

Special Issue Reprint

Advanced Technologies for Maritime and Underwater Archaeology

2nd Edition

Edited by
Javier Prieto, Fabio Bruno, Antonio Lagudi, Michela Ricca, Mauro Francesco La
Russa, George Papatheodorou and Nikola Mišković

mdpi.com/journal/jmse

Advanced Technologies for Maritime and Underwater Archaeology—2nd Edition

Advanced Technologies for Maritime and Underwater Archaeology—2nd Edition

Guest Editors

Javier Prieto

Fabio Bruno

Antonio Lagudi

Michela Ricca

Mauro Francesco La Russa

George Papatheodorou

Nikola Mišković



Basel • Beijing • Wuhan • Barcelona • Belgrade • Novi Sad • Cluj • Manchester

Guest Editors

Javier Prieto
University of Salamanca
Salamanca
Spain

Fabio Bruno
University of Calabria
Cosenza
Italy

Antonio Lagudi
University of Calabria
Cosenza
Italy

Michela Ricca
University of Calabria
Cosenza
Italy

Mauro Francesco La Russa
University of Calabria
Cosenza
Italy

George Papatheodorou
University of Patras
Patras
Greece

Nikola Mišković
University of Zagreb
Zagreb
Croatia

Editorial Office

MDPI AG
Grosspeteranlage 5
4052 Basel, Switzerland

This is a reprint of the Special Issue, published open access by the journal *Journal of Marine Science and Engineering* (ISSN 2077-1312), freely accessible at: https://www.mdpi.com/journal/jmse/special_issues/VXWEOJX35A.

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

Lastname, A.A.; Lastname, B.B. Article Title. <i>Journal Name</i> Year , Volume Number, Page Range.
--

ISBN 978-3-7258-8667-8 (Hbk)

ISBN 978-3-7258-8668-5 (PDF)

<https://doi.org/10.3390/books978-3-7258-8668-5>

© 2026 by the authors. Articles in this reprint are Open Access and distributed under the Creative Commons Attribution (CC BY) license. The reprint as a whole is distributed by MDPI under the terms and conditions of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) license (<https://creativecommons.org/licenses/by-nc-nd/4.0/>).

Contents

About the Editors	vii
Preface	xi
Javier Prieto, Fabio Bruno, Antonio Lagudi, Michela Ricca, Mauro Francesco La Russa, George Papatheodorou and Nikola Mišković	
Advanced Technologies for Maritime and Underwater Archaeology—2nd Edition	
Reprinted from: <i>J. Mar. Sci. Eng.</i> 2026 , 14, 1200, https://doi.org/10.3390/jmse14131200	1
Alessio Calantropio and Filiberto Chiabrando	
Underwater Cultural Heritage Documentation Using Photogrammetry	
Reprinted from: <i>J. Mar. Sci. Eng.</i> 2024 , 12, 413, https://doi.org/10.3390/jmse12030413	6
Nathan Helfman, Josef Rott and Deborah Cvikel	
Revisiting the Serçe Limanı Sail Plan	
Reprinted from: <i>J. Mar. Sci. Eng.</i> 2024 , 12, 937, https://doi.org/10.3390/jmse12060937	26
Ehud Galili, Liora Kolska Horwitz, Ilaria Patania, Amir Bar and Isaac Ogloblin Ramirez	
Identifying Anthropogenic Versus Natural Submerged Prehistoric Landscapes: Two Case Studies from the Sicilian Channel	
Reprinted from: <i>J. Mar. Sci. Eng.</i> 2024 , 12, 1981, https://doi.org/10.3390/jmse12111981	42
Jorge Herrera-Santos, Marta Plaza-Hernández, Sebastián López-Florez, Vladimir Djapic, Javier Prieto Tejedor and Emilio Santiago Corchado-Rodríguez	
Edge Computing Architecture for the Management of Underwater Cultural Heritage	
Reprinted from: <i>J. Mar. Sci. Eng.</i> 2024 , 12, 2250, https://doi.org/10.3390/jmse12122250	71
C. Ferrero-Martín, A. Izquierdo, M. Bethencourt and T. Fernández-Montblanc	
A Risk Assessment of Underwater Cultural Heritage for Wave-Induced Hazards: The Impact of Climate Change on Cadiz Bay	
Reprinted from: <i>J. Mar. Sci. Eng.</i> 2025 , 13, 136, https://doi.org/10.3390/jmse13010136	88
Gil Gambash, Ehud Arkin-Shalev, John Wood, Emmanuel Nantet and Timmy Gambin	
<i>Caesarea SubMaritima</i> : Insights into the Entrance of the Roman Harbour of Sebastos as Obtained Through High-Resolution Multimodal Remote Sensing Surveys	
Reprinted from: <i>J. Mar. Sci. Eng.</i> 2025 , 13, 940, https://doi.org/10.3390/jmse13050940	111
Christoforos Benetatos, Stefano Costa, Giorgio Giglio, Claudio Mastrantuono, Roberto Mo, Costanzo Peter, et al.	
Exploring the Mediterranean: AUV High-Resolution Mapping of the Roman Wreck Offshore of Santo Stefano al Mare (Italy)	
Reprinted from: <i>J. Mar. Sci. Eng.</i> 2025 , 13, 1921, https://doi.org/10.3390/jmse13101921	122
Soledad Estrella Solana Rubio, Felipe Cerezo Andreo, Sebastián Federico Ramallo Asensio, Francisco López-Castejón, Darío Bernal-Casasola, Miguel Ángel Cau Ontiveros, et al.	
Sub-Bottom Profiler in Underwater Archaeology: Comparative Analysis for Non-Intrusive Surveying and Documentation of Underwater Cultural Heritage in Spain	
Reprinted from: <i>J. Mar. Sci. Eng.</i> 2026 , 14, 943, https://doi.org/10.3390/jmse14100943	137

About the Editors

Javier Prieto

Javier Prieto is an Associate Professor at the Computer Science Department of the University of Salamanca. He is also a member of the Institute of Biomedical Research of Salamanca (IBSAL). His research interests include explainable artificial intelligence and blockchain to develop smarter and secure cities, IoT and Edge Computing technologies to improve social welfare and environmental sustainability, and Quantum Machine Learning to trigger the next revolution of Artificial Intelligence. Javier Prieto has published more than 200 papers in international journals, books and conferences, participated in more than 175 research projects, and has been the author of three Spanish patents. Moreover, he has served as Editor-in-Chief for the *Smart Cities* journal in the Internet of Things, Computing, and Communications Technologies in Smart Cities Section, as an associate editor for *Frontiers in Public Health*, and the *Sensors* journals, as a Guest Editor for numerous journals, and has served as a past senior editor for the *IEEE Communications Letters*, and the *Wireless Communications and Mobile Computing* journal. A Senior Member of the IEEE, he is the chair of the IEEE Communications Society and Signal Processing Society Joint Chapter (2023-2027), and the founder and past Coordinator of the IEEE Blockchain Spain Local Group (2020-2024).

