Integrated Geoinformatics for Reconstructing the Cultural Dynamics in Coastal and Shallow Submerged Sites

Nikos Papadopoulos and Nasos Argyriou

Laboratory of Geophysical Satellite Remote Sensing and Archaeoenvironment (GeoSat ReSeArch Lab), Institute for Mediterranean Studies (IMS), Foundation for Research and Technology Hellas (FORTH), Rethymno, Crete, Greece – nikos@ims.forth.gr

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Abstract

Shallow-water cultural heritage occupies a dynamic land-sea interface where coastal erosion, sediment transport, limited visibility and burial processes hinder conventional archaeological investigation. This paper presents an integrated geoinformatics framework for reconstructing the cultural dynamics of coastal and shallow submerged archaeological landscapes in southeastern Crete, Greece. The methodology combines multispectral remote sensing, satellite-derived and in situ bathymetry, UAV and shallow-water photogrammetry, marine geophysics, GIS-based coastal vulnerability, fuzzy logic multi-criteria risk assessment and digital dissemination through augmented reality. The workflow was applied at five representative case studies, including Stomio, Ierapetra harbour, Koufonisi, Chryse and associated coastal sectors. Optical data from Pleiades-1A, PlanetScope, and Sentinel-2A were used for shoreline mapping, feature enhancement, and satellite-derived bathymetry. Geophysical and bathymetric surveys covered more the 4.5 and 10 hectares respectively. UAV photogrammetry produced high resolution orthomosaics, while the proposed experimental Remote Control (RC) boat extends documentation potential to very shallow submerged environments. Integrated interpretation clarified palaeo-shorelines, submerged harbour structures, fish tanks, architectural continuities and archaeological risk hotspots. The results demonstrate a scalable and transferable framework for documenting, interpreting, monitoring, and communicating endangered shallow-water cultural landscapes.

1. Introduction

Coastal and shallow submerged zones preserve archaeological remains of exceptional historical value, including settlements, harbour works, coastal villas, fish tanks, breakwaters, bath complexes and maritime infrastructure. These landscapes are often the product of long-term interactions between human occupation, shoreline mobility, tectonics, sedimentation, and sea-level change. Yet they remain methodologically challenging because they lie within a transitional zone where terrestrial and underwater survey techniques individually perform only partially.

The southeastern coast of Crete in Greece offers an ideal natural laboratory for testing integrated approaches. The region combines intense Holocene coastal transformation, active tectonic setting (Mourtzas et al., 2016) and a dense archaeological record related to long-term maritime networks (Theodoulou, 2011.). Ancient remains now occur in various conditions exposed on land, partly submerged, buried under marine sediments or preserved as discontinuous traces at the seabed. Previous work has shown the potential of remote sensing, marine geophysics and coastal analysis for these contexts (Papadopoulos, 2021), but shallow-water archaeological research still lacks operational workflows that explicitly connect multi-source inputs, validation steps, archaeological interpretation and management-oriented outputs.

The present study develops and tests an integrated geoinformatics framework for reconstructing cultural dynamics in such environments in the southeastern coast of Crete combining satellite remote sensing, photogrammetry, bathymetry, geophysics, GIS-based multi-criteria risk modelling and digital dissemination. Particular emphasis is placed on the data requirements of each methodological component, the connectivity between input and output datasets, the archaeological synthesis enabled by multi-sensor integration and the extension of the workflow towards risk assessment and science communication.The paper should have the following structure:

2. Study area and archaeological context

The study concerns five representative coastal and shallow submerged archaeological contexts in southeastern Crete: Stomio Bay, the harbour and coastal strip of Ierapetra, Koufonisi and Chryse islets (Figure 1). These case studies were selected sine they represent statistically and geomorphologically complementary examples of shallow-water cultural heritage under pressure from coastal change, sediment dynamics and partial submergence.

