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Exploring Balıklı Archaeological Settlement and Its Surrounding Landscape via GIS and Geophysical Survey

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Research Article

Abstract − This study utilizes a multi-scale methodology that combines geophysical surveys with Geographic Information Systems (GIS)-based analysis of satellite imagery and Digital Elevation Models (DEM) at the Balıklı Archeological Settlement. Ground Penetrating Radar (GPR) revealed potential subsurface structures, while regional analyses, including satellite imagery, DEM, slope, aspect, Normalized Difference Vegetation Index (NDVI), watershed delineation, mass movement susceptibility, and viewshed assessments, offered a comprehensive understanding of the area's topography, hydrology, and landscape suitability. The results suggest that Balıklı should be strategically situated on relatively flat, south-facing terrain near water catchments, providing favorable conditions for living and strong visual control of the surrounding landscape. Gathering integrated spatial and geophysical data is crucial in archeology, as it offers valuable insights into how ancient societies engaged with their surroundings. This data also forms a foundational spatial framework that supports further investigations into settlement patterns, land use, and cultural evolution.

Keywords *– Balıklı archeological settlement, GIS, archeological prospection, DEM, satellite imagery*

1. Introduction

In recent decades, airborne remote sensing technologies, such as aerial photography, satellite imagery, and Light Detection and Ranging (LiDAR) [1-3], alongside ground-based methods like geophysical surveys [4-6], have significantly transformed archeological research. The non-invasive nature of remote sensing and geophysical techniques allows for efficient mapping and detection surface and subsurface remains. When integrated with Geographic Information Systems (GIS), these technologies offer powerful tools for analyzing spatial relationships, reconstructing ancient environments, and contextualizing archeological features within broader landscapes [7-9]. GIS allows researchers to combine diverse data sources such as maps, satellite images, LiDAR data, and information on soil, water availability, and elevation within a single interactive system. This integration facilitates analyzing how different factors interact and influence past settlement patterns. When these data layers are viewed together, patterns that might be overlooked in isolation become more apparent, enabling deeper insights into the landscape and human behavior over time [9,10]. Today, considering the importance of digitalization, the need for integrated evaluation of increasing diverse datasets, and the accessibility of local-scale data, GIS-based analysis has increasingly been applied in archeological research in Türkiye. For instance, a data catalogue for the study of the Roman and Byzantine water supply systems in Istanbul was developed using remote sensing and surface survey data [11]. A web-based GIS

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platform was created for documenting the cultural heritage of Safranbolu, emphasizing the integration of various datasets [12]. Similarly, 3D models of Istanbul's historical Golden Horn were developed using remote sensing and GIS technologies to support heritage documentation, restoration planning, and conservation monitoring [13]. A combined interpretation of geophysical and GIS-based remote sensing data was conducted at the Kerkenes archeological site [14]. Detailed spatial analysis using DEM-derived slope, aspect, and visibility data was performed in the ancient city of Alinda to explore the relationship between topography and planning principles [15]. A GIS database incorporating topographic, photographic, and archeological data was created for the Malazgirt battlefield [16]. Predictive modeling for potential archeological sites in Silifke was achieved by integrating remote sensing data with GIS-based analysis of slope, river networks, and other environmental variables [17]. High-resolution remote sensing data, soil surveys, and archeological findings were used to study paleochannels in the Cilicia region [18]. High-resolution DSMs derived from Ikonos and ASTER stereo-pairs supported the development of a base map for archeological surveys in the Hierapolis-Phrygia territory [19]. Spatial analysis of the Knidos archeological site involved DEMs, slope, and visibility to interpret settlement patterns [20]. In the same region, GIS-based spatial analysis incorporating aspect, elevation, slope, and visibility data was used to build a comprehensive archeological database [21]. A GIS based analysis applied in Cilicia to evaluate environmental impact on archeological sites [22]. An integrated remote sensing approach involving GPR, resistivity, and Unmanned Aerial Vehicles (UAV)-based infrared thermography was employed to trace remains of the ancient Silk Road [23]. A relational GIS database derived from UAV-based DEM analysis was developed for the ancient city of Anemurium [24]. UAV photogrammetry and GIS analysis were applied to document the Yazılıkaya Midas Fortress [25]. At the Savatra site, GPR survey data were integrated into a 3D GIS system by combining volumetric data with DEM analysis [26]. UAV-based photogrammetry and DEM analysis were used to digitally record the historic architecture of Harran, including the basilica and mosque [27]. In Aşağıpınar, the living environment of a prehistoric settlement was analyzed through slope, aspect, hydrological, and geomorphological data within a GIS framework [28].

Balıklı is documented as an early Neolithic site (c.8300-7900 BC) and located in Gülağaç District, Aksaray in Türkiye (Figure 1). It is thought that abundant natural resources should attract the Balıklı community to this locality [29]. Salvage excavation began in 2018, and based on initial studies, Balıklı covers approximately 1.0 hectares, featuring an archeological deposit that ranges in thickness from 1.0 to 2.5 meters [30]. Two main occupational phases have been identified at Balıklı. The upper phase dates to a time after the settlement had been entirely abandoned, when some buildings were reused as burial grounds. The earlier phase reflects the primary habitation, characterized by a community of roughly 100 to 150 individuals mainly relying on hunting and gathering, supplemented by some small-scale farming. The buildings at Balıklı display a uniform layout, characterized by similar dimensions and alignments that indicate a standardized construction method. Typically oval, these structures feature stone and mud walls, plastered floors, and various internal elements, including burials. They generally measure about 5 to 6 meters in diameter. A notable feature is a rounded section within most buildings, believed to have served as a small ventilation shaft [29-31].

Despite its acknowledged significance, Balıklı and its surrounding landscape remain insufficiently studied regarding spatial organization and environmental interaction. This study addresses that gap by integrating GIS-based analysis of satellite imagery, DEM, and geophysical methods to investigate Balıklı. Combining geophysical surveys, satellite image interpretation, and spatial analysis of DEM data, the research aims to serve as a preliminary work to provide a foundation for future studies, identification of new problems about settlement organization, land-use patterns, and the dynamics of human-environment interaction at the Balıklı archeological settlement.

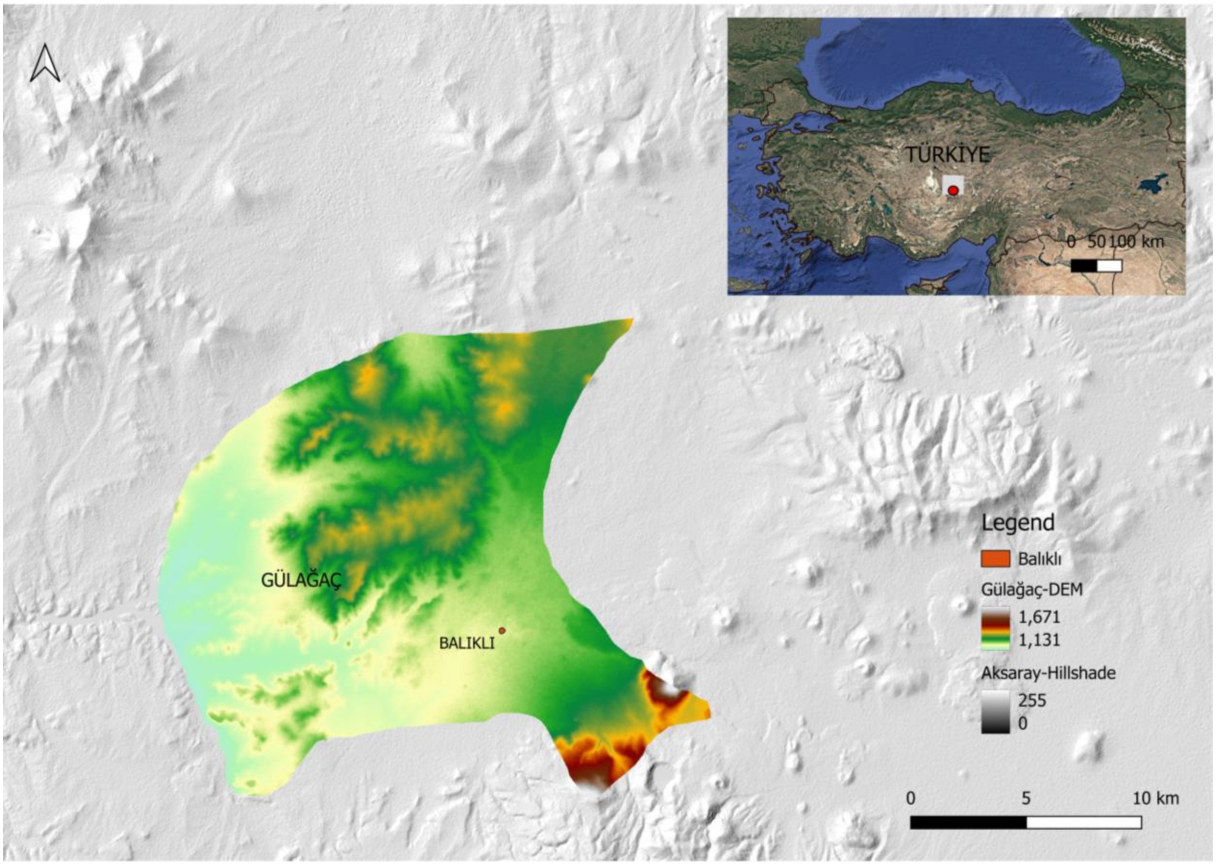


Figure 1. Location of Gülağaç District and Balıklı Settlement, represented on Digital Elevation Model from ALOS PALSAR

It appears that during the Neolithic Period, a true turning point marked by the transition from a nomadic lifestyle to settled living, along with the advent of agriculture and animal domestication, the geography of the study area offered a natural environment that allowed prehistoric humans to settle in one place for long periods without needing to migrate constantly [32,33]. According to the research findings and the data obtained, it has been understood that different phases of the Paleolithic, Epipaleolithic, and Neolithic periods exist in region [30]. The region known as Western Volcanic Cappadocia includes the province of Aksaray, which is characterized by a rich geological structure. Within this area lie the volcanic Hasandağ and Ekecik Mountains, part of the broader volcanic landscape, including the Melendiz Mountains. Volcanic activity has also shaped the northeastern, eastern, and southern parts of Aksaray, forming extensive plateaus [33]. Prehistoric communities utilized various hard and soft rocks for tool-making and daily activities. One of the significant raw materials found in the region is obsidian, also known as natural or volcanic glass. The nearest and directly associated sources of obsidian are Nenezi and Göllüdağ, the two prominent volcanic features of the area [34]. Other materials are tuff, andesite, pumice, basalt, and rhyolite [35]. In addition to this, another important natural resource in the region is copper. Within the borders of Aksaray province, a notable copper source is located near Alayhan, specifically in the Düğüz area, where a copper pit has been identified [36]. In terms of hydrological properties of the region, Gülağaç region is surrounded by several rivers.