Fabio Bruno

Fabio Bruno is a Full Professor at the Department of Mechanical, Energy and Management Engineering (DIMEG) of the University of Calabria, where he teaches courses related to rapid prototyping, digital documentation, and multimedia technologies for cultural heritage. He became a Researcher in 2005, an Associate Professor in 2012, and a Full Professor in 2023. Since November 2025, he has served as Vice-Rector for Research at the University of Calabria. He is also a founder and President of 3D Research, a spin-off company of the University of Calabria. He coordinated the European projects BLUECULTOUR, Art4Sea, CREAMARE, and BLUEMED PLUS, and has served as scientific coordinator or research-unit leader in more than 20 national and international projects funded under Horizon Europe, Horizon 2020, Creative Europe, Interreg, EMFF, PNRR, and national research programmes. His research focuses on underwater 3D imaging, virtual and augmented reality, marine robotics, digital cultural heritage, and technologies for the documentation and monitoring of submerged environments. He has authored or co-authored more than 200 scientific publications, including 148 Scopus-indexed works, and is co-inventor of seven national and international patents. Prof. Bruno is a member of the Italian Association of Design Methods and Tools for Industrial Engineering (ADM), the Interuniversity Centre of Integrated Systems for the Marine Environment (ISME), and the International Society for Photogrammetry and Remote Sensing (ISPRS). He is also an Editorial Board Member of the *Journal of Marine Science and Engineering* and has served on the scientific and organising committees of several international conferences on underwater imaging and cultural heritage.

Antonio Lagudi

Antonio Lagudi is a Researcher at the Department of Mechanical, Energy and Management Engineering (DIMEG) of the University of Calabria, where he conducts research and teaching activities in 3D modelling, rapid prototyping, photogrammetry, and digital technologies for cultural heritage. He received his Ph.D. in Mechanical Engineering from the University of Calabria in 2015. He is also a founder of BlueMech Engineering, a spin-off company of the University of Calabria. His

research interests include underwater optical and acoustic 3D imaging, multi-sensor data fusion, computer vision, marine robotics, and extended reality technologies. He has served as Scientific Manager of the SMILE and HerMaTec projects and has participated in several national and European research projects funded under the Horizon 2020, Interreg, PON, and PNRR programmes. He is co-inventor of an international patent concerning an intelligent underwater acoustic imaging system and has authored or co-authored more than 50 Scopus-indexed publications in the fields of underwater 3D reconstruction, marine robotics, virtual and augmented reality, and digital cultural heritage. Dr. Lagudi is a member of the Italian Association of Design Methods and Tools for Industrial Engineering (ADM), the Interuniversity Centre of Integrated Systems for the Marine Environment (ISME), and the International Society for Photogrammetry and Remote Sensing (ISPRS) Working Group II/9. He is also an Editorial Board Member of the *Journal of Marine Science and Engineering*.

Michela Ricca

Michela Ricca is an Associate Professor at the Department of Biology, Ecology and Earth Sciences (DiBEST), University of Calabria, and, since December 2025, Coordinator of the Bachelor's Degree Programme in Conservation and Restoration of Cultural Heritage. In 2023, she obtained the Italian National Scientific Qualification for Full Professor in the disciplinary sector GEOS-01/D (Mineral Resources and Mineralogical-Petrographic Applications for Environment and Cultural Heritage).

Her research activity is primarily focused on archaeometry and diagnostic methodologies applied to cultural heritage materials, with a specific emphasis on stone materials used in historic architecture. Her scientific interests include the mineralogical and petrographic characterisation and provenance assessment of natural and artificial stone materials, the investigation of weathering and degradation mechanisms under different environmental conditions (aerial, indoor, outdoor, and marine contexts), and the development and testing of innovative protective and consolidating treatments for the conservation of cultural heritage.

Since 2011, she has been involved in numerous competitively funded national and international research projects (including PON, POR, PRIN, EASME, Interreg MED Programme, and MSCA), also serving as Principal Investigator in several of them. She is the author of more than 110 peer-reviewed scientific publications in international journals and has contributed to over 130 presentations at national and international scientific conferences.

Mauro Francesco La Russa

Mauro F. La Russa has been a Full Professor of Mineral Resources and Mineralogical-Petrographic Applications for Environment and Cultural Heritage since 1 October 2022. His scientific activity is primarily focused on applied petrography in the fields of cultural heritage and environmental studies, within which he has achieved significant national and international recognition. Throughout his academic career, he has combined research activities with extensive institutional responsibilities. From October 2019 to October 2020, he served as Delegate for the Italian University Network for Sustainable Development (RUS). Since 2020, he has been Rector's Delegate for postgraduate education, including Master's programmes and summer schools, and Coordinator of the joint PhD programme "Technology Applied to Cultural Heritage". Since October 2025, he has also been Head of the Department of Biology, Ecology and Earth Sciences (DiBEST) at the University of Calabria. At the national and international level, he previously served as President of the Italian Association of Archaeometry (since 2020), the leading scientific society founded in 1990, bringing together more than 400 researchers from universities and research institutions working on cultural

heritage studies. He is the author of more than 200 scientific publications and has coordinated numerous competitively funded national and European research projects in the fields of cultural heritage and geo-resources.