Koufonisi was a strategically important harbour and Roman town along maritime routes linking Crete, Africa, and the wider eastern Mediterranean. Archaeological remains include theatre, baths, water-management systems, submerged building elements and evidence suggesting a different coastal morphology and harbour setting. Chryse preserves evidence of Minoan and Roman occupation, including Roman fish tanks, harbour-related remains, and a submerged stone breakwater indicating major diachronic shoreline change. At Stomio, a Roman villa is now partly submerged due to coastal retreat, while the Ierapetra coastal zone and harbour retain evidence of palaeo-shoreline displacement and maritime infrastructure. These sites jointly illustrate how archaeological landscapes in Crete have been reshaped by coastal evolution and now require integrated documentation, interpretation, and monitoring.

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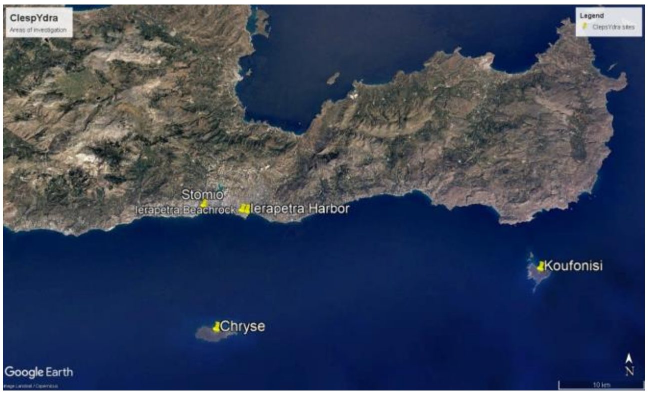

Figure 1. Location of the study areas of Ierapetra, Koufonisi, Chryse, and Stomio in southeastern Crete.

3. Materials and methods

3.1 Workflow logic and dataset connectivity

The workflow follows a connected sequence of methods (Figure 2). Satellite and aerial remote sensing provide regional reconnaissance, shoreline-change mapping and first-order detection of shallow seabed features. Satellite-derived bathymetry supplies continuous nearshore geomorphological context and supports the selection of sectors for denser survey. UAV and underwater photogrammetry contribute high-resolution geometry and orthophoto products for exposed and shallow submerged remains. Marine geophysical methods test whether visible features continue below the seabed and identify buried architecture. All outputs are integrated within a Geographical Information System (GIS) platform for archaeological interpretation and subsequently entered into risk modelling and dissemination products.
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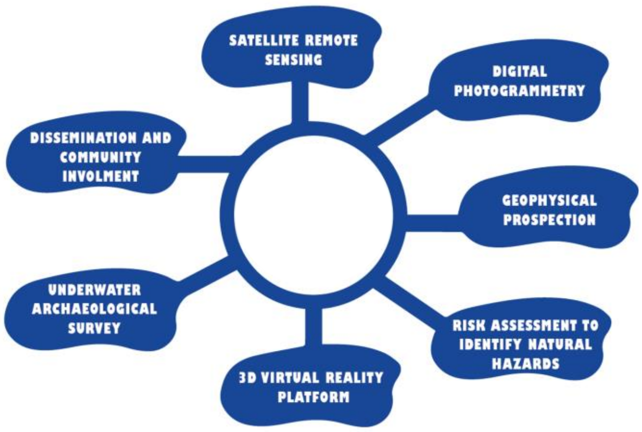

Figure 2. Integration of the different research modules to fulfil the scientific objectives for the documentation and monitoring of littoral cultural heritage sites.

3.2 Satellite remote sensing and feature extraction

The remote sensing component formed the broad-scale detection and spatial-context layer of the workflow using high and medium-resolution optical imagery. Multispectral datasets included Pleiades-1A (0.5m), PlanetScope (3m) and Sentinel-2A (10m), to support shoreline reconstruction, shallow-water feature detection, seabed visibility assessment and coastal hazard analysis In the project workflow, multispectral scenes were normalized, reprojected and combined with indices such as NDWI for water masking and NDVI for vegetation discrimination. Principal Component Analysis (PCA) was used to improve spectral detectability of archaeological traces. Morphology-based feature extraction with adaptive thresholds were aimed at enhancing subtle anthropogenic linear anomalies in coastal setting.