This paper is organized as follows: Section 2 outlines the methodological framework employed herein, detailing each component within its respective subsection. Section 3 presents the methodological outcomes derived from the case study area and a comprehensive discussion of the findings, emphasizing their significance in advancing the understanding of archeological settlement organization and its interaction with the surrounding landscape.

2. Material and Methods

2.1. Regional Scale GIS-Based Analysis

The primary application of GIS in archeology lies in its capacity to analyze and interpret spatial relationships among archeological features. By examining landscapes, GIS enables researchers to identify patterns in past human behavior, settlement dynamics, and land-use practices. Further, GIS supports advanced spatial analyses, such as viewshed and proximity studies, which provide insights into site visibility, accessibility, and resource exploitation. Integrating archeological, environmental, and topographic data within GIS facilitates the generation of multi-layered maps that enhance the analytical depth and the visual presentation of findings [37]. As a result, GIS has become an indispensable tool in archeological research, offering a robust framework for synthesizing and interpreting complex spatial datasets. In this study, the study area is explored using three different datasets: Planet satellite imagery [38], ALOS PALSAR [39] sourced DEM, and a geophysical survey by GPR. The normalized Difference Vegetation Index map is evaluated and compared with geophysical data. Topographic and landscape analysis from DEM data, including Hillshade, Slope, Aspect, Landform Classification analysis, Mass movement susceptibility analysis, Hydrological analysis, and Viewshed (Visibility), are adopted.

2.1.1. NDVI Analysis from Planet Satellite Dataset

NDVI analysis is a technique applied to remote sensing data. NDVI measures vegetation health by analyzing the reflectance of near-infrared (NIR) and red light. Healthy vegetation reflects more NIR and less red light, resulting in high NDVI values. In archeology, subsurface features such as walls, roads, or foundations can influence the health of vegetation growing above them. For instance, stone features may hinder root development and retain less moisture, causing vegetation stress or sparsity, which is reflected in lower NDVI values. Thus, NDVI makes an essential contribution to archeology by detecting and monitoring changes in vegetation that may indicate the presence of possible buried archeological features [40-43]. This study utilized high-resolution Planet imagery with 3m/px spatial resolution, orthorectified and radiometrically corrected and including the NIR spectral band to calculate the NDVI. The selected image featured minimal cloud coverage and focused spatially on the Balıklı environment. The satellite data were pre-processed using Quantum GIS (QGIS) v.3.34.9 to facilitate band management. Red and NIR bands correspond to Bands 3 and 4 for Planet satellite data, respectively. The expression was executed using the Raster Calculator (2.1) tool in QGIS and the resulting NDVI raster was normalized to a scale ranging from 0 to 1 (0-0.33 low: 0.33-0.66 medium, and 0.66-1.00 high vegetation). Color symbology was applied using a standardized vegetation color ramp to enhance interpretability.

$$NDVI = (NIR - RED) / (NIR + RED) \tag{2.1}$$

2.1.2. Terrain Analysis and Landform Classification

The methodology for conducting terrain analysis begins with a DEM, which provides elevation data for each raster cell. The DEM used in this study was sourced from ALOS PALSAR, with a spatial resolution of 12.5 px/m, covering an extended area of the target region. After the pre-processing phases in QGIS, the DEM model was clipped to the boundaries of the Gülağaç district. Once the DEM was correctly set up, slope analysis was performed using the Slope tool. This tool calculates the rate of elevation change for each cell in the DEM and outputs a new raster layer representing slope, which can be expressed in degrees [44]. The resulting slope map is also used for landform classification and aspect analysis applications. Additionally, a landform classification approach is adopted. This process involves categorizing the Earth's surface into distinct geomorphological units such as hills, valleys, plains, ridges, and basins. The classification is primarily based on DEM terrain attributes, including slope, aspect, curvature, and relative elevation. In the context of environmental archeology at a regional scale, landform classification from DEMs plays a critical role in understanding the relationship between ancient human activity and physical landscape. By identifying specific landforms, archeologists can infer areas likely to contain archeological sites, such as elevated terraces, gentle slopes, or floodplains where human settlement was favorable.

Furthermore, landform data helps assess site preservation potential, as different landform types are subject to varying degrees of erosion or sediment deposition. Ultimately, landform classification enhances cultural landscape analysis, allowing archeologists to interpret how past societies interacted with and shaped their environments over time. In QGIS, landform classification is conducted using Geographic Resources Analysis Support System (GRASS) GIS toolsets, integrated into QGIS's processing toolbox, offering powerful options such as Topographic Position Index (TPI)-based classification, geomorphon analysis, and terrain derivatives like slope and curvature. The tool r.geomorphon, available in GRASS, enabled detailed mapping of landform patterns.

2.1.3. Aspect Analysis

Aspect analysis is a geospatial technique determining a slope's compass direction derived from a DEM [44]. This analysis is particularly valuable in archeology because the orientation of terrain often played a crucial role in ancient site selection, agriculture, and settlement planning. For example, ancient communities usually favored south-facing slopes in the Northern Hemisphere due to their increased exposure to sunlight, which offered warmth and better agricultural conditions. As such, analyzing aspects can provide insight into why specific locations were chosen for settlement or ritual use, shedding light on human-environmental interactions in the past. This information may support broader landscape archeology studies by contextualizing archeological findings within their environmental settings. The methodology for conducting aspect analysis in QGIS involves some steps. After pre-processing DEM data, the Aspect tool calculates directional values from 0° to 360°, representing north through west. This raster data can then be symbolized or reclassified into categorical directions for easier interpretation (such as east and north), which this study prefers.

2.1.4. Mass Movement Susceptibility Analysis

Balıklı is situated in a flat area without significant slopes. However, mass movement activity is common in the surrounding regions, particularly in the districts of Güzelyurt, Gülağaç, and Aksaray (central district), shaped by volcanic activity from Hasandağ and Melendiz [45]. In the east and southeast of Aksaray, young volcanic rocks such as tuff and ignimbrite have weak physical strength and undergo weathering under atmospheric conditions, developing a fractured and cracked structure, which poses a falling hazard, especially in steep areas [45]. Mass movement susceptibility maps were generated in QGIS to analyze this, providing essential information about landslides or other forms of soil movement in the target area. It is typically created using a combination of spatial data layers such as slope, aspect, elevation, and other environmental factors that influence mass movement. By conducting a weighted overlay analysis in QGIS, each layer is assigned a weight based on its importance in contributing to mass movement. For instance, steep slopes (derived from the slope map) are more likely to experience mass movement, while aspects can influence moisture levels and vegetation, affecting soil stability. A weighted overlay analysis was performed, assigning a 50% weighting to slope and aspect values. This resulted in a new map that represents the combined impact of both slope and aspect on mass movement susceptibility, and the final output map is generated, which classifies areas based on their susceptibility to mass movement. This information is crucial for archeological sites because it helps identify areas at high risk of erosion or landslides, which could damage archeological features. By understanding mass movement risks, archeologists can make informed decisions on site preservation, excavation planning, and developing mitigation strategies to protect cultural Heritage from environmental threats [44].

2.1.5. Watershed Analysis

Watershed analysis from a DEM is a technique used to identify the natural drainage patterns of a landscape by analyzing its surface terrain [44,46]. It provides crucial information, such as the boundaries of drainage basins, flow direction, stream networks, and areas of water accumulation. For archeology, watershed analysis is particularly valuable as it helps researchers understand how past human populations interacted with their environment or essential natural sources [37,47]. In QGIS, this process involves filling surface depressions in the DEM, calculating flow direction and accumulation, defining stream thresholds, and delineating watersheds from selected outlet points. These operations are performed using GRASS's hydrology toolbox.