George Papatheodorou

George Papatheodorou is a Full Professor of “Environmental and Geological Oceanography” in the Geology Department of the University of Patras (Greece) and he has served as Head of the Department (2013–2017) and Dean of the School of the Natural Sciences (2018–2024). He is Director of the Oceanus-Lab and serves as Director of two Interdepartmental Postgraduate Programmes in “Oceanography” and “Environmental Sciences”. His research spans a broad range of marine science disciplines, including marine geology, with emphasis on active faults, submarine landslides, and seabed fluid flows; marine pollution, (marine litter and heavy metals in sediments); marine geoarchaeology; coastal erosion; anoxic and hypoxic landlocked water bodies; and the mapping of marine and lacustrine habitats. He has served as coordinator and/or principal researcher in more than 170 National, European, and International research projects across diverse fields of marine science. He has conducted numerous marine geoarchaeological surveys in coastal areas of major archaeological significance in Greece (e.g., Salamis Straits, ancient harbours of Aegina, Zea–Munichia, Naval Battles of Navarino and Lepanto), as well as locations throughout the Mediterranean, including Alexandria (Egypt), Croatia, Lebanon, Cyprus, and Corsica, and in Argentina. He has authored more than 180 papers in international peer-reviewed journals and over 200 full papers in the proceedings of international conferences.

Nikola Mišković

Nikola Mišković is a tenured Full Professor at University of Zagreb, Faculty of Electrical Engineering and Computing, where he teaches courses related to control theory and marine robotics. He received his diploma and Ph.D. degrees in electrical engineering from the University of Zagreb, Faculty of Electrical Engineering and Computing (FER), Zagreb, Croatia, in 2005 and 2010, respectively. In 2016 he was promoted to Associate Professor, became a Full Professor in 2019, and Full Tenured Professor in 2024. He is an Associate Member of the Croatian Academy of Science and Arts.

He is the Head of Laboratory for Underwater Systems and Technologies (LABUST). He is the Director of a European “Centre of Excellence in Maritime Robotics and Technologies for Sustainable Blue Economy – CoE MARBLE” funded under the Teaming call of the Horizon Europe Programme. He participated in 20 European projects (Horizon Europe, H2020, FP7, DG-ECHO, INTERREG). He also participated in six Office of Naval Research Global (ONR-G) projects (coordinated three), two NATO projects, one Schmidt Ocean Institute project, and 18 national projects (coordinated 10). He published more than 130 papers in journals and conference proceedings in the area of navigation, guidance and control, as well as cooperative control in marine robotics.

Prof. Mišković is a member of IEEE (president of Chapter for Robotics and Automation of the Croatian Section from 2016 to 2017, member of the IEEE Oceanic Engineering Society Administrative Committee from 2023 to 2025), IFAC (member of the Technical Committee on Marine Systems) and Centre for Underwater Systems and Technologies (vice-president since 2010).

Preface

Underwater cultural heritage (UCH) is a crucial asset for the knowledge of humankind's history and traditions. It is tangible evidence of past human life that must be protected to ensure its accessibility for present and future generations.

The documentation, preservation, and dissemination of UCH is an open challenge that is strongly interdisciplinary because it involves collaboration among various experts from different sectors, such as archaeology, geology, biology, marine science, engineering, robotics, computer science, and numerous other disciplines.

This Reprint collects original and high-quality research articles and technical notes devoted to the knowledge of underwater materials and promotes innovative methodologies, applications, and emerging technological solutions about the materials that lie underwater.

The Reprint provides a multidisciplinary forum for cutting-edge scientific and technological contributions in materials science, underwater archaeology, archaeometry, cultural heritage, alteration and ageing, climate impact, case studies, and other related fields involving the large and varied community of experts from around the globe working in the underwater cultural heritage field.

**Javier Prieto, Fabio Bruno, Antonio Lagudi, Michela Ricca, Mauro Francesco La Russa,
George Papatheodorou, and Nikola Mišković**

Guest Editors

Editorial

Advanced Technologies for Maritime and Underwater Archaeology—2nd Edition

Javier Prieto ^{1,*}, Fabio Bruno ², Antonio Lagudi ³, Michela Ricca ⁴, Mauro Francesco La Russa ⁴, George Papatheodorou ⁵ and Nikola Mišković ^{6,7}

¹ Faculty of Science, University of Salamanca, 37008 Salamanca, Spain

² Department of Mechanical, Energy and Management Engineering, University of Calabria, 87036 Rende, CS, Italy; fabio.bruno@unical.it

³ 3D Research s.r.l., 87036 Rende, CS, Italy; antonio.lagudi@3dresearch.it

⁴ Department of Biology, Ecology and Earth Sciences, University of Calabria, 87036 Rende, CS, Italy; michela.ricca@unical.it (M.R.); mlarussa@unical.it (M.F.L.R.)

⁵ Department of Geology, Oceanus-Lab, University of Patras, 26504 Patras, Greece; gpapathe@upatras.gr

⁶ Faculty of Electrical Engineering and Computing, University of Zagreb, 10000 Zagreb, Croatia; nikola.miskovic@fer.hr

⁷ CoE MARBLE—Centre of Excellence in Maritime Robotics and Technologies for Sustainable Blue Economy, 10000 Zagreb, Croatia

* Correspondence: javierp@usal.es

1. Introduction

Underwater cultural heritage (UCH) is one of the richest and most vulnerable records of humankind's past. Shipwrecks, submerged settlements, and harbours preserve unique evidence of ancient trade, navigation, and coastal life, yet they lie in environments that are difficult to access and are increasingly exposed to natural deterioration, human pressure, and the accelerating effects of climate change [1,2]. Protecting this heritage, and keeping it accessible to present and future generations, requires documenting it as accurately and as non-intrusively as possible, a principle explicitly promoted by the 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage through its emphasis on non-destructive techniques and in situ conservation [3,4]. Meeting this goal is an interdisciplinary endeavour that brings together archaeology, geology, biology, marine science, conservation, engineering, robotics, and computer science.

In recent years, the field has been reshaped by rapid technological progress. Acoustic and geophysical methods, such as the synthesis of bathymetric and marine geophysical datasets in common three-dimensional (3D) platforms [5,6], together with sub-bottom profilers, multibeam and side-scan sonar, and autonomous underwater and surface vehicles (AUVs and USVs) [7,8], now allow large areas of the seafloor to be surveyed and documented at high resolution, with few constraints related to water depth. At the same time, underwater photogrammetry provides detailed and accurate 3D models that support both research and long-term monitoring [9,10].