Multi-temporal aerial photographs and satellite images were further digitized and analyzed using Digital Shoreline Analysis System (DSAS) to derive shoreline positions and rates of change. In the Ierapetra area, imagery spanning from 1945 to 2022 was used, while for Koufonisi and Chryse, the main temporal comparisons involved 1992 and 2022, with additional archival data where available. The extracted shoreline positions formed one of the principal environmental inputs for later vulnerability and risk modelling (Figure 3).

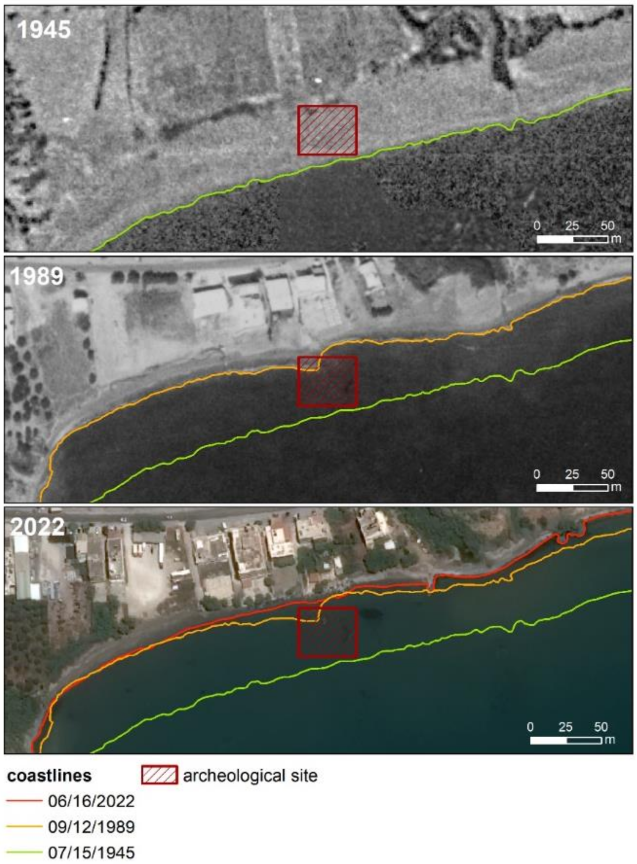

Figure 3: Coastal erosion in the area of Stomio Roman villa from analysis of historical aerial and satellite images.

3.3 Satellite-derived bathymetry

Satellite-derived bathymetry (SDB) was implemented using an empirical blue/green band-ratio approach (Stumpf et al., 2003) following a semi-automated workflow. Processing steps included single-band separation, NDWI masking with a threshold of 0.2, NDTI-based turbidity evaluation, median filtering, band-ratio calculation and calibration with EMODnet bathymetric points using depths shallower than 15 m to optimize performance in coastal waters.

The resulting SDB models for Chryse and Koufonisi achieved RMSE values from 1.1m to 2.2m, with the best performance obtained from PlanetScope over Chryse (Figure 4). These products provided first-order reconstructions of shallow marine morphology, suitable for archaeological prospection and hazardoriented spatial analysis guiding interpretation, survey targeting, and hazard evaluation (Lassak et al., 2023).

