousia Mountains act as a natural barrier. In this area, mobility was concentrated through the Messara plain, a strategic zone connecting the interior and coastal regions, where natural corridors such as valleys, plains and mountain passes served as critical conduits of past movements.

From a historical perspective, these identified mobility axes underline the importance of accessibility in shaping the distribution and development of sites on ancient Crete. Major urban centres, such as Kydonia, Knossos, Malia, Phaistos, Gortyna, Ierapytna or Gournia, are strategically located along these primary mobility corridors. This correlation suggests that proximity to accessible routes was a decisive factor in the growth of these communities. The enhanced connectivity facilitated by these corridors likely supported economic activities, social interaction and cultural exchanges, contributing to the sociopolitical complexity observed in these areas during the analysed periods. The emphasis on accessibility also provides insights into the spatial organisation of settlements, suggesting that historical populations strategically utilised natural corridors to optimise communication and resource distribution. Thus, the observed patterns of mobility indicate that the rugged landscape of Crete served not only as a constraint but also as an enabler of connectivity and interaction, thereby shaping the island's sociocultural and socioeconomic trajectories.

Beyond demonstrating patterns of accessibility, the reconstructed corridors may indicate how mobility, and in essence, proximity and access to major routes, shaped the social and cultural landscapes of ancient Crete. The alignment of these routes with major centres suggests that mobility networks did more than facilitate commerce and economic exchange;

they also structured intercommunity relationships. In several instances, terrestrial corridors intersected with coastal nodes, creating points where land and sea routes converged and reinforcing the dual importance of overland and maritime communication. These intersections likely served as hubs for the redistribution of goods, ideas and people, embedding mobility into nearly every aspect of society. It is important to note, however, that most major Cretan centres, with some significant exceptions such as Roman Hierapytna, were situated inland at a considerable distance from the coast. Knossos, for example, which controlled more than one harbour in the present-day Heraklion area, lies about 5 km from the shoreline. Overall, the reconstructed routes should not be viewed simply as technical models of past movement but as integral elements in the negotiation of power, identity and interaction within the Cretan world.

Consequently, settlement strategies on Crete adapted not only to shifts in resource availability and ecological conditions but also to human capabilities, illustrating the resilience of its societies. Its enduring role as a socioecological 'historical palimpsest'—i.e., a layered record of coevolutionary interactions between human and non-human forces, with each period leaving its imprint on the landscape—highlights the intricate interplay shaping Crete's natural and social trajectories. Understanding these landscapes as both a physical and dynamic social record of human–environment interactions provides a robust foundation for interpreting Crete's historical and ecological narratives.

At the second level, the analytical approach centred on the overall network structure emphasised the specific roles of individual routes and nodes within the network's dynamics. Utilising flow accumulation values and the Spatial Design Network Analysis (sDNA) toolkit, the analysis quantified topological key network metrics such as degree centrality, closeness, and betweenness to identify the multifaceted roles of nodes (e.g., key connection points) and edges (e.g., mobility corridors) within these networks. These metrics allowed for a nuanced understanding of the connectivity, strategic importance and accessibility of routes at different spatial scales. (i) Degree centrality: This metric highlighted the overall connectivity within specific radii (20 and 50 km), identifying intersections or crossings with the highest concentration of connections. Weighted by flow intensity, degree centrality underscored how certain routes facilitated high levels of circulation, making them essential for maintaining the network's coherence. (ii) Betweenness centrality: The analysis of betweenness centrality was pivotal in identifying key corridors within the network. These routes, frequently used as intermediaries connecting different parts of the network, emerged as critical to its stability. Their disruption could fragment communication and exchange, illustrating their centrality in maintaining the network's integrity. (iii) Closeness centrality: By focusing on accessibility, this metric provided insights into routes that enabled rapid and direct mobility across the network. The metrics underscored the importance of certain pathways in optimising connectivity and fostering direct interactions between different zones.

Collectively, the results reveal a comprehensive picture of the historical networks in Crete, delineating the strategic corridors and urban centres that optimised both local and regional connectivity. These elements likely had profound implications for the island's socio-spatial dynamics, influencing patterns of interaction, communication and territorial development over time. Thus, the application of this approach to the study of ancient Cretan connections has yielded significant insights into the spatial and relational dynamics of historical settlements and their connective infrastructure. Therefore, this analysis has revealed a nuanced 'big picture' of how distinct elements structured and influenced patterns of communication, exchange and social interaction within the ancient Cretan landscapes.

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Data Availability Statement: All the data and associated information are available at https://peraia.es/gazetteer/ (accessed on 23 July 2025).

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Abbreviations

The following abbreviations are used in this manuscript:

GIS	Geographic Information Systems
DEM	Digital Elevation Model
ACS	Accumulated Cost Surface
sDNA	Spatial Design Network Analysis
FMN	Focal Mobility Network
MADO	Modelo de Acumulación de Desplazamiento Óptimo

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