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Bridging archaeological visibility analysis and real-time 3D visualization

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ABSTRACT

This paper investigates the integration of geographic information systems (GIS)-based visibility analysis—commonly known as viewshed analysis—with real-time 3D rendering in unreal engine, specifically within the context of archaeological and cultural heritage applications. Visibility maps are an essential tool in archaeological research, helping scholars understand the spatial relationships, sightlines, and symbolic visibility between structures, monuments, and landscapes. However, traditional GIS viewshed analysis is often static and limited to 2D environments. This project proposes a method to bring visibility analysis into immersive 3D environments by visualizing GIS-generated data within unreal engine. The methodology involves generating a viewshed from a given digital elevation model (DEM) using established GIS software. The resulting raster is then exported and processed into a texture or material mask compatible with unreal engine. Once imported, the data is mapped onto a 3D landscape model, allowing users to explore visibility dynamically, including first-person or VR-based navigation. This interdisciplinary approach contributes to the field of digital archaeology by enhancing spatial interpretation and audience engagement through immersive geovisualization. It also outlines a flexible pipeline for integrating geospatial datasets into 3D environments, potentially applicable to site management, public education, and digital preservation efforts.

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1. INTRODUCTION

In recent years, the integration of digital tools into archaeological research and cultural heritage management has opened new possibilities for spatial analysis, visualization, and public engagement [1]. Among these tools, geographic information systems (GIS) have become essential for analyzing landscapes, site distributions, and spatial relationships between archaeological features [2]–[4]. One powerful analytical technique within GIS is viewshed analysis, which calculates the areas visible from a specific observation point based on terrain elevation. This technique has been used to investigate visibility patterns related to defense, ritual, communication, and symbolism in ancient contexts [5].

However, most GIS-based viewshed analyses are performed in 2D environments and presented as static raster images or overlays on maps. While useful for analytical purposes, these representations lack interactivity and immersion, making it difficult to convey the lived experience of visibility in the past. In response, recent developments in real-time rendering engines such as unreal engine offer promising solutions. These engines allow the creation of immersive, interactive 3D environments that can visualize archaeological data in new, engaging ways [6]. Unreal engine was selected for this study because it provides native support for large-scale terrain rendering, physically based real-time visualization, and an accessible Blueprint system that facilitates rapid development of interactive archaeological scenes. Other platforms such as Unity or CesiumJS offer strong alternatives, particularly for web-based or lightweight visualizations, but unreal engine was most suitable for the high-fidelity landscape immersion required by our case study. This project presents a methodology for importing GIS-derived visibility data into unreal engine to visualize and explore ancient viewsheds in an interactive 3D environment. By combining traditional spatial analysis techniques with real-time game engine technology, the project aims to enhance both scholarly interpretation and public understanding of archaeological landscapes [7]. The methodology is designed to be reproducible and scalable, offering a foundation for future applications in site presentation, digital reconstructions, and educational experiences related to cultural heritage [8]. Archaeology and education represent the primary target applications, while site management is mentioned only as a secondary potential use-case.

Samos, as noted in Constantine Porphyrogenitus' [9] work De Thematibus, derives its name from an ancient term meaning "the area of high mountains." Samos, along with its neighboring islands Ikaria and Fournoi, is characterized by elevated mountain ranges whose slopes extend directly to the coastline. Due to these topographical features, a dense network of fortifications emerged on the island of Samos during the transitional period (7^{th}–9^{th} centuries AD), forming strategic visual connections with fortifications on the islands of Ikaria and Fournoi [10], [11]. This distinctive geomorphology motivated the selection of the interconnection between these islands as the focus of a GIS- and unreal engine-based investigation. To incorporate all three sites, the location of Avanti on Samos was chosen, as it is one of the few places on the island offering visual contact with both Fournoi and Ikaria, as shown in Figure 1. On the background Samos (Kerkis mountain, right). The small islets in the middle are Fournoi. The island on the back is Ikaria.

Figure 1. Avanti site

The site of Avanti is situated approximately 4 km south of the village of Spatharaioi, on the southern coastline of the island of Samos. It lies at the point where Mount Ampelos projects sharply and terminates into the sea to the south, directly facing the islet of Samiopoula. Positioned between the areas of Apostolos Pavlos and Limnionaki, it is roughly 4 km in a straight line from the site of Kalogeriko. Access to the site is achieved via a winding rural road that descends from Spatharaioi through the steep slope of Birnias. The site lies only 200 meters from the coastline.

The fortification is built atop one of the soft, low hills that define the region and are noted for their geomorphological uniformity. The location is absent from any known topographical sources. The strategic character of the area is underscored by its expansive agricultural potential. The entire slope from Spatharaioi to the sea is structured in terraces, shaped to optimize cultivation. These terraces, though abandoned since the previous century, attest to long-term human presence, as habitation evidence is scattered throughout the broader area.

At the summit of the hill, a wall approximately 1m. in thickness is preserved, surviving to a height of nearly 3 meters. It is constructed using roughly hewn stones forming the outer face, with some portions seemingly built directly against the natural rock. The space between the inner and outer wall faces is filled with smaller stones tightly wedged together. The masonry technique bears similarities to the walls of other sites on Samos such as Pnaka, Kamara, Tsok, and Pyrgaki, suggesting a possible contemporaneity in construction.

Today, the interior of the structure is largely obscured by substantial soil accumulation and covered with dense vegetation. Among the few visible elements is a carved space within the natural rock, remarkably similar in form to those found at the Loulouda fortress, supporting the interpretation of the site as a fortified installation. A staircase and doorway leading outward were also identified on the southern, seaward-facing side. This suggests that access to the site was oriented toward the sea, a feature parallel in the small fortress at Prophet Elias in KambosVourlioton, where the entrance is likewise positioned on the seaward side. In one area of the site, a cluster of ceramic sherds was found, consisting primarily of amphorae fragments of types LRA 1 and LRA 2. A small quantity of storage and utility wares, as well as tile fragments, was also recovered. Based on the ceramic evidence and architectural characteristics, the site is tentatively dated to the transitional centuries (7^{th}–9^{th} AD). However, as the site was identified at a late stage in the fieldwork, further investigation is necessary to clarify its chronology and function [12].

The existence of a small fortress in this location is entirely plausible, given the area's agricultural character and strategic setting. The site maintains visual contact with the region of Marathokampos and communicates directly with the fortification of Kastraki at Agios Ioannis in Kambos. Furthermore, as has already been mentioned, Avanti has visual contact with Ikaria and Fournoi. The connection with Ikaria is established via Kapsalino castle, on the SE part of the island. The NE part of Fournoi has not been thoroughly examined yet, but in Chrysomilia there are remains of an ancient tower with traces of later use. The tower in Chrysomilia and Kapsalino castle also share visual contact [13].

2. METHOD

This chapter outlines the technical workflow for transferring visibility analysis results from ArcGIS to unreal engine. The process is divided into five main stages: i) data preparation in ArcGIS, ii) execution of viewshed analysis, iii) export and conversion of raster data, iv) import and integration into unreal engine, and v) visualization setup in the 3D environment. The tools and technologies used throughout this workflow are summarized in Table 1.

Table 1. Tools and technologies used in the viewshed analysis and unreal engine visualization workflow

Tool/technology	Description	Use in methodology
ArcGIS	GIS	Creation and analysis of viewsheds using DEM and observer points
Digital elevation model (DEM)	DEM	Basis for visibility analysis and 3D terrain generation
GPS	Global positioning system	Accurate field positioning of fortification sites

2.1. Data preparation in ArcGIS

The study area for this research is the island of Samos, located in the eastern Aegean Sea, Greece. The island is known for its rich archaeological landscape, including a significant number of Classical, Hellenistic, and Byzantine fortifications. The DEM used in this project was manually generated through digitization of topographic maps provided by the Hellenic Military Geographical Service (HMGS), at a contour interval of 4 meters [14]. These printed maps were georeferenced in ArcGIS using their original grid coordinates, then vectorized by tracing the contour lines to create a set of elevation isolines. The resulting vector data were interpolated using a triangulated irregular network (TIN) method [15].

Observation points were established using high-accuracy GPS devices during archaeological fieldwork conducted between 2022 and 2024. These points correspond to hilltop fortifications and towers that were either visually identified in situ or geolocated from excavation reports. Each GPS point was enriched with attribute data including name, elevation, and estimated observer height (e.g., 1.70 meters or tower height when available). This geospatial dataset forms the foundation for subsequent viewshed analysis and 3D visual reconstruction in unreal engine [16].

2.2. Viewshed analysis

Building upon the geospatial dataset developed in the previous stage, viewshed analysis was conducted to assess intervisibility between fortification sites across the island of Samos. The analysis aimed to reconstruct patterns of visual communication, surveillance, and strategic control in the ancient landscape, focusing particularly on coastal defense and inland signaling networks. The ArcGIS viewshed tool was employed to calculate visibility from each observation point across the terrain. The input raster was the

5 meter resolution DEM derived from digitized HMGS maps [17]. Each observation point was assigned an observer height of 1.70 meters (for human eye level), and where relevant, additional height was added based on architectural remains or historical reconstruction data (e.g., towers estimated at 8–10 meters).

Earth curvature correction was applied, and vegetation cover was excluded from the model to simulate a “bare-earth” condition, reflecting optimal visibility scenarios likely applicable in antiquity, particularly for stone-built structures above tree height [18]. The output was a binary raster layer for each site, where visible pixels were coded as “1” and non-visible as “0.” These rasters were then combined into cumulative visibility maps that revealed zones of overlapping surveillance, potential signaling corridors, and visual dominance over harbors or inland passes. This analytical stage provided the quantitative foundation for subsequent visual interpretation and 3D scene integration in unreal engine [19].

2.3. Export and conversion

Following the viewshed analysis in ArcGIS, the resulting raster layers required transformation into 3D-compatible formats suitable for integration into unreal engine. This stage involved both geometric conversion and material preparation, ensuring that the spatial accuracy of the archaeological data was preserved in the virtual environment. Each binary viewshed raster (representing visible and non-visible areas) was exported as a GeoTIFF and imported into Blender for 3D mesh generation [20]. Using the elevation values from the original DEM, a corresponding terrain mesh was created within Blender. The viewshed data was mapped onto this terrain as a texture or vertex color layer, allowing visibility information to be encoded directly onto the 3D geometry. To facilitate interoperability with unreal engine, the 3D models and textures were exported from Blender in FBX format, including baked materials and UV maps. A consistent scale (meters) and coordinate system (WGS84 projected to local UTM) were maintained throughout the pipeline to prevent spatial distortion during import [21].

2.4. Import into unreal engine

The final phase of the methodology involved the import and integration of the processed geospatial data into unreal engine for real-time visualization and interactive exploration. Unreal engine was selected for its advanced rendering capabilities, flexibility in handling large terrains, and support for dynamic material systems and user interaction. The FBX files exported from Blender were imported into unreal engine’s content browser, ensuring that the spatial reference system and scale were preserved. Upon import, terrain meshes representing the DEM were positioned within the world space, maintaining geographic accuracy relative to a global coordinate framework. The viewshed texture layers were assigned as vertex colors or material masks, enabling dynamic visualization of visible and non-visible zones.

Custom Unreal materials were developed to highlight areas of visual prominence, using shader logic to blend transparency and color based on visibility data. These materials allowed toggling between different viewshed layers, facilitating comparative analysis between multiple observation points or temporal phases [22]. Finally, performance optimization techniques, including level-of-detail (LOD) settings and occlusion culling, were applied to ensure smooth real-time rendering on standard hardware configurations, making the virtual environment accessible and responsive.

2.5. Visualization and interaction

The final component of the methodological framework focuses on the visualization and interactive exploration of the imported archaeological visibility data within unreal engine. This phase leverages the engine’s powerful rendering pipeline and user interface capabilities to create an immersive and informative virtual environment tailored for archaeological research and heritage education. Visual representation combines realistic terrain rendering with dynamically modulated viewshed overlays, allowing users to intuitively discern visible areas from each observation point [23]. The customized shaders employ color gradients and transparency effects to distinguish zones of full visibility, partial visibility, and occlusion, enhancing spatial comprehension of sightlines and surveillance networks [24].

User interaction is facilitated through unreal engine’s Blueprint visual scripting system, enabling intuitive navigation controls, such as first-person and fly-through camera modes. Furthermore, the system supports toggling between multiple temporal scenarios or observation points, enabling comparative analysis of visibility changes over time or between different sites. This dynamic functionality fosters a deeper understanding of strategic positioning and landscape use in antiquity [25]. Finally, the integration of real-time user feedback, such as dynamic labeling and path highlighting, enhances the educational value and usability of the application, making it an effective tool for researchers, educators, and heritage professionals. All processing and visualization steps are summarized in the following flowchart, which outlines the full pipeline from GIS-based visibility analysis to 3D rendering in unreal engine as presented in Figure 2.

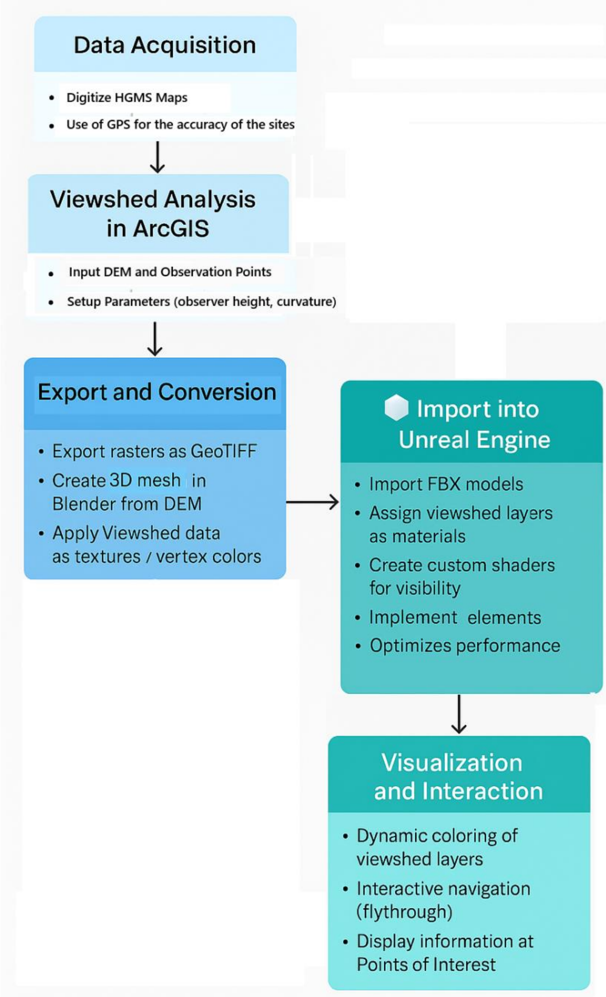

Figure 2. Workflow diagram illustrating the complete process pipeline

3. RESULTS

The case study presented in this work focuses on the fortifications site of Avanti, located on the island of Samos, and aims to demonstrate the transformation of GIS-derived visibility data into an interactive 3D environment using unreal engine. The initial phase of the analysis involved conducting a classical viewshed analysis in a GIS environment, using a DEM of the area to calculate the visible regions from a specific observation point near Avanti. The resulting raster output as shown in Figure 3 highlights in red the areas that are theoretically visible, taking into account terrain elevation and curvature, while occluding regions that fall behind ridges or beyond the line of sight. This conventional visualization is effective for providing a quick understanding of spatial reach and topographic intervisibility, but remains inherently limited by its static, top-down, two-dimensional representation. Although suitable for analytical purposes within the GIS environment, it often fails to communicate the lived, experiential quality of visibility—especially in disciplines like archaeology and landscape studies where human perception and spatial experience are crucial.

In the next stage of the project, the same visibility data was imported into unreal engine, where it was mapped onto a highly detailed 3D model of the terrain created from the same DEM source. This model was enhanced with physically based rendering techniques, dynamic lighting, and atmospheric effects to simulate realistic environmental conditions. The viewshed was applied as a color-coded overlay directly onto the terrain mesh, visually marking visible zones in red and leaving non-visible areas in their natural color. The resulting scene as presented in Figure 4 offers a significant advancement over traditional methods, as it allows the user to explore the landscape from the exact viewpoint used in the GIS calculation, navigating freely through the 3D space and perceiving the visibility in real-time from a first-person or flyover perspective.

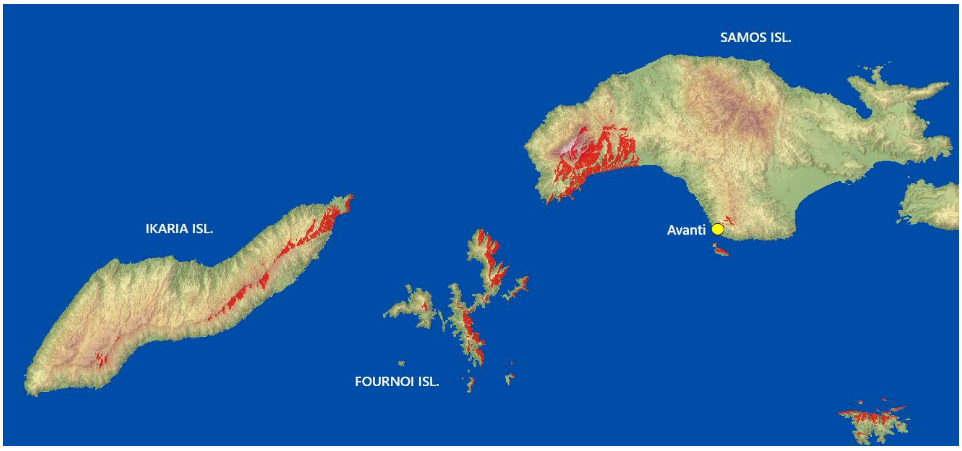

Figure 3. Visibility analysis of the avanti region conducted in GIS using a DEM

Figure 4. 3D Visualization of the Avanti viewshed in unreal engine

The benefits of this approach are manifold. One of the key advantages of importing GIS-derived visibility data into unreal engine is the enhanced interactivity and immersion it offers. Unlike traditional 2D GIS maps, the 3D environment allows users to freely navigate the landscape using features such as zoom in/out, first-person or flight-mode navigation, and real-time camera movement as shown in Figure 5. Model rotation (Figure 5(a)) enables panoramic inspection of the landscape and visibility zones from various angles; and (Figure 5(b)) a zoom-in view focused on the Avanti fort site illustrates the detailed topographic context and line-of-sight relationships on a local scale. This dynamic interaction facilitates a deeper spatial understanding of the terrain and visibility relationships. Users can explore how visibility changes with altitude, orientation, and proximity to landmarks or terrain features. Such immersive analysis is particularly valuable for archaeological research, landscape studies, cultural heritage visualization, and even public engagement, as it enables experts and non-experts alike to intuitively experience how past observers may have perceived their surroundings.

Also, it recontextualizes the visibility analysis within a spatially immersive setting, enabling researchers to assess not only which areas are visible, but also how they are perceived in terms of scale, proximity, and alignment within the broader terrain. For example, in Figure 2, the observer can immediately appreciate the dramatic ridge lines that define the viewshed’s boundary, as well as the spatial continuity between Samos, Ikaria, and the Fournoi archipelago. This adds a layer of phenomenological understanding that is entirely absent from the GIS output.

Additionally, this form of visualization supports hypothesis testing and narrative building in archaeological research. By placing viewers in the landscape, one can evaluate whether certain visual connections between ancient sites or monuments are intentional, symbolic, or merely incidental. This is particularly relevant in a region like the Eastern Aegean, where maritime visibility and inter-island connectivity were central to cultural exchange and strategic planning in antiquity. Finally, from a technological standpoint, the use of unreal engine introduces real-time rendering capabilities that support frame rates exceeding 60 fps on consumer-level GPUs, making it suitable for both desktop and VR exploration. The integration pipeline from GIS to game engine is robust, scalable, and reproducible, opening new avenues for interdisciplinary research across archaeology, geography, and digital humanities.

(a) (b)

Figure 5. Interactive navigation within the 3D environment in unreal engine: (a) model rotation and (b) zoom-in view

4. CONCLUSION

This study presents a novel workflow that integrates GIS-based viewshed analysis with real-time 3D visualization in Unreal Engine while preserving spatial accuracy, addressing a gap in existing visibility analysis approaches. By directly translating analytical GIS outputs into an immersive and interactive environment, the framework advances beyond static 2D representations and conventional visualization-only applications. The proposed methodology enables dynamic exploration of visibility patterns in a realistic 3D context, offering new analytical and communicative possibilities for archaeological and heritage research. It supports multi-point and temporal visibility analyses within a single virtual environment and emphasizes the use of generalized environmental obstructions to model line-of-sight conditions without introducing speculative reconstructions. Future work will focus on structured user studies, performance benchmarking, and the selective integration of additional environmental layers, as well as potential extensions to AR/VR platforms. Overall, this research establishes a foundational approach for combining rigorous spatial analysis with interactive 3D visualization, positioning Unreal Engine as a valuable tool for cultural heritage analysis and dissemination.

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Georgia Delli	✓			✓		✓	✓	✓	✓	✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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