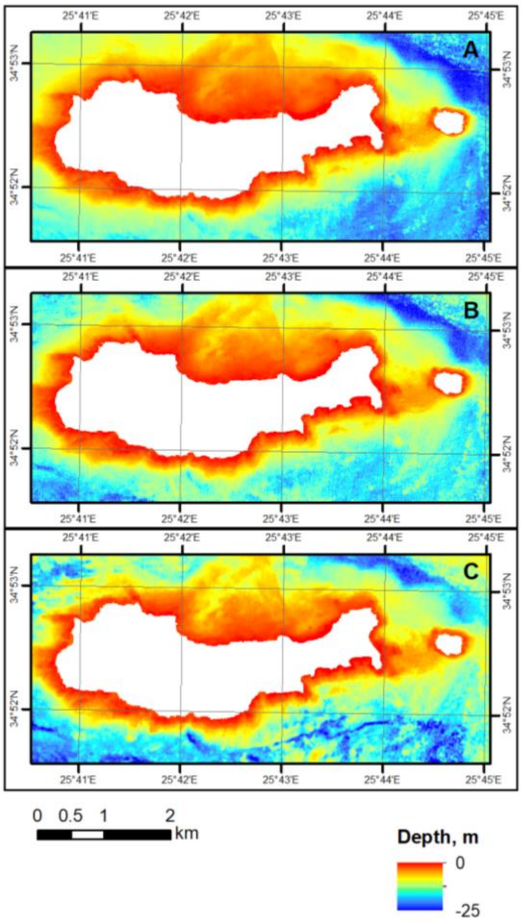

Figure 4. Bathymetry models for Chryse island derived from Pleiades (A), PlanetScope (B) and Sentinel imageries (C).

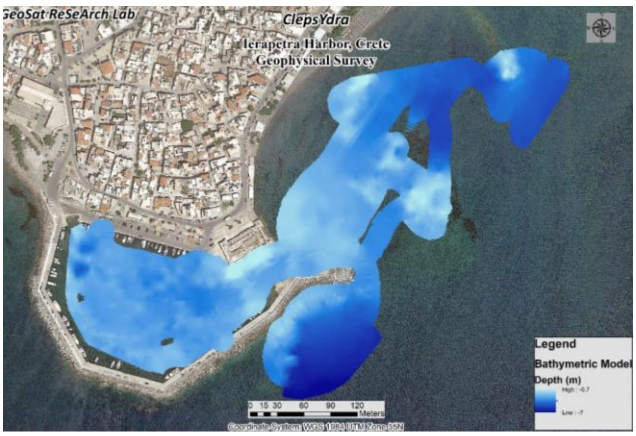

Figure 5. Digital bathymetric model of Ierapetra harbor resulted by the sonar survey.

In situ bathymetry complemented the satellite approach. Very shallow waters were surveyed using a DGPS mounted on a vertical pole, while broader shallow sectors were mapped using a vessel-based or remotely operated bathymetric configuration equipped with an Ohmex SonarMite BTX EchoSounder sonar and GNSS. Across sites, more than 108,000 m² area was covered with more than 20,500 bathymetric points (Figure 5).

3.4 Photogrammetry and the RC platform

The photogrammetric component was used for high-resolution surface documentation of exposed and partly submerged remains and operated at two levels: aerial/UAV mapping of coastal archaeological sectors and underwater photographic acquisition of shallow submerged remains. The Koufonisi survey produced an orthomosaic with 2.40 cm/pixel resolution, DEMs, contours, sections and 3D products. Archaeologically, these products confirmed that many built structures are only faintly visible because of sand accumulation and wind transport, but they also suggested subtle submerged traces potentially related to construction beyond the present shoreline (Figure 6).

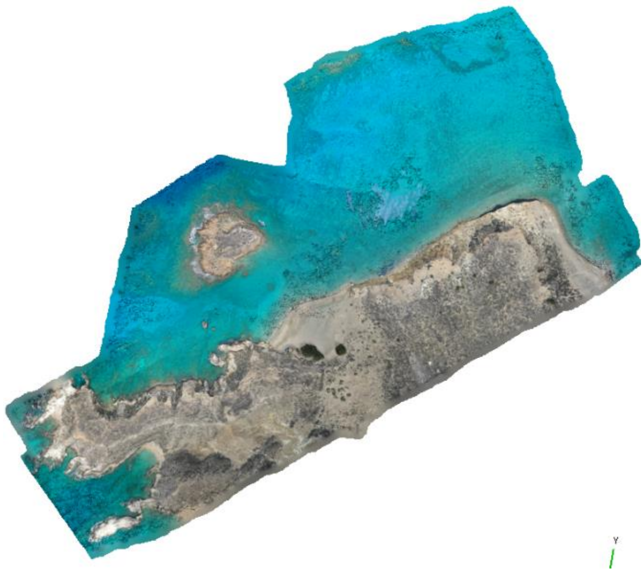

Figure 6. Orthophoto of the coastal and shallow water site in Koufonisi compiled through the photogrammetric reconstruction of drone aerial image.