In parallel, dedicated underwater tools and robotic systems support in situ conservation and the maintenance of submerged structures [11,12], and digital technologies are enabling underwater sites to be opened for sustainable and responsible tourism [13,14]. At the same time, frontier technologies such as the Internet of Underwater Things (IoUT), Edge Computing (EC), and Artificial Intelligence (AI) are transforming how UCH is monitored and managed. AI is becoming central to this area since it supports the detection and classification of features of archaeological interest, the fusion and interpretation of heterogeneous

sensor data, and the identification and assessment of risks that environmental change and human activity pose to submerged sites.

Together with new methods for assessing the impacts of climate change on shallow-water cultural heritage, these advances are redefining the scope of what can be documented, understood, and preserved underwater.

2. Overview of Contributions

This Special Issue is the second edition of “Advanced Technologies for Maritime and Underwater Archaeology”, building on the success of its first edition [1]. It brings together original and high-quality research articles and technical notes devoted to the study, documentation, and conservation of underwater cultural heritage. The collection promotes innovative methodologies, applications, and emerging technological solutions for investigating, monitoring, and preserving archaeological materials, sites, and cultural landscapes located in underwater environments. The eight contributions collected here were selected from a larger pool of submissions and cover a broad range of underwater cultural heritage contexts, including shipwrecks, submerged harbours, and coastal environments. They also showcase diverse technologies, from acoustic and remote sensing surveys to AI, photogrammetry, and the assessment of climate change impacts on submerged cultural heritage.

Calantropio and Chiabrandio (2024) (contribution 1) provide a comprehensive review of underwater photogrammetry for the documentation of underwater cultural heritage, currently the most widely used metric technique thanks to its non-destructive and relatively inexpensive nature. The authors discuss the production of high-resolution 3D models and 2D orthomosaics for monitoring, conservation, expert study, replica reproduction, and dissemination, while addressing the specific challenges posed by the optical properties of water, light penetration, visibility and suspension, and radiometric issues.

Helfman et al. (2024) (contribution 2) revisit the sail plan of the 11th-century Serçe Limanı ship. Using computational fluid dynamics and hydrostatic stability analysis to evaluate hull resistance, sail propulsion, and heeling moments, the authors reassess the previously proposed double-masted rig and investigate an alternative single-sail configuration. Their results indicate that a sail area of at least 150 m² would have been required to propel the vessel, leading to the selection of a feasible single-sail rig as an alternative reconstruction.

Galili et al. (2024) (contribution 3) develop a methodological framework to distinguish anthropogenic features from natural formations in submerged landscapes. The framework integrates geological and geomorphological evidence, sea-level reconstructions, associated archaeological remains, the broader archaeological context, and direct visual inspection by underwater archaeologists. Applying these criteria to two previously published case studies in the Sicilian Channel, the authors conclude that the investigated features are more plausibly attributable to natural processes than to human origin, and stress that remote sensing cannot substitute in situ verification.

Herrera-Santos et al. (2024) (contribution 4) propose an architecture that combines the IoUT and EC for the real-time monitoring, localization, and management of UCH. Data are processed by a central unit installed on a buoy near the heritage site, and the integration of acoustic communication systems, LoRa technology, and non-terrestrial networks, together with AI models deployed at the edge node, enables continuous risk assessment even in remote maritime areas and without relying on cloud connectivity.

Ferrero-Martín et al. (2025) (contribution 5) describe a new methodology to assess the impact of climate change on the preservation of underwater cultural heritage in shallow waters, focusing on wave-induced hazards such as decontextualization, scouring, and wear

erosion. Applying hybrid downscaling of bias-corrected wave fields under the RCP4.5 and RCP8.5 climate scenarios, the authors evaluate future risk patterns in the Bay of Cádiz. Their results indicate that, despite an overall reduction in wave energy flux, local increases at rocky outcrops may significantly alter hazard levels, with wear erosion emerging as the most affected risk factor.

Gambash et al. (2025) (contribution 6) report on high-resolution multimodal remote sensing surveys conducted at the sunken Herodian harbour of Sebastos, in the Roman city of Caesarea Maritima. Using diver-based photogrammetry to generate a detailed 3D reconstruction of the harbour entrance, the authors identify two distinct architectural styles on either side of the channel, suggesting different building phases and a possible later renovation. The study provides new insights into the development, operation, and progressive deterioration of one of the largest artificial harbours of the Roman period.

Benetatos et al. (2025) (contribution 7) present the first underwater survey of a 1st-century B.C. Roman shipwreck located off Santo Stefano al Mare, in the Ligurian Sea (Italy), carried out with an autonomous underwater vehicle (AUV). Equipped with a multi-beam echosounder, a side-scan sonar, and inertial navigation systems, the AUV acquired high-resolution bathymetric and acoustic data that were subsequently analysed using geospatial techniques. The results revealed a clearly defined assemblage of amphorae and other seabed anomalies directly associated with the wreck, demonstrating the effectiveness of integrating AUV technologies and spatial analysis methods for underwater archaeological investigations.

Solana Rubio et al. (2026) (contribution 8) assess the use of a high-resolution sub-bottom profiler (SBP) as a non-intrusive technique for surveying and documenting UCH in different regions of Spain. Through a series of geophysical surveys conducted under varying depths and environmental conditions, the authors evaluate the effectiveness of a SBP for underwater archaeological investigations. The study highlights its potential to document submerged heritage without disturbing the remains, in line with the principles of non-destructive documentation and in situ conservation promoted by the 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage.

3. Conclusions

This second edition of the Special Issue “Advanced Technologies for Maritime and Underwater Archaeology” illustrates both the breadth of UCH and the rapid evolution of the technologies used for its exploration and documentation. Most of the contributions present remarkable case-studies that span a wide range of sites and environments, from Roman shipwrecks in the Ligurian and Mediterranean seas to the Herodian harbour of Caesarea, prehistoric submerged landscapes in the Sicilian Channel, and heritage along the Spanish coast. At the same time, these contributions cover an equally wide methodological spectrum, from acoustic and geophysical surveying with sub-bottom profilers to autonomous underwater vehicles, high-resolution photogrammetry, and 3D reconstruction. Moreover, the growing role of AI, together with the IoUT and EC, is enabling the capture and processing of heterogeneous sensor data, the detection and classification of features of archaeological interest, and the assessment and mitigation of risks affecting underwater cultural heritage.