2.1.6. Viewshed Analysis

Viewshed analysis is a spatial technique used to determine the visible areas from a specific observation point or set of points [48] based on the terrain elevation provided by DEM. In archeology, viewshed analysis is significant in interpreting site placement and landscape use [49-53]. It helps assess whether a location was chosen for strategic visual control, surveillance over routes or resources, or symbolic visibility within the cultural landscape. For example, hillforts, burial mounds, or temples might have been deliberately placed for maximum visibility or to oversee nearby valleys, water sources, or movement corridors. Conversely, viewshed analysis can also identify hidden or secluded areas, which helps understand rituals or practices meant to be kept out of view. By modeling what ancient inhabitants could or could not see, viewshed analysis enhances our understanding of spatial decision-making, socio-political point of view [54], and territorial control in past societies [51]. It calculates which parts of the landscape can be seen from a given location (assuming 1.7m as the average viewing height of a standing person and with max distance from viewpoint is 5 km), considering the terrain. In QGIS, viewshed analysis GRASS GIS's r.viewshed tool was used to compute visibility across the surrounding terrain. The result is a raster output where visible and non-visible areas are distinguished, usually in binary or gradient form.

2.2. Geophysical Survey in Balıklı Archeological Settlement

GPR is a non-invasive geophysical technique widely used in archeology to explore and map subsurface structures. The method works by emitting electromagnetic waves into the ground, traveling through different soil layers, and reflecting off archeological materials such as walls, foundations, or artifacts. These reflected signals are captured by the receiver antenna and analyzed to create detailed images of the subsurface Compared to other geophysical methods used in archeology, GPR provides notable advantages, particularly in terms of resolution. Through the use of radargrams and the ability to generate 2D depth slices and 3D volumes, GPR enables effective monitoring of subsurface anomalies across various depths and dimensions of archeological target features. Its application extends beyond open-air rural or urban sites to indoor environments, making it increasingly valuable in the investigation and conservation of cultural heritage monuments in Türkiye. The method's non-invasive nature and high-resolution imaging capabilities have established it as a critical tool in both archeological and architectural research.

At ancient Ephesos, GPR served to detect subsurface elements such as sacred roads and architectural remains [55]. In the vicinity of the Agios Voukolos Church, GPR was combined with magnetometry and electrical resistivity tomography to explore the surrounding features [56]. At the Temple of Augustus in Ankara, radargram analysis led to the creation of detailed two- and three-dimensional visualizations [57]. In Hierapolis, detailed interior maps and ancient topographical data were produced and incorporated into a digital archeological map of the site [58]. Investigations also targeted the Temple of Apollo [59] and other sectors of the city [60]. The method has shown its utility in funerary archeology as well, with graves identified at the Agadere Cemetery. In a Hittite region of Anatolia, integrated surveys combining GPR with other geophysical methods enhanced the identification of anthropogenic fills [61]. At Pisidian Antioch, buried architectural features were detected using GPR and visualized through depth slices and 3D volumetric imaging [62]. Subsequent comparative studies at Keber Tepe examined different site sectors with both GPR and resistivity methods [63]. In the Gallipoli Peninsula, the spatial extent of a potential martyrdom site was defined through GPR analysis, contributing to the historical context of the region [64]. At Aizanoi, additional research continued to demonstrate GPR's non-destructive capabilities in archeological mapping [65].

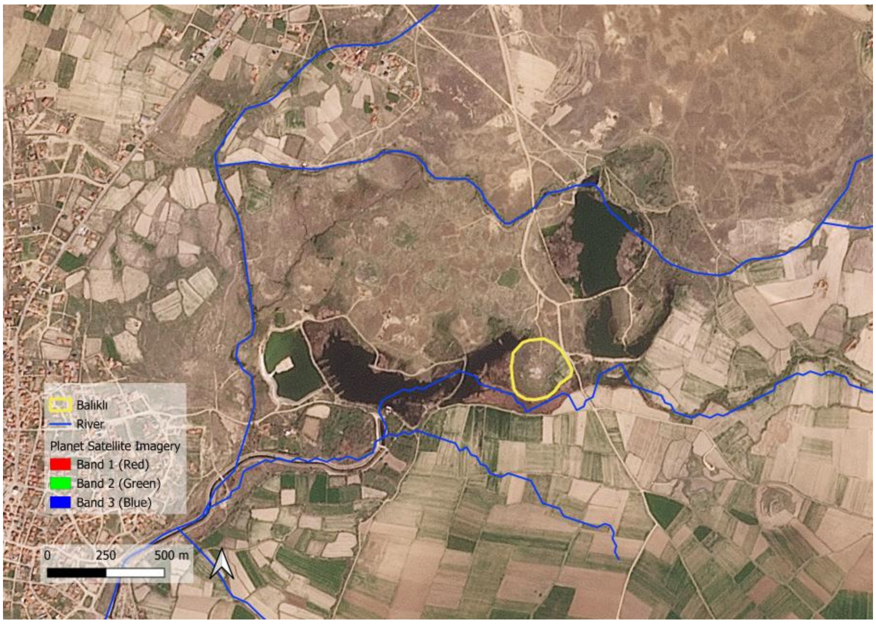
The use of GPR in indoor heritage evaluation has also expanded significantly in Türkiye. Subfloor investigations of the Yerebatan Cistern identified deformation zones critical to structural restoration efforts [66]. Subsurface anomalies detected in the basement and walls of a historic mosque contributed to preservation strategies [67]. Burial-related features were mapped within enclosed spaces, affirming the method's applicability to funerary contexts indoors [68]. In sacred architectural contexts, integrated geophysical investigations at a Byzantine church in Nicosia revealed the buried layout of a basilica [69]. Within the Hagia Sophia, floor depressions and cracking patterns were analyzed [70], complemented by similar GPR work at the Chora Museum focusing on subsurface floor conditions [71]. At the Nysa archaeological site, GPR was used to define the layout of a temple and to support investigations conducted within enclosed spaces [72].

In GPR studies, selecting an effective and appropriate antenna frequency and configuring the survey setup plays a critical role in the study's success. These choices must consider the properties of the archeological materials sought, the soil conditions and target depth. Within the scope of this study, a GSSI SIR 3000 ground-penetrating radar system was used along with a 400 MHz antenna, selected based on the desired investigation depth. The GPR survey and layout of the study area were planned by considering conditions that could reduce the signal-to-noise ratio or generate noise sources.

In archeological studies, topographic surveys divide the measurement area into grids. At Balıklı, five large grids were established across the entire area, using the locations of existing excavation sites as references. GPR data acquisition was conducted in these grids with dimensions of Grid A: 30x20; Grid B: 30x20; Grid C: 30x20; Grid D: 25x30; and Grid E: 30x30. Within these grids, profile intervals are determined based on the targeted estimated geometric properties (e.g., size and thickness). A 50 cm profile interval was used within each grid to obtain high-resolution data. A total of 295 profiles were collected, covering a combined area of 3450 m². The data collected within parameters 8 bit, 512 sample per radar scan, 5120 sampling frequency and 50 ns two-way travel time window. GPR data processing was done by using GPR Slice Software. Basic processing steps (Figure 9) applied to the GPR data included post-processing pulse regaining to enhance the visibility of raw radar pulses and improve reflections at deeper depths using a defined gain curve. A bandpass filter (low-pass 868 Mhz-high-pass 119 Mhz) was applied to the radargrams to eliminate unwanted frequencies present in the raw data. This filter was designed based on the power spectrum plot, which displays the amplitude distribution across various frequencies. Background removal filtering was then performed to reduce banding noise, which appears as horizontal reflection artifacts unrelated to subsurface features. This process involves computing the average signal either across the whole radargram or within a specified moving window and then subtracting this average from each individual recorded trace. An estimated microwave velocity of approximately 0.09 m/ns was obtained by fitting hyperbolic curves to the raw field data. This velocity was then used to calculate the penetration depth achieved during the GPR survey. These processing steps helped improve the clarity and interpretability of the radargrams before further analysis. After pre-processing each radargram collected on the site, 2D depth slice maps are generated. These maps are derived from three-dimensional amplitude volume models constructed by integrating data from all collected radargrams along multiple survey lines. Once the full subsurface volume is generated, it can be sliced in horizontally and optional thicknesses to produce 2D depth slices. These amplitude slice maps provide valuable insights into the depth, shape, and spatial distribution of archeological features, enabling a more detailed interpretation of buried structures.

3. Results and Discussion

The NDVI map is applied to evaluate the insights into surface conditions that may indicate subsurface features. The analysis focuses on the closer surroundings of Balıklı, where Planet image data are available. The NDVI results reveal predominantly medium to low vegetation index values, suggesting areas of sparse or stressed vegetation cover. Notably, at the exact location of Balıklı, zones with very low NDVI values correspond directly with known recent excavation trenches, validating the use of NDVI in identifying anthropogenic disturbances. The original Red Green Blue (RGB) satellite imagery (Figure 2a) and reclassified images included NIR (Figure 2b) is presented. Within the defined boundaries of the settlement, the northern section exhibits a concentration of low NDVI values, which may indicate the presence of buried archeological materials or architectural remains affecting vegetation growth (Figure 2c). This spatial pattern provides a non-invasive means of targeting areas for further investigation.



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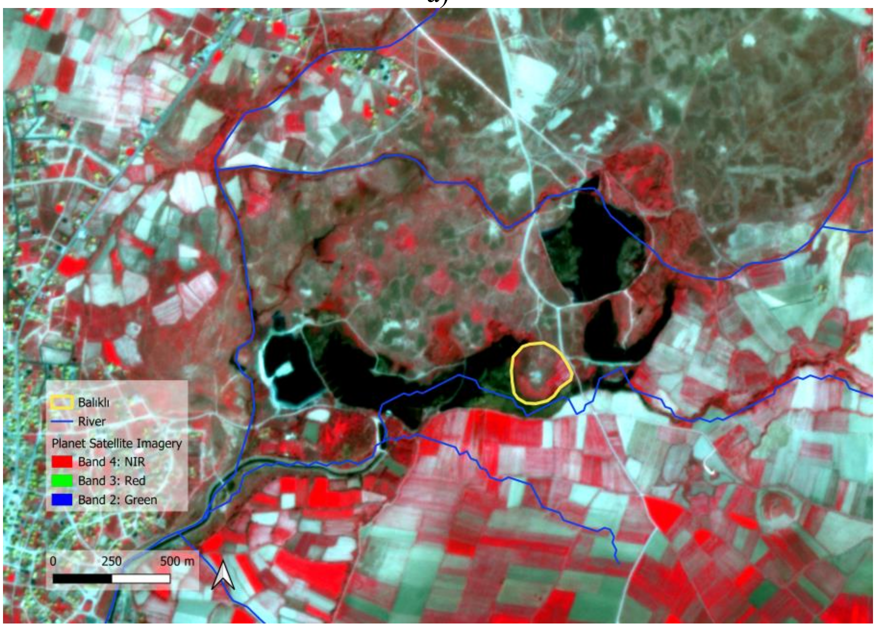
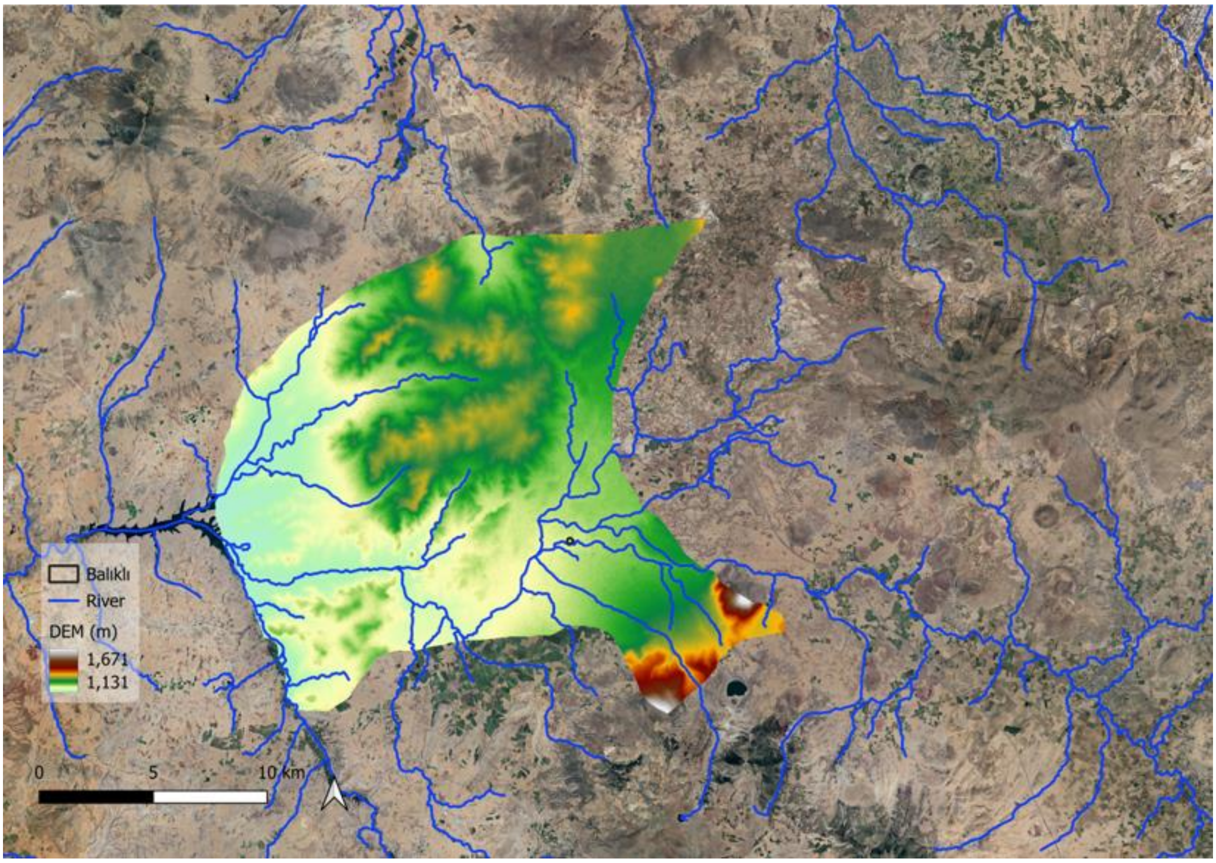


b)

Figure 2. Spatial Analysis from Planet Satellite Imagery **(**Image © 2025 Planet Labs PBC**)** a) Original satellite image b) Reclassification of satellite image

Figure 2. (Continued) Spatial Analysis from Planet Satellite Imagery (Image © 2025 Planet Labs PBC) c) NDVI index map

Spatial analysis of the DEM of the study area is crucial for understanding past human-environment interactions. In this study, DEM data derived from ALOS PALSAR were processed using QGIS to evaluate terrain characteristics such as elevation, slope, aspect, hydrological properties, mass movement susceptibility, and viewshed. The elevation model and slope map help identify areas suitable for past human settlement and understand how the terrain may have influenced movement and land use. Based on DEM (Figure 3a) for this specific boundary, elevation values are 1131- 1671 meters above sea level (masl.). Balıklı is located at an approximate elevation of 1176 masl., placing it near the lower end of the area's elevation range. Based on the slope map (Figure 3b), the slopes vary from 0 to 34 degrees across the study area, while Balıklı has an approximate slope of 5 degrees. In addition to this basic observation, the landform classification approach was adopted using GRASS and the r.geomorphon plugin, which provides 12 geomorphological terrain forms. This plugin categorizes landform types: here, only five are focused on: Flat (areas with relatively uniform elevation), Peak (the highest point in the local terrain), Ridge (elevated linear areas with steep slopes on both sides), Slope (areas with a consistent downward gradient) and Valley (expressed linear areas between ridges or hills). These classifications are derived by comparing each pixel to its surrounding neighborhood based on analyzing 8-cell neighborhoods around each cell in the DEM. Based on this landform classification, Balıklı settled on a flat landform (Figure 4). Flat terrains are often chosen for settlements due to easy access and proximity to water sources. Such locations would have given the inhabitants agricultural advantages, mobility, and defensive visibility.



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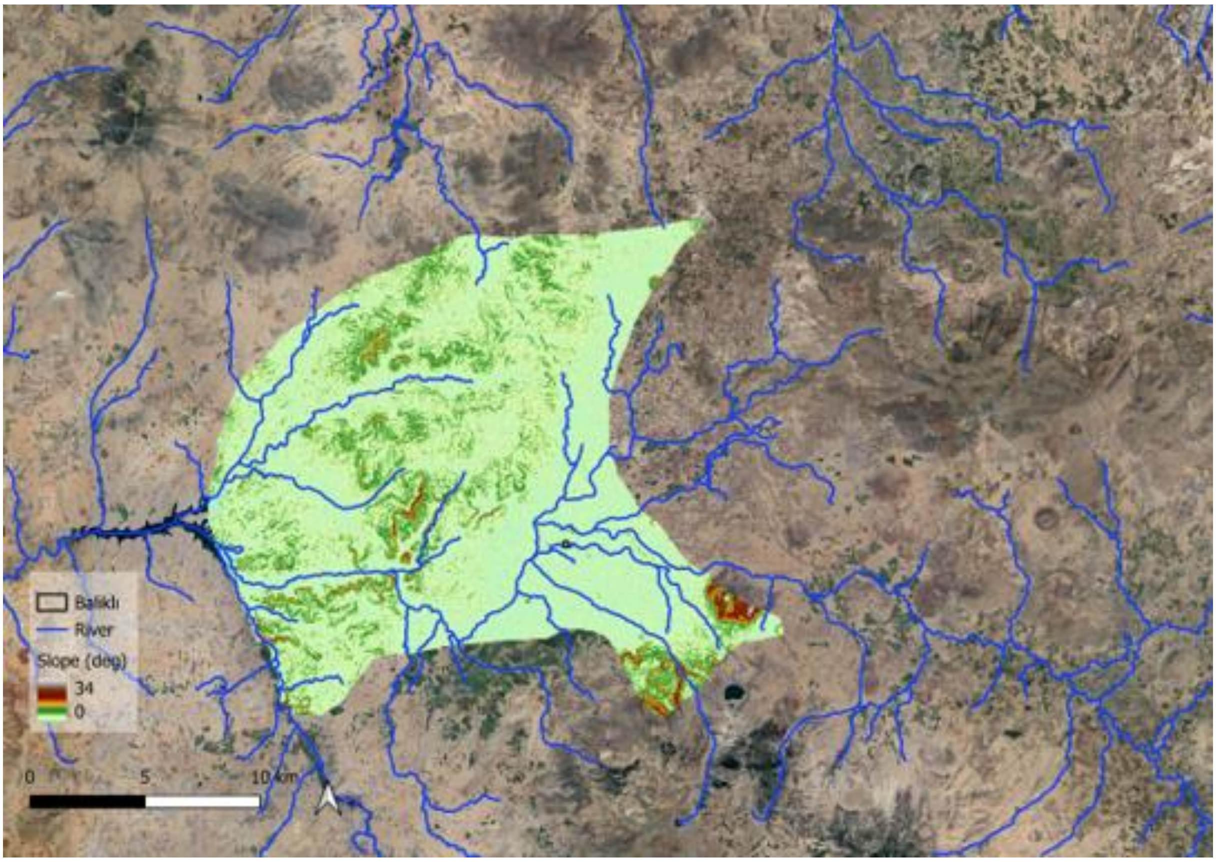


b)

Figure 3. a) Digital Elevation Model b) Slope map of Gülağaç District

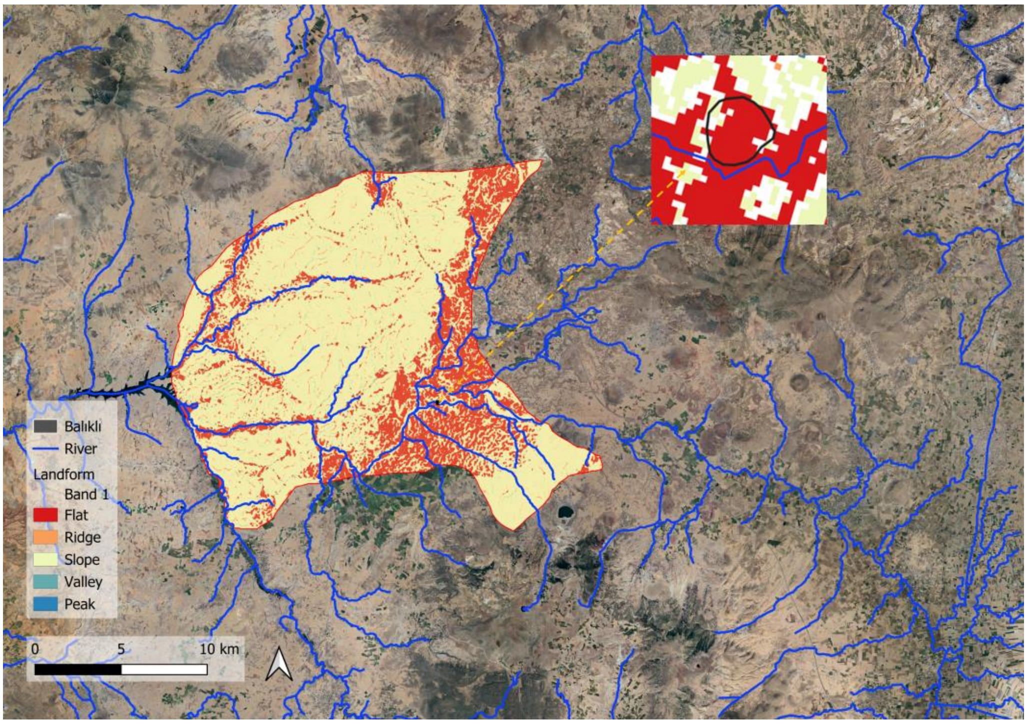


Figure 4. Landform Classification results for Gülağaç boundary and Balıklı Settlement

To conduct a more detailed analysis, the study first integrated the river network data from the European Environment Agency [73] and adopted watershed analysis using DEM (Figure 5). A water basin, also known as a watershed or micro-catchment, is the upslope area that contributes surface runoff to a specific point, in this case, the archeological settlement of Balıklı. As illustrated in the figures, Balıklı is surrounded by several rivers and is located at the intersection of small-scale water basins (approximately 1,000 m²) and moderately sized water basins (around 2,000 m²) based on water basin analysis. This positioning indicates consistent water availability and suggests favorable conditions for both temporary and long-term settlement and the potential for agricultural activity. Larger basins imply a greater capacity for water collection, which could have supported larger populations or prolonged habitation.

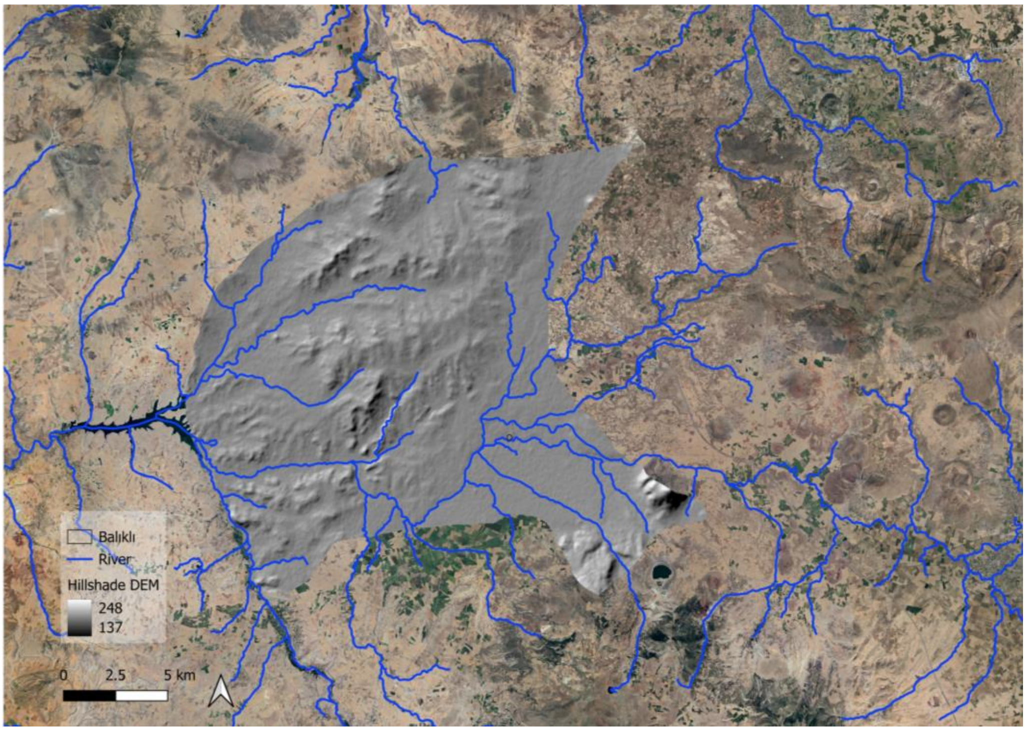


Figure 5. Hydrological spatial analysis a) River networks around Gülağaç Region

Figure 5. (Continued) Hydrological spatial analysis b) Watershed (Hydro-basin) analysis for Balıklı Settlement and its environment

As previously mentioned, aspect analysis can be a valuable tool in archeology in evaluating key site characteristics such as visibility, defensibility, and erosion risks. The results of the aspect analysis indicate that Balıklı was established on a south-facing slope (Figure 6), which could be a strategic choice likely made for several important reasons. South-facing environments receive more sunlight, which would have been advantageous for agricultural activities, improving crop yields and extending the growing season.

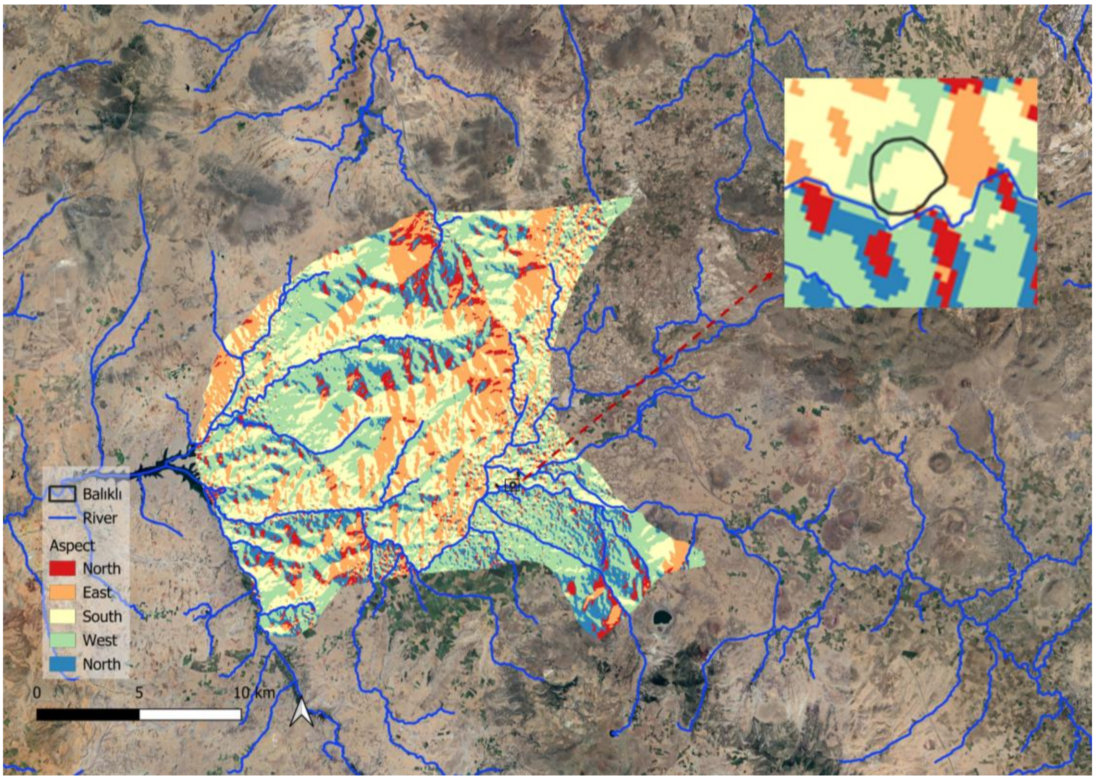


Figure 6. Aspect Analysis for Gülağaç Region and, Balıklı Settlement and its surroundings

Although Balıklı appears flat based on DEM, topographic classification, and slope analysis, the broader Gülağaç region is known to be prone to mass movements [27]. This study assessed mass movement susceptibility using terrain-based data (specifically slope and aspect) due to limited data about the target site. As shown in Figure 7, while there is no significant risk in the environment of settlement scale, a closer look focusing on the approximate dimensions of Balıklı reveals that the southeastern part of Balıklı, closer part also to the river, shows potential susceptibility. This insight can help prioritize archeological surveys in vulnerable areas. For a more detailed susceptibility map in QGIS, incorporating additional topographic, geological, and environmental factors would be ideal. However, slope and aspect remain fundamental terrain indicators and are widely recognized for their role in mass movement risk.

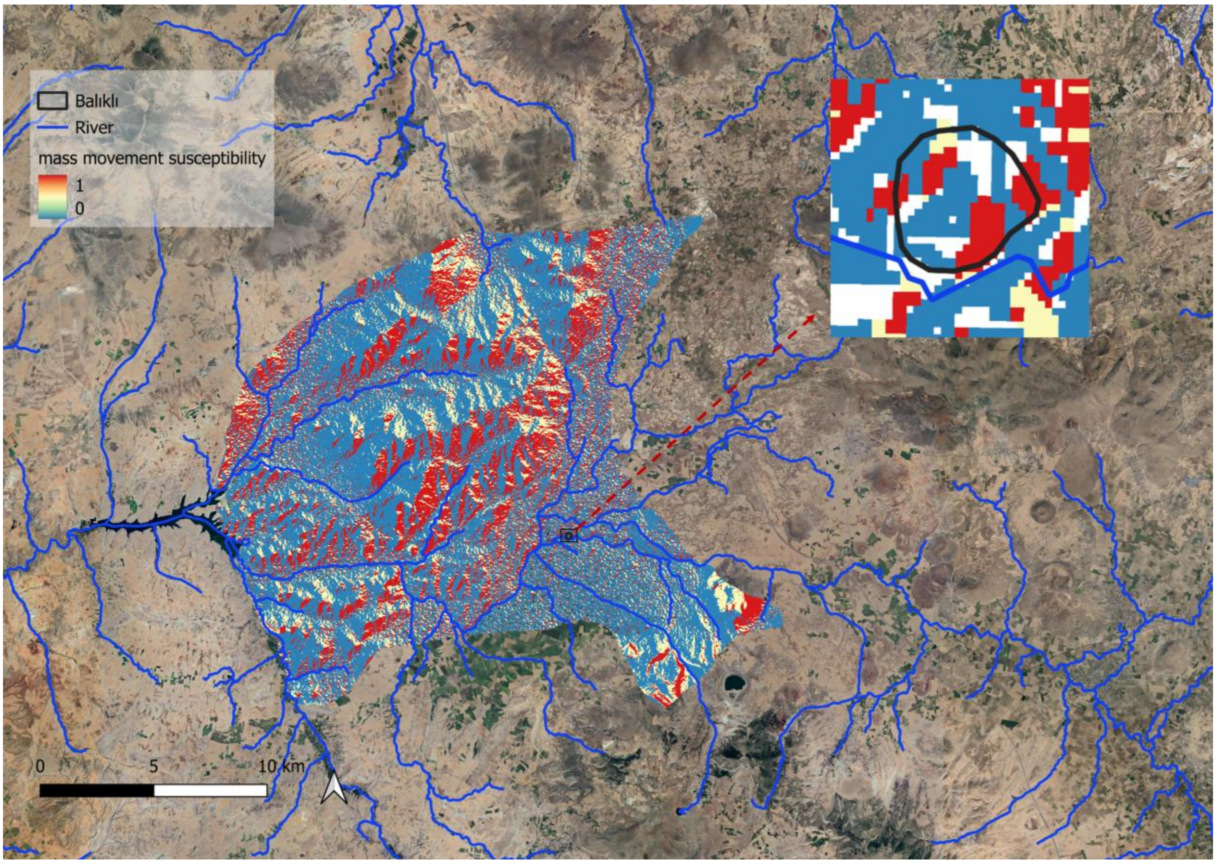
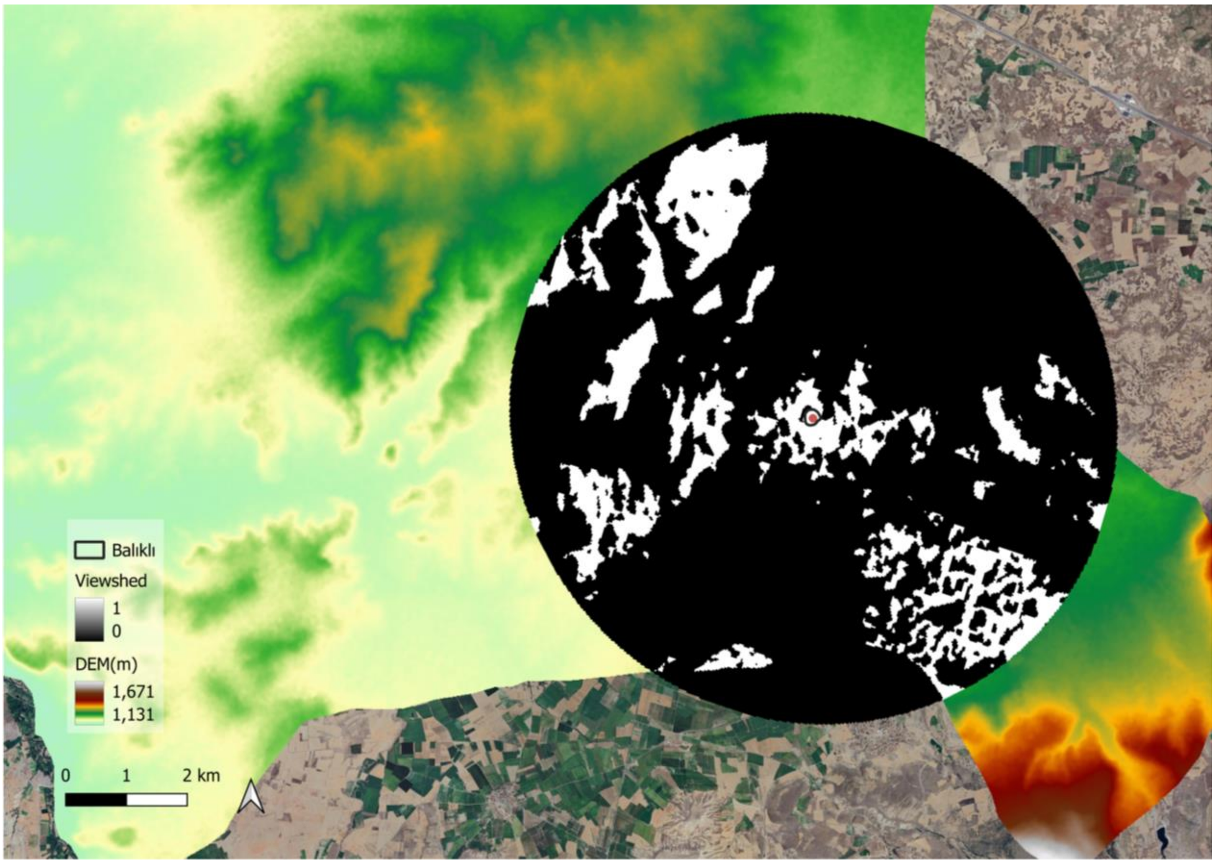


Figure 7. Mass Movement Susceptibility analysis for Gülağaç region, Balıklı Settlement and its surroundings.

The visibility results indicate that from Balıklı, the white areas on the map are visible, while the black areas are not (Figure 8). This suggests a clear line of sight to certain regions, which could have implications for understanding prehistoric settlement layouts, enclosures (if any existed), and communication routes. In archeology, such visibility analysis is essential because it helps researchers reconstruct past landscapes and interpret how ancient communities interacted with their environment and one another. Visibility studies can reveal why a site was chosen and how it may have functioned within a broader cultural or strategic context.



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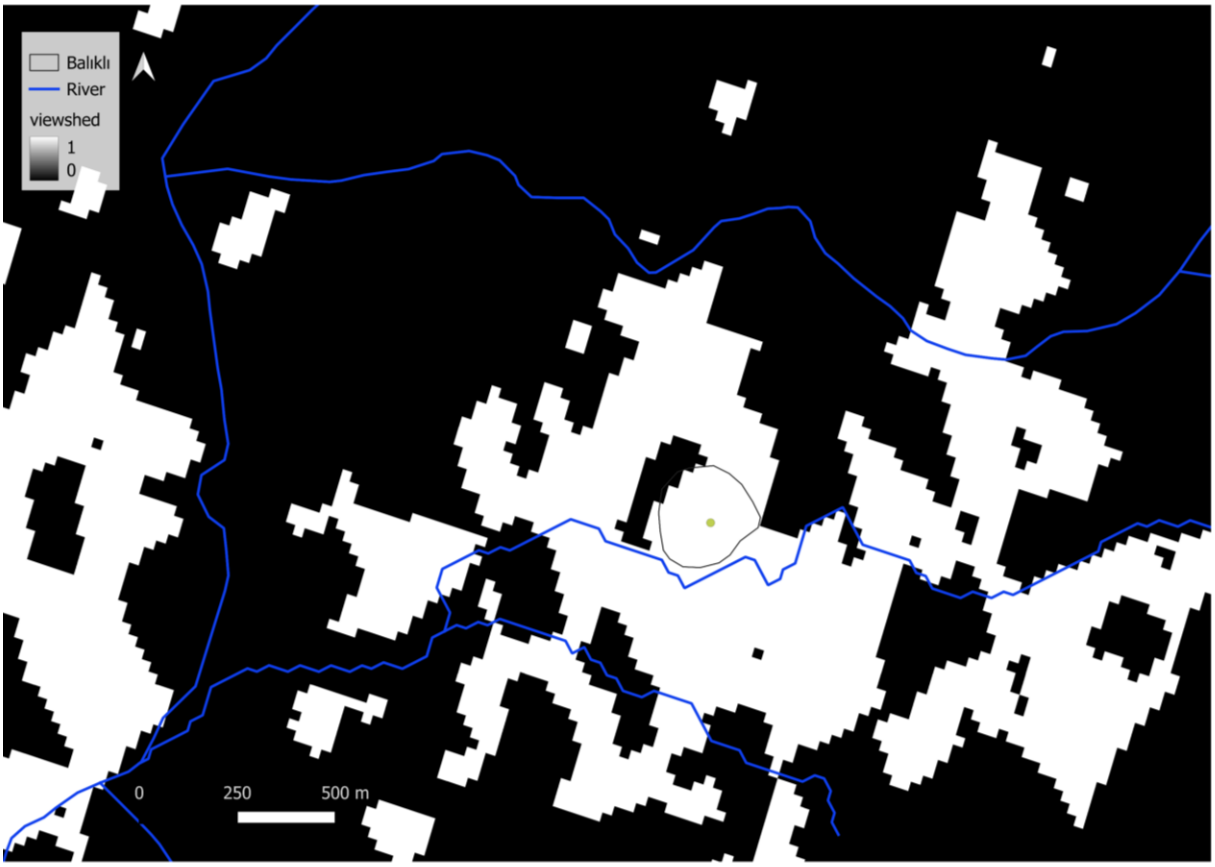

b)

Figure 8. a) Visibility Analysis for Gülağaç b) Balıklı Settlement and its environment

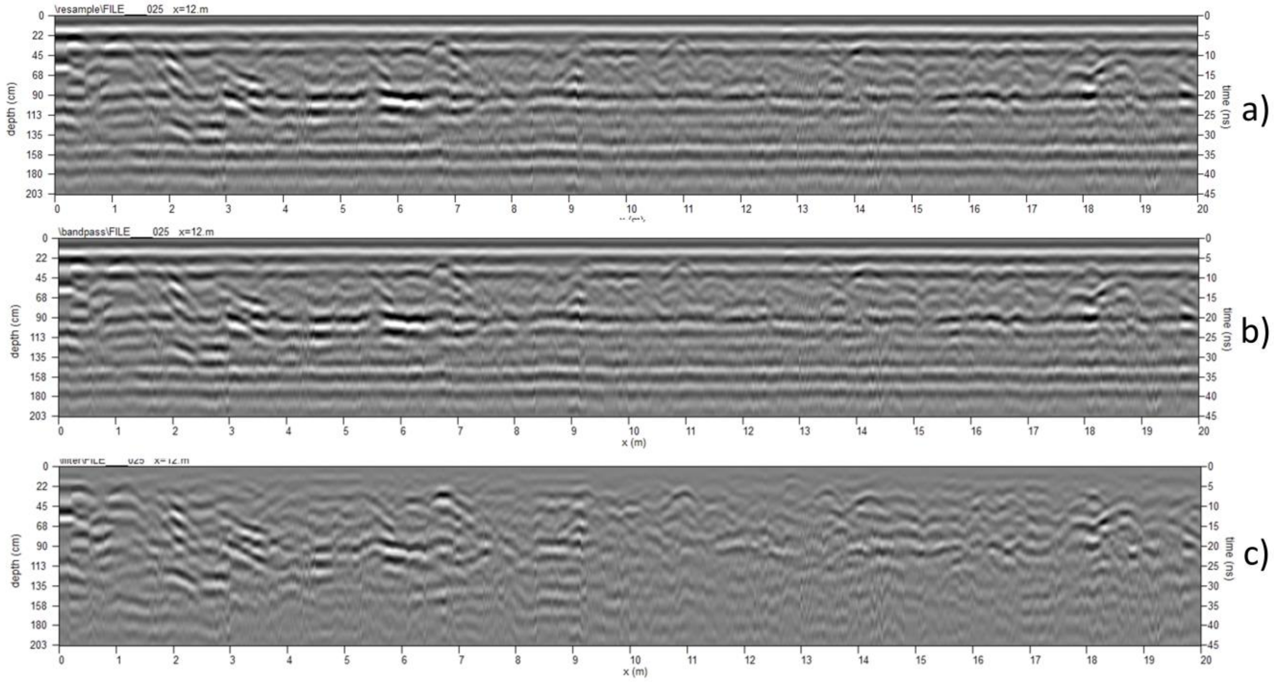

Figure 9. Processing steps on sample radargram a) Resample data b) Bandpass filter (low-pass 868 Mhz-high-pass 119 Mhz) c) Background removal filter

Figure 9 illustrates a sample radargram along with the fundamental data processing steps used to interpret subsurface features. Figure 10 shows the GPR results for the 30–60 cm depth slice overlaid on a Google Earth image. Figure 11 provides a detailed interpretation of depth slice between 30-60 cm, revealing circular anomalies highlighted in yellow. These features exhibit similar depth and geometry to the settlement remains identified by the excavation trenches. Figure 12 shows the depth slice of 60-90 cm where we can observe there is no significant anomaly in these levels. This suggests that the possible foundations or subsurface remains of the buildings are relatively shallow, with a thickness not exceeding 30 cm. Geophysical surveys often detect cumulative anomalies rather than distinct structural outlines in Neolithic and other early settlement sites, where architectural remains are typically less robust than those of later periods. Excavation results also indicate that some subsurface features were found in a disturbed or collapsed state or were dispersed due to modern agricultural activities on the surface. The effectiveness of GPR at this site is also affected by the presence of strong plant roots, pits, and large stones in the study area introduced noise into the dataset, resulting in complex interpretations. Among geophysical techniques, GPR offers distinct advantages in delineating geometry, including the extent, orientation, shape, and depth of buried structures, particularly when soil and environmental conditions are favorable for data collection.

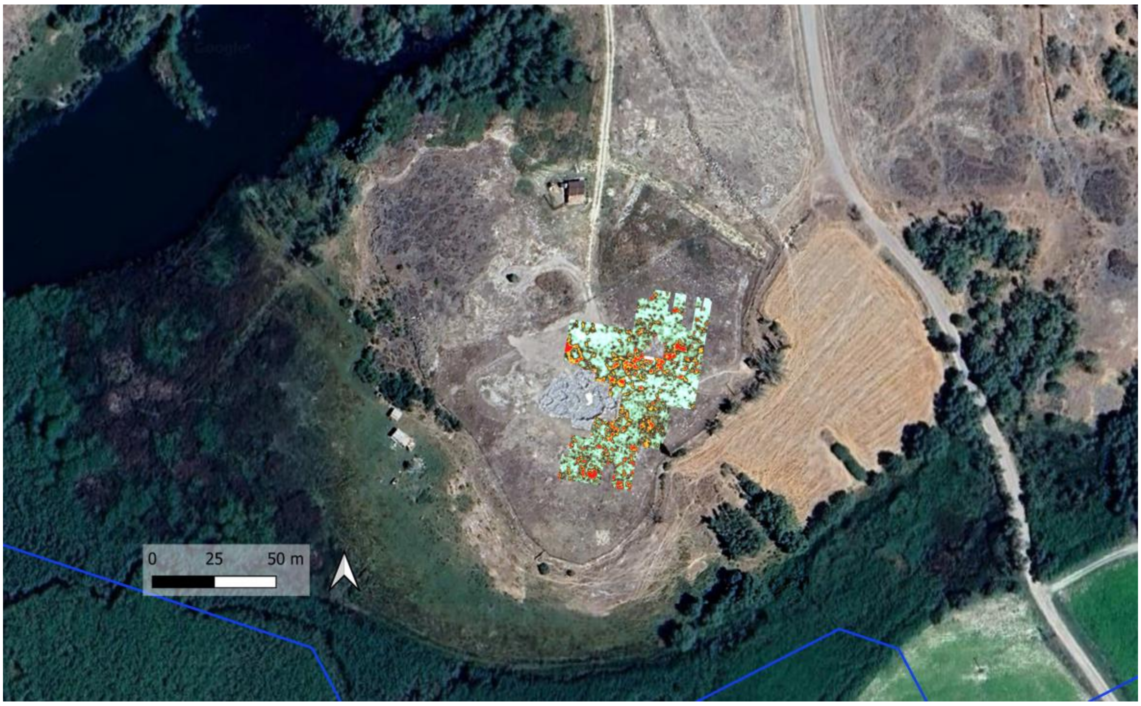

Figure 10. GPR results (depth slice 30-60 cm) overlayed on Google Earth Image using GIS, 2024

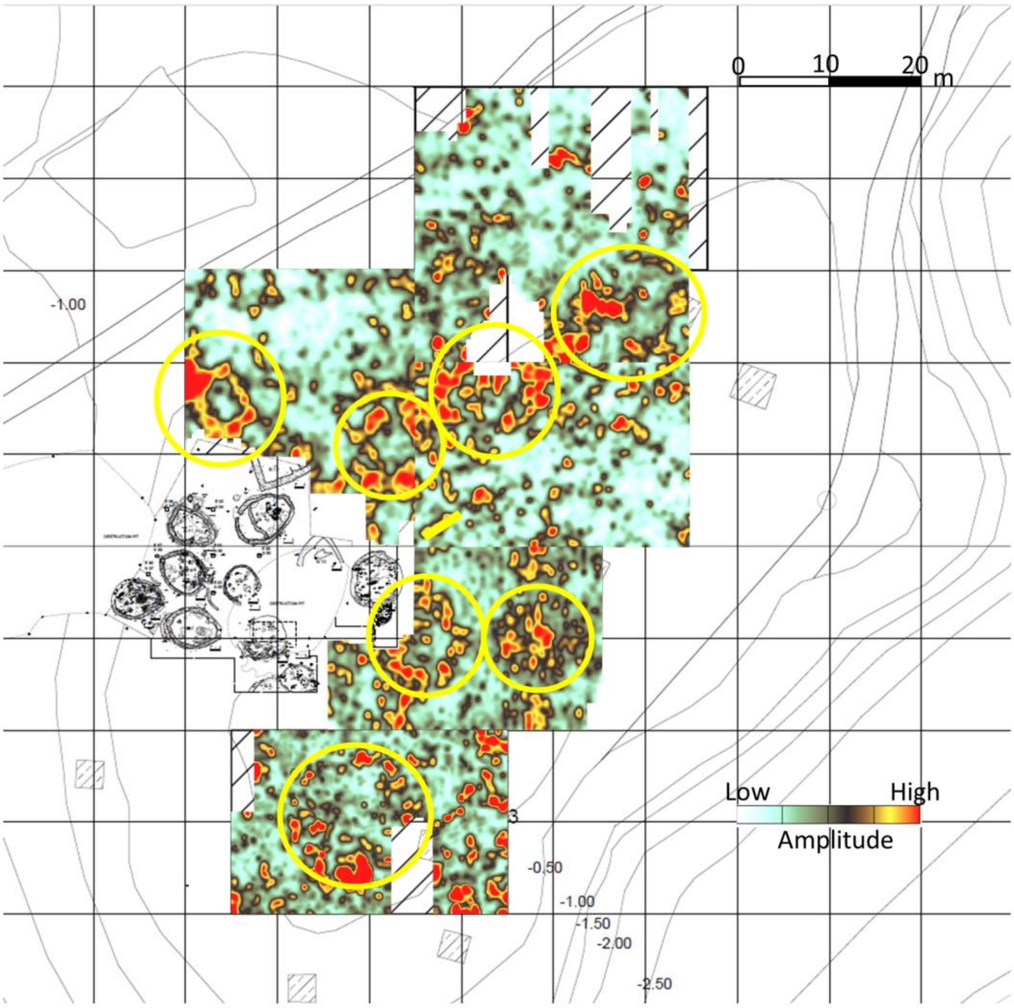

Figure 11. Ground penetrating radar 2D depth slice of 30-60 cm on Balıklı settlement (Yellow circular marks presented the possible ruins below the surface

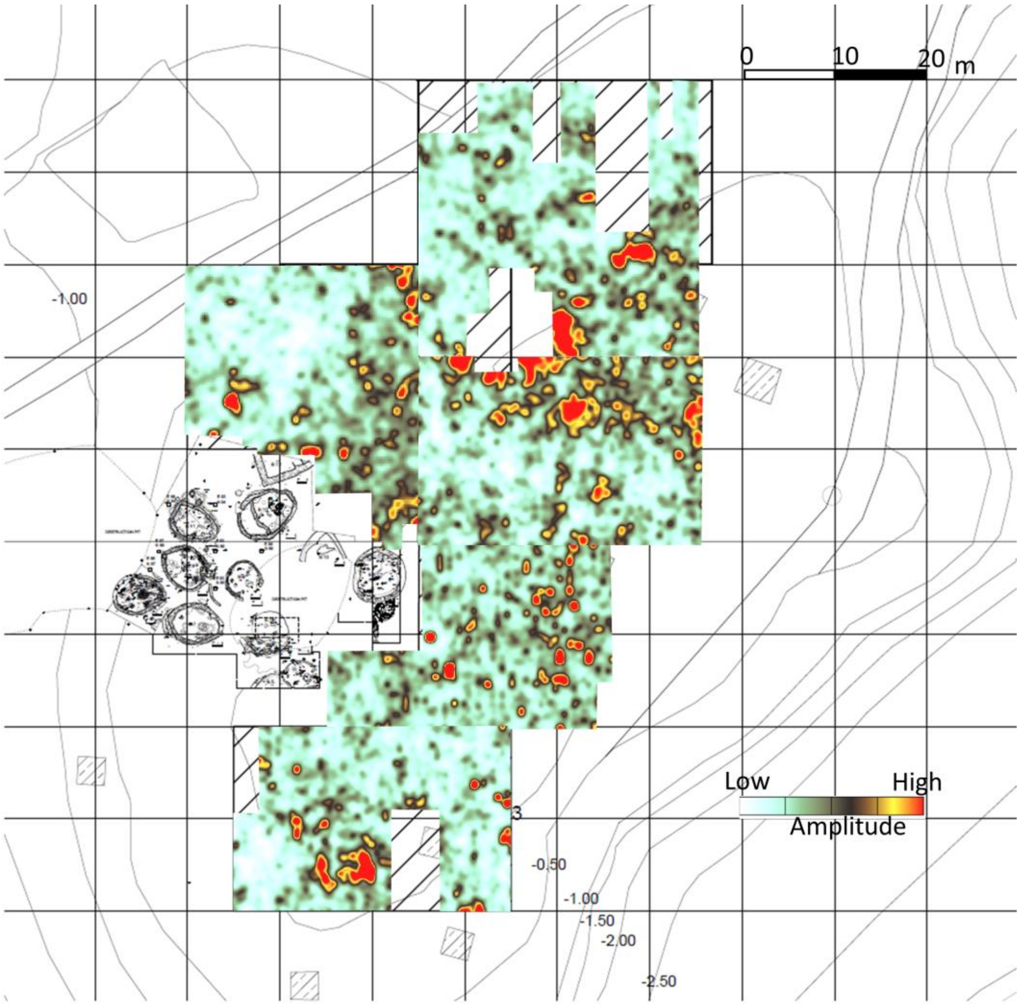

Figure 12. Ground penetrating radar 2D depth slice of 60-90 cm on Balıklı settlement (There is no significant anomalies in this level)

4. Conclusion

This multi-scale analysis of Balıklı Archeological Settlement highlights the complex relationship between environmental conditions and human settlement strategies. Local-scale GPR surveys revealed subsurface features, including probable round-ellipsoidal-shaped buildings, though partially collapsed, while regional-scale GIS analyses offered insight into broader environmental patterns that shaped the site's occupation. To obtain complementary results, in any case secondary geophysical survey with different methodology is recommended such as Magnetometry and Electrical resistivity tomography. Vegetation analysis using NDVI identified low vegetation areas, especially in the northern part of the settlement, potentially indicating buried structures. DEM-based spatial analysis shows the settlement is located on relatively flat terrain (~5° slope) at ~1176 masl., favoring agriculture, mobility, and resource access. Landform classification confirmed its placement on flat ground, a strategic choice for practical and environmental reasons. Hydrological analysis shows Balıklı is situated at the intersection of small and moderate catchments, suggesting reliable water availability that would have supported need for habitation and farming. Aspect analysis indicates a south-facing orientation, enhancing sunlight exposure and agricultural potential. Viewshed analysis demonstrated significant visibility from the site, implying strategic advantages for surveillance, defense, and road access.

Additionally, mass movement susceptibility mapping identified southeastern slopes as more prone to instability, offering insights into site preservation concerns. Overall, this integrated approach emphasizes the role of environmental factors in ancient settlement planning and provides valuable clues for understanding how past communities adapted to and modified their landscapes broadly. The results also underscore the importance of combining archeological and environmental datasets for holistic site interpretation. The study area remains largely unexplored and offers significant potential for future research that expands upon this and similar lines of investigation. Future research may incorporate additional geophysical survey methods, such as magnetometry and electrical resistivity, to better understand the settlement's subsurface structure and spatial organization. Seasonal NDVI data and remote sensing analyses can be employed to detect vegetation changes potentially linked to buried archeological features, offering indirect evidence of past human activity. Furthermore, detailed hydrological and topographical modeling could shed light on water management systems and their influence on settlement placement and sustainability. These interdisciplinary approaches offer promising avenues for deepening our understanding of Balıklı's environmental adaptations and broader significance within the region. Although this study primarily aims to investigate the spatial organization of buried archeological remains at a localized scale, as well as to assess environmental conditions at a broader, regional level, the current approach remains insufficient for a comprehensive understanding of the settlement dynamics and human behaviors associated with the site. The use of computer-based approaches provides valuable insights into the overall characteristics of the subsurface and the spatial distribution of architectural or cultural features. However, these data represent only one dimension of archeological interpretation. To move toward a more holistic reconstruction of past human activity, it is essential to integrate additional lines of evidence. Techniques such as micromorphological and stratigraphic analyses can elucidate formation processes and site usage patterns, while high-resolution UAV-based surveys contribute detailed topographic and spatial data. Furthermore, paleoenvironmental investigations, climatic analysis, including core sampling, sediment analysis, and pollen studies, offer crucial information about the natural context and climatic conditions that influenced human settlement and land use over time. Chronological frameworks established through radiocarbon dating or other absolute dating methods are also indispensable for situating these findings within a broader temporal narrative. Despite the significant contributions of these scientific techniques, the most critical components of archeological interpretation lie in the integration of cultural, anthropological, religious, and ritual-based perspectives. Without contextualizing the material findings within the framework of human belief systems, social practices, and symbolic behaviors, interpretations remain limited. This is aimed as a next step with the collaboration of experts from different disciplines.

Author Contributions

The author read and approved the final version of the paper.

Conflict of Interest

The author declares no conflict of interest.

Ethical Review and Approval

No approval from the Board of Ethics is required.

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