To extend photogrammetric documentation into the very shallow submerged zone, the project also designed an open-hardware automated remotely controlled (RC) boat platform. The platform includes a waterproof hull, IP67 electronics enclosure, brushless motors, dual propellers, navigation controls, rechargeable batteries, radio link, autonomous navigation system and imaging sensors. The concept was developed specifically to address the acquisition gap between UAV imaging and diver-based underwater photogrammetry, where refraction, limited visibility and overlap control make documentation difficult. The prototype is intended to follow predefined paths with controlled overlap while capturing underwater-oriented imagery and associated sensor data. In the broader framework, it functions as a transitional acquisition platform linking shallow-water image capture with photogrammetric processing and GIS integration.

3.5 Marine and coastal geophysics

Marine and coastal geophysics provided the subsurface dimension of the framework. The project applied Electrical Resistivity Tomography (ERT), Seismic Refraction Tomography (SRT), Ground Penetrating Radar (GPR), magnetic gradiometry and Electromagnetic Induction (EMI). The geophysical methods were specifically adapted to the shallow marine environment through submerged and dynamic ERT configurations, floating and submerged magnetic survey setups, EMI mounted on an inflatable canoe and submerged hydrophone-streamer seismic acquisition.

Across the five project sites, the campaign covered more than 170 ERT lines (total length 6,921m), 8 SRT lines (total length 330m), more than 46,600m² of magnetic coverage and 2,280m² of GPR, Underwater ERT used both fixed and dynamic submerged acquisition modes, generally with 0.5m electrode spacing and 1m inter-line spacing for 3D reconstruction of shallow submerged targets. Magnetometry employed a SENSYS MX multi-channel system in both submerged and floating configurations with 0.5m by 0.1m sampling resolution. GPR surveys used a Noggin Plus Smart Cart with a 250 MHz antenna, typically at 0.5m transect spacing and 2.5cm along-line sampling, where soil conductivity allowed effective penetration.

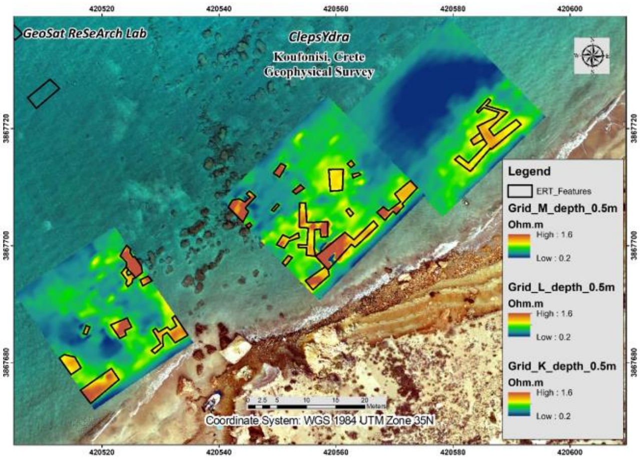

Figure 7. ERT depth slice of 0.5m of all grids registered on Koufonisi orthophoto where the warm colors denote architectural remains buried below the sea bed.

Each method served a distinct role. Magnetometry highlighted anomaly fields related to buried or displaced features. ERT resolved resistivity contrasts associated with architecture and sediment packages (Figure 7). GPR aided shallow subsurface mapping in coastal terrestrial sectors. SRT and EMI provided supporting information on shallow stratigraphy and material change. Together, these methods offered validation and extension of the surface observations from remote sensing, bathymetry, and photogrammetry.

3.6 GIS integration, coastal vulnerability and risk assessment

All spatial outputs were normalized within a GIS environment. Practically, remote sensing identified candidate archaeological features and coastal change, bathymetry reconstructed depth and seabed morphology, photogrammetry documented exposed and nearshore remains at centimetric scale, geophysics imaged buried continuations and archaeology provided contextual interpretation,

The coastal vulnerability (Figure 8) was assessed through the estimation of the weighted Coastal Vulnerability Index (CVI). Variables included shoreline change, cliff/beach height, coastal slope, beach width, lithology, beachrock presence, vertical ground motions, wind speed, significant wave height, wind-wave effect, and sea-level change. Shoreline change rates were derived from aerial and satellite datasets using DSAS, while topographic, geomorphological, geological, meteorological, and marine variables were integrated from field data, imagery interpretation, Copernicus products, and existing spatial datasets (Novikova et al., 2025).

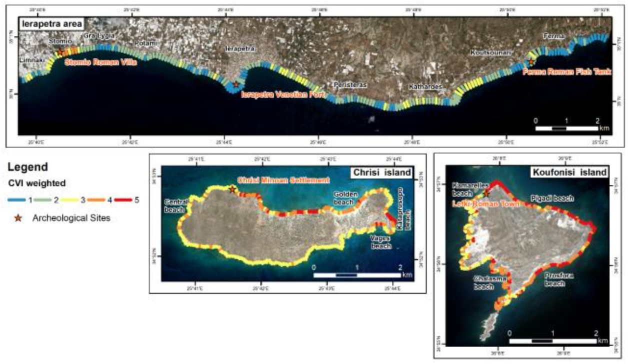

Figure 8. Weighted coastal vulnerability index for South-Eastern Crete.

For broader site-scale risk assessment, a GIS-based Multi-Criteria Decision Analysis (MCDA) model using Fuzzy Logic was developed. The model grouped ten criteria into anthropogenic, geological, geomorphological and coastal factors. Each criterion was reclassified to a common risk scale, then weighted and combined in alternative scenarios. This modelling layer made it possible to move from isolated site observations to structured spatial prioritization of cultural heritage risk (Figure 9).

Figure 9. Overall risk assessment model of the southeastern coast in Crete integrating anthropogenic, geological, geomorphological and coastal vulnerability factors though the MCDA.

3.7 Augmented reality and exhibition-based dissemination

the augmented reality (AR) application translated project outputs into public-facing scientific storytelling. The application transformed printed images into AR-triggered experiences that integrated 3D reconstructions, videos, animated layers and narrative audio. The thematic modules corresponded to geoarchaeology, underwater archaeology, geophysics, remote sensing and risk assessment, thus directly reusing project outputs. This dissemination component demonstrated how multi-source scientific outputs can be repackaged into coherent interpretive narratives for wider audiences. In the overall workflow, the AR layer is not separate from research as it depends on the validated spatial and archaeological products generated by the preceding steps (Figure 10).

Figure 10. Visitors interacting with the AR application in situ. The mobile application transforms physical artworks into immersive experiences by overlaying layered visualizations, 3D reconstructions, and narrated explanations aligned with the thematic areas of the project.

4. Results

The strongest result of the study is the convergence of heterogeneous datasets on archaeologically meaningful patterns rather than the performance of any single method. At Stomio, the combined use of bathymetry and shallow-water geophysical imaging supports the interpretation of a submerged Roman villa extending beyond the features that are nowadays visible on the seabed (Figure 11). The site also emerges as a high-priority hazard case because historical shoreline retreat transformed formerly terrestrial architecture into a shallow submerged zone.

Figure 11. Aerial view of the relics of a Roman structure submerged at Stomio.

At Koufonisi bathymetry, photogrammetry, geophysical mapping and archaeology support a broader coastal-landscape interpretation. The northern settlement area and the submerged building elements suggest a formerly different coastal geometry. The site’s baths, theatre, and water-management structures confirm the complexity and prosperity of the ancient urban-maritime landscape (Figure 12).

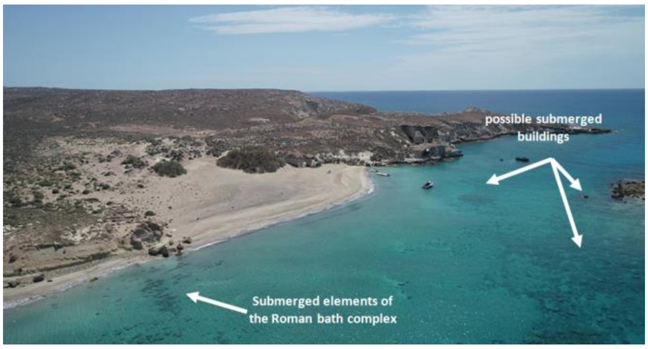

Figure 12. Submerged building elements in the shallow marine part of Koufonisi.

At Chryse, the archaeological survey documented a complex of Roman rock-cut fish tanks, submerged building remains and a stone breakwater near the coast. Shallow submerged buildings indicate that parts of the present marine zone were terrestrial in antiquity. Bathymetric and remote-sensing data support the interpretation of a harbour-related coastal morphology and the combination of visible and submerged remains indicates a broader anthropogenic landscape than what survives on land alone.

At Ierapetra, underwater archaeology confirmed multiple harbour basins and breakwaters, while shoreline-change analysis and risk modelling supplied a wider environmental frame. The combined evidence makes it possible to distinguish between preserved harbour morphology and modern coastal alteration and to interpret within a dynamic coastal system rather than as a static monument.

The overall synthesis shows that the archaeological value of the framework lies in reconstructing entire cultural dynamics including harbour function, palaeo-shoreline displacement, coastal segmentation, architectural continuity and environmental pressures on occupation. This wider archaeological reading is only possible because the outputs from remote sensing, bathymetry, photogrammetry, geophysics and field archaeology are treated as connected evidence streams rather than parallel products.

5. Discussion

The paper’s central argument is that shallow-water archaeology requires explicit interoperability between sensors, scales and interpretive stages. Remote sensing alone can indicate possible anthropogenic traces, but cannot reliably determine whether they continue below the seabed. Photogrammetry can document visible geometry, but not buried architecture. Geophysics can detect subsurface anomalies, but is substantially strengthened when acquisition is constrained by prior bathymetric and archaeological evidence. The RC boat concept is particularly valuable because it addresses a transitional data-acquisition problem that standard platforms handle poorly. GIS integration is therefore not a final visualization step but constitutes the operational environment in which one dataset conditions the next.

The archaeological interpretation also benefits from multi-source synthesis. At Koufonisi and Chryse, the value of the framework lies in reconstructing maritime use zones rather than only isolated ruins: harbours, breakwaters, bath complexes and submerged building continuities become legible within broader coastal configurations shaped by erosion, sedimentation and sea-level change.

The workflow also extends beyond documentation into management and communication. The fuzzy-logic MCDA model convert survey outputs into spatially explicit heritage-risk scenarios, while the AR application translates the same research into public-facing narratives. The photogrammetric, geophysical, remote sensing and risk layers were transformed into gallery-based interactive exhibits. This demonstrates that integrated geoinformatics can support both research interpretation and heritage dissemination.

6. Conclusions

This paper presented an integrated geoinformatics framework for reconstructing the cultural dynamics of coastal and shallow submerged archaeological sites in southeastern Crete. The approach combines multispectral remote sensing, satellite-derived and in situ bathymetry, UAV and shallow-water photogrammetry, marine geophysics, GIS-based coastal vulnerability, fuzzy MCDA risk modelling and AR-supported dissemination.

The study demonstrated that: a) multi-resolution satellite imagery and SDB can effectively support shoreline analysis, shallow seabed reconstruction and archaeological targeting, b) UAV photogrammetry provides centimetric documentation of coastal archaeological landscapes while remotely controlled (RC) boat. concept extends acquisition potential into the ultra-shallow submerged zone, c) geophysics is indispensable for revealing buried and submerged continuities of archaeological structures, d) GIS-based vulnerability and risk modelling convert research outputs into management-oriented spatial decision tools and e) AR and exhibition deployment provide a robust pathway for communicating scientific results to broader audiences.

The proposed methodology is readily transferable to other coastal regions facing similar challenges, providing a scalable and adaptable toolset for the documentation and preservation of underwater cultural heritage. The findings also highlight the value of multi-sensor integration for shallow-water archaeology and point to several directions for future research. These include the incorporation of advanced classification and machine learning methods for automatic feature detection, the refinement of low-cost autonomous survey platforms and the tighter coupling of environmental modelling with heritage risk assessments.

Acknowledgements

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