We expect these directions to shape the next stage of research in maritime and underwater archaeology. We hope that this Special Issue contributes to that effort and inspires further work across the many disciplines that this field brings together.

Author Contributions: J.P., F.B., A.L., M.R., M.F.L.R., G.P. and N.M. jointly developed the concept and co-wrote this Editorial. All authors have read and agreed to the published version of the manuscript.

Funding: The work done by the editors in this Special Issue was partially supported by the TECTONIC project funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 873132.

Conflicts of Interest: Antonio Lagudi was employed by the company 3D Research s.r.l. The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

List of Contributions:

1. Calantropio, A.; Chiabrandi, F. Underwater Cultural Heritage Documentation Using Photogrammetry. *J. Mar. Sci. Eng.* **2024**, *12*, 413. <https://doi.org/10.3390/jmse12030413>.
2. Helfman, N.; Rott, J.; Cvikel, D. Revisiting the Serçe Limanı Sail Plan. *J. Mar. Sci. Eng.* **2024**, *12*, 937. <https://doi.org/10.3390/jmse12060937>.
3. Galili, E.; Horwitz, L.K.; Patania, I.; Bar, A.; Ogloblin Ramirez, I. Identifying Anthropogenic Versus Natural Submerged Prehistoric Landscapes: Two Case Studies from the Sicilian Channel. *J. Mar. Sci. Eng.* **2024**, *12*, 1981. <https://doi.org/10.3390/jmse12111981>.
4. Herrera-Santos, J.; Plaza-Hernández, M.; López-Florez, S.; Djapic, V.; Prieto Tejedor, J.; Corchado-Rodríguez, E.S. Edge Computing Architecture for the Management of Underwater Cultural Heritage. *J. Mar. Sci. Eng.* **2024**, *12*, 2250. <https://doi.org/10.3390/jmse12122250>.
5. Ferrero-Martín, C.; Izquierdo, A.; Bethencourt, M.; Fernández-Montblanc, T. A Risk Assessment of Underwater Cultural Heritage for Wave-Induced Hazards: The Impact of Climate Change on Cadiz Bay. *J. Mar. Sci. Eng.* **2025**, *13*, 136. <https://doi.org/10.3390/jmse13010136>.
6. Gambash, G.; Arkin-Shalev, E.; Wood, J.; Nantet, E.; Gambin, T. *Caesarea SubMaritima*: Insights into the Entrance of the Roman Harbour of Sebastos as Obtained Through High-Resolution Multimodal Remote Sensing Surveys. *J. Mar. Sci. Eng.* **2025**, *13*, 940. <https://doi.org/10.3390/jmse13050940>.
7. Benetatos, C.; Costa, S.; Giglio, G.; Mastrantuono, C.; Mo, R.; Peter, C.; Pirri, C.F.; Rovere, A.; Verga, F. Exploring the Mediterranean: AUV High-Resolution Mapping of the Roman Wreck Offshore of Santo Stefano al Mare (Italy). *J. Mar. Sci. Eng.* **2025**, *13*, 1921. <https://doi.org/10.3390/jmse13101921>.
8. Solana Rubio, S.E.; Cerezo Andreo, F.; Ramallo Asensio, S.F.; López-Castejón, F.; Bernal-Casasola, D.; Cau Ontiveros, M.Á.; Sabio González, R.; Gamo Pazos, E. Sub-Bottom Profiler in Underwater Archaeology: Comparative Analysis for Non-Intrusive Surveying and Documentation of Underwater Cultural Heritage in Spain. *J. Mar. Sci. Eng.* **2026**, *14*, 943. <https://doi.org/10.3390/jmse14100943>.

References

1. Prieto, J.; Bruno, F.; Lagudi, A.; Ricca, M.; La Russa, M.F.; Papatheodorou, G.; Mišković, N. Advanced Technologies for Maritime and Underwater Archaeology. *J. Mar. Sci. Eng.* **2023**, *11*, 593. [CrossRef]
2. Ricca, M.; Alexandrakis, G.; Bonazza, A.; Bruno, F.; Davidde Petriaggi, B.; Elkin, D.; Lagudi, A.; Nicolas, S.; Novák, M.; Papatheodorou, G.; et al. A Sustainable Approach for the Management and Valorization of Underwater Cultural Heritage: New Perspectives from the TECTONIC Project. *Sustainability* **2020**, *12*, 5000. [CrossRef]
3. UNESCO. *Convention on the Protection of the Underwater Cultural Heritage, Paris, 2 November 2001*; UNESCO: Paris, France, 2001. Available online: <https://www.unesco.org/en/legal-affairs/convention-protection-underwater-cultural-heritage> (accessed on 6 June 2026).
4. Secci, M. Survey and Recording Technologies in Italian Underwater Cultural Heritage: Research and Public Access Within the Framework of the 2001 UNESCO Convention. *J. Marit. Archaeol.* **2017**, *12*, 109–123. [CrossRef]
5. Gkionis, P.; Papatheodorou, G.; Geraga, M. The Benefits of 3D and 4D Synthesis of Marine Geophysical Datasets for Analysis and Visualisation of Shipwrecks, and for Interpretation of Physical Processes over Shipwreck Sites: A Case Study off Methoni, Greece. *J. Mar. Sci. Eng.* **2021**, *9*, 1255. [CrossRef]

6. Janowski, Ł.; Pydyn, A.; Popek, M.; Kotarba-Morley, A.M.; Tysiąc, P. Automated Feature Extraction and Classification of Submerged Cultural Heritage Assets in the Puck Lagoon via Multisensor Remote Sensing. *Archaeol. Prospect.* **2026**, *33*, 397–421. [CrossRef]
7. Gil-Docampo, M.; Peña-Villasenín, S.; Bettencourt, A.M.S.; Ortiz-Sanz, J.; Peraleda-Vázquez, S. 3D Geometric Survey of Cultural Heritage by UAV in Inaccessible Coastal or Shallow Aquatic Environments. *Archaeol. Prospect.* **2025**, *32*, 19–34. [CrossRef]
8. Huang, Z.; Liu, T. The Application of Marine Intelligent Platforms in Underwater Archaeology. *Measurement* **2026**, *275*, 121373. [CrossRef]
9. Wright, A.E.; Conlin, D.L.; Shope, S.M. Assessing the Accuracy of Underwater Photogrammetry for Archaeology: A Comparison of Structure from Motion Photogrammetry and Real Time Kinematic Survey at the East Key Construction Wreck. *J. Mar. Sci. Eng.* **2020**, *8*, 849. [CrossRef]
10. Aragón, E.; Munar, S.; Rodríguez, J.; Yamafune, K. Underwater Photogrammetric Monitoring Techniques for Mid-Depth Shipwrecks. *J. Cult. Herit.* **2018**, *34*, 255–260. [CrossRef]
11. Scalercio, E.; Sangiovanni, F.; Gallo, A.; Barbieri, L. Underwater Power Tools for In Situ Preservation, Cleaning and Consolidation of Submerged Archaeological Remains. *J. Mar. Sci. Eng.* **2021**, *9*, 676. [CrossRef]
12. Wang, S.; Han, Y.; Mao, S. Innovation Concept Model and Prototype Validation of Robotic Fish with a Spatial Oscillating Rigid Caudal Fin. *J. Mar. Sci. Eng.* **2021**, *9*, 435. [CrossRef]
13. Bruno, F.; Ricca, M.; Lagudi, A.; Kalamara, P.; Manglis, A.; Fourkiotou, A.; Papadopoulou, D.; Veneti, A. Digital Technologies for the Sustainable Development of the Accessible Underwater Cultural Heritage Sites. *J. Mar. Sci. Eng.* **2020**, *8*, 955. [CrossRef]
14. Perez-Alvaro, E. Underwater Cultural Heritage: The Societal Glue for a Blue Economy. In *Handbook of Sustainable Blue Economy*; Leal Filho, W., Salvia, A.L., Eustachio, J.P.P., Dinis, M.A.P., Eds.; Springer: Cham, Switzerland, 2024. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

Review

Underwater Cultural Heritage Documentation Using Photogrammetry

Alessio Calantropio ^{1,*} and Filiberto Chiabrando ²¹ Department of Humanities and Social Sciences, University of Sassari, 07100 Sassari, Italy² Department of Architecture and Design, Polytechnic University of Turin, 10126 Turin, Italy; filiberto.chiabrando@polito.it

* Correspondence: acalantropio@uniss.it; Tel.: +39-366-226-8538

Abstract: Underwater cultural heritage (UCH) is an irreplaceable resource with intrinsic value that requires preservation, documentation, and safeguarding. Documentation is fundamental to increasing UCH resilience, providing a basis for monitoring, conservation, and management. Advanced UCH documentation and virtualization technologies are increasingly important for dissemination and visualization purposes, domain expert study, replica reproduction, degradation monitoring, and all other outcomes after a metric survey of cultural heritage (CH). Among the different metric documentation techniques, underwater photogrammetry is the most widely used for UCH documentation. It is a non-destructive and relatively inexpensive method that can produce high-resolution 3D models and 2D orthomosaics of underwater sites and artifacts. However, underwater photogrammetry is challenged by the different optical properties of water, light penetration, visibility and suspension, radiometric issues, and environmental drawbacks that make underwater documentation difficult. This paper introduces some of the recent applications of photogrammetric techniques and methods for UCH documentation, as well as the needs and shortcomings of the current state of the art.

Keywords: underwater cultural heritage (UCH); underwater photogrammetry; geomatics; digital twins; underwater archaeology; 3D models

1. Introduction

Underwater exploration is inherently interdisciplinary, requiring collaboration between researchers in diverse fields such as geology, biology, archaeology, engineering, and geomatics. Due to the remoteness and limited accessibility of underwater archaeological sites, it is essential to use 3D metric techniques to record these sites and their elements accurately and comprehensively [1]. Geomatics techniques offer many tools and solutions for monitoring and documenting marine assets [2].

The importance of modern technologies and innovative methods used today for the documentation of heritage [3–6] is not only linked to the ease with which they allow for dissemination among groups of scholars and researchers but is also fundamental to the involvement of the general public. In particular, the study of submerged heritage contributes to the formation of cultural identity both locally and internationally [7]. Most wrecks and loads carried are located in international contexts, deriving directly from ancient trade routes; for this reason, ships and their contents can often be located today at a great distance from their context of origin or destination [8,9].

Recent advancements in archaeological research have witnessed the integration of photogrammetry as a powerful scientific tool, bridging terrestrial and marine environments to unravel historical mysteries. Marín-Buzón et al. [10] highlights the burgeoning worldwide trends in utilizing photogrammetry within archaeology, showcasing its potential for comprehensive documentation and analysis. However, amidst this enthusiasm, McAllister [11] raises pertinent concerns regarding the application of ‘Digital Realism’ in underwater

archaeology, particularly emphasizing the complexities of photogrammetric digital 3D visualization and interpretation. At the same time, Skarlatos et al. [12] emphasizes critical steps and considerations for image-based underwater 3D reconstruction in cultural heritage contexts.

The scientific community has fully addressed the increasing demand for high-resolution products with metric and colorimetric content for terrestrial applications; therefore, several commercial and non-commercial solutions and standard procedures are already available [13–15]. Conversely, high-resolution 3D reconstruction, radiometric correction capability, and positioning in an underwater context are ongoing issues. From a geomatics point of view, the presence of a water medium and the related additional drawbacks complicate scientific work as compared to the terrestrial field. Yet, Pulido Mantas et al. [16] advocates for a unified approach, transcending land and sea boundaries, demonstrating the versatility of photogrammetry in studying diverse environments.

Following conventional photogrammetry and computer-vision-based algorithms (the Structure from Motion approach), image collection and processing still represent a significant ongoing issue in underwater contexts [17]. Photogrammetric methods allow for the precise mapping of the underwater landscape and a detailed three-dimensional reconstruction of archaeological remains and evidence, which is useful for evaluating the health state of these findings [18]. Another aspect is the correction of color variation incurred by light propagating in water, which can be addressed through image enhancement [19].

2. Underwater Photogrammetry

The study of underwater cultural heritage (UCH) using geomatics, including photogrammetry, is consistent with emerging documentation requirements. Photogrammetry allows domain experts to study inaccessible CH sites remotely or indirectly (Figure 1).

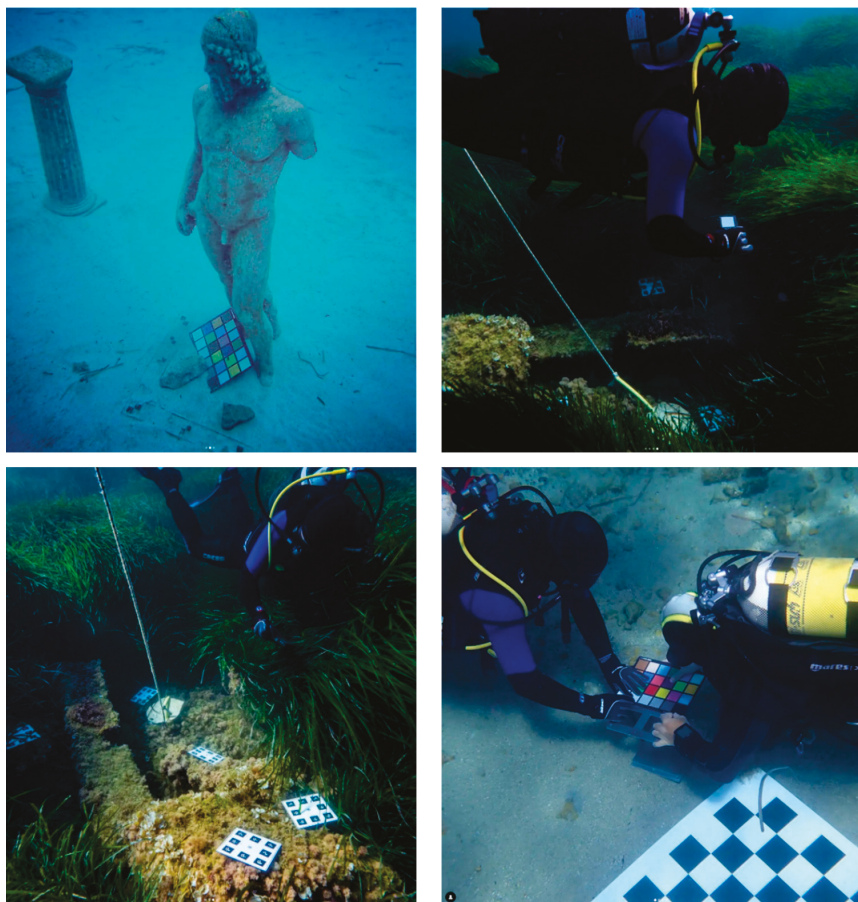


Figure 1. Some practical examples of underwater photogrammetry applications.

Underwater photogrammetry has become one of the most affordable and widely adopted methods for documenting and reconstructing submerged archaeological assets. In the digital evolution of photogrammetry, images are captured to exploit (using computer-vision-based procedures such as image matching and Structure From Motion solutions) their intrinsic metric contents.

Despite its widespread adoption, underwater photogrammetry still faces significant challenges, especially in acquiring and processing underwater images. One challenge is that the documentation is often insufficient and must be supported by careful georeferencing and the consistent use of the same reference system [20]. Additionally, generating an accurate 3D replica of a surveyed object or site requires addressing specific issues, such as maintaining consistent radiometry and avoiding blurry, low-contrast, or over-/under-exposed images. To overcome these challenges, Costa [21] outlines several adaptations to photogrammetry techniques specifically for low-visibility environments, such as high-resolution cameras and strobe lighting, wide-field-of-view cameras, image stabilization and motion compensation, and image preprocessing techniques, such as noise reduction and denoising. These techniques can further improve image quality and reduce the impact of low-visibility conditions.

2.1. Preliminary Consideration in Underwater Photogrammetric Data Acquisition and Processing

Application considerations must be addressed to ensure the effectiveness and accuracy of a photogrammetric survey. In this section, we first discuss key factors such as application restrictions, reconstruction accuracy requirements, and the time involved in modeling. Then follows a brief description of the input data, the acquisition methods, and the processing algorithms used in underwater photogrammetry.

2.1.1. Acquisition Depth and Time Restrictions

The successful application of underwater photogrammetry is contingent upon various environmental factors influencing the operator's ability to capture high-quality images and data. These factors include the depth of the sea, water clarity, and environmental conditions such as currents and visibility. Deeper water presents challenges for operators due to increased pressure, reduced visibility, and limited bottom time. The depth of the sea may necessitate specialized equipment and techniques to ensure safe and effective data acquisition. Water clarity plays a crucial role in the quality of images captured during photogrammetric surveys. Turbid or murky waters can obscure details and limit the accuracy of reconstructions. Operators may need to employ strategies such as artificial lighting or underwater filters to mitigate the effects of poor water clarity. Factors such as currents, tides, and weather conditions can impact the stability and safety of the survey environment. Operators must exercise caution and adapt their methodologies to account for these variables, ensuring the safety of personnel and equipment during data acquisition.

2.1.2. Photogrammetric Acquisition Methods

The fundamental input data for underwater photogrammetry consist of a carefully captured sequence of photographs taken from multiple viewpoints. These photographs should cover the target object or scene comprehensively, ensuring sufficient overlap between images to create a dense point cloud. This captured sequence of photographs should be of high quality with high resolution and low noise. The images should also be well exposed and have an accurate color balance. In addition, it is necessary to have sufficient overlap between the images so that the software can accurately determine the relationship between the different viewpoints. This overlap is typically between 50% and 80% [22]. It is important to acquire high-quality images of the underwater scene. This is typically carried out using a specialized underwater camera, such as a DSLR or mirrorless camera with housing and external strobes. There are two main methods for acquiring images for underwater photogrammetry:

Manual: Divers or underwater robots can manually capture images of the target using handheld or tethered cameras. This method is labor-intensive, and it can be difficult to control the camera's position and orientation, but it can be used to capture high-quality images of intricate details [23].

Automated: Autonomous underwater vehicles (AUVs) or remotely operated vehicles (ROVs) can be programmed to fly or swim along a predefined path while photographing. This method is more efficient and allows for a wider coverage of the target. Still, it can be challenging to ensure that the AUV or ROV follows the path accurately and captures high-quality images [24].

2.1.3. Reconstruction Accuracy

Various parameters, including the camera-to-object distance, acquisition geometry, and sensor resolution, influence the reconstruction accuracy required for underwater cultural heritage surveys. Achieving high levels of accuracy is essential for producing detailed and reliable 3D models of surveyed assets. Maintaining an optimal camera-to-object distance is critical for capturing detailed images with sufficient overlap for accurate reconstruction. Operators must carefully plan their survey trajectories and camera positions to ensure consistent coverage of the target area. The arrangement and orientation of cameras relative to the subject impact the accuracy and completeness of the resulting 3D model. Different acquisition geometries, such as grid or spiral patterns, may be employed to optimize coverage and minimize distortion. The resolution of the imaging sensor used in photogrammetric surveys directly influences the level of detail captured in the resulting images. Higher-resolution sensors can enhance the accuracy of reconstructions but may also require greater computational resources for processing. It is important to specify that the accuracy of the survey will be certifiable only if enough GCPs (Ground Control Points), CPs (Check Points) and/or redundant scalebars are located in the surveyed area in order to correctly georeference the survey and the related products.

2.1.4. Processing Algorithms

The time required for modeling, encompassing the computation of the acquired data using photogrammetry and structure-from-motion software, is critical in underwater cultural heritage documentation projects. This time is influenced by the number of images captured, their resolution, and the scene's complexity. Increasing the number of captured images can improve the final 3D model's accuracy and completeness but also prolong the processing time. Operators must strike a balance between the data acquisition efficiency and computational resources. Higher-resolution images contain more detail but require more processing power and time for alignment and reconstruction. Operators should carefully consider the trade-offs between image resolution and processing efficiency.

The core processing algorithms in underwater photogrammetry are similar to those used in terrestrial photogrammetry, but they are adapted to address the specific challenges of an underwater environment. SfM algorithms reconstruct the 3D structure of a scene from a set of 2D photographs. They estimate the 3D coordinates of points in the scene by analyzing the relative positions of corresponding points in the images. A comprehensive overview of underwater 3D reconstruction technology based on optical images is provided in [25].

2.2. Optical and Physics Issues Related to Underwater Photogrammetry

For submerged heritage, for which it is necessary to work in a marine environment, the phase of the survey is one of the most important phases (together with the planning phase), as it helps understand not only the current state of the assets but also to make historical hypotheses and assumptions, as well as define the successive steps of valorization. Marine environments and conditions cause specific alterations that require the collaboration of different scientists in a multidisciplinary approach. Basic knowledge of the physical

principles that regulate light transmission helps to understand the optical phenomena and the “countermeasures” to be adopted when performing a photogrammetric survey.

2.2.1. The Underwater Spectrum of Light and Selective Absorption

An important factor that influences a survey is the depth in which the assets are located; this is related to a degradation in the visible electromagnetic spectrum, and it is an important aspect for the study and recognition of materials, both for photographic and photogrammetric purposes.

Sunlight is electromagnetic radiation emitted by the Sun. It is a broad spectrum of electromagnetic waves, ranging from radio waves with wavelengths of tens of meters to gamma rays with wavelengths of less than a trillionth of a meter. The most intense portion of the Sun’s radiation that reaches the Earth’s surface is visible light, with wavelengths ranging from about 400 to 700 nanometers. The light spectrum is all the different wavelengths of light that compose sunlight. It is a continuous spectrum, meaning no gaps exist between the different wavelengths. The visible light spectrum is a small portion of the overall light spectrum, but it is the only portion we can see. Focusing on visible colors, these range from red to violet in the following order: red, orange, yellow, green, light blue, blue, and violet. Like many other substances, water absorbs part of the light that passes through it. This absorption is not homogeneous but occurs differently depending on the mass of water crossed by the light for the various colors. The phenomenon, precisely because it occurs selectively on the various colors, is called “selective absorption”.

Underwater images are, therefore, affected by inconsistencies in radiometry due to the optical properties of water. When light propagates in water, all (but mainly higher wavelengths) colors are affected by a degradation in intensity. As we mentioned, this degradation changes based on the examined wavelength, mainly concerning the acquisition depth, the camera-to-object distance, and the water’s physical characteristics and conditions for a given site in a specific acquisition time frame. Water causes a significant attenuation of light while it passes through it, making its intensity exponentially weaker the more it travels [26]. The attenuation of light underwater is frequency-dependent, meaning that red light is attenuated over much shorter distances than blue light, as well as the backscattering of blue and green, resulting in a change in the observed color of an object at different distances from the camera and light source [27].

Another factor that should not be underestimated is the presence of materials in the water; for example, if we consider the delta of a river or a lagoon environment [21], the suspended sand and clay particles will probably give the water a more turbid color, tending toward brown. The presence of phytoplankton is another cause of color distortion in underwater environments; in fact, it absorbs blue and red, resulting in a reflection of green. In practice, where there is water with phytoplankton, its color will be more green than blue. This seemingly useless information is extremely important; studying the color of the ocean allows scientists to assess the distribution and location of phytoplankton worldwide.

In digital cameras, the “white balance” feature allows the camera to interpret the colors appropriately by eliminating the chromatic dominants due to the light that, instead of being white, can be colored. White balance eliminates this unpleasant effect by returning more natural colors, which cannot happen when using film. Compared to traditional film photography, the advantage of digital images is that they automatically correct colors and give them more similar aspects to the real colors. However, there are some limits: the camera can reduce the intensity of a chromatic component, for example, blue, if this predominates over the others, but certainly cannot create red where it is absent.

This first problem can be partially solved by using the flash. Its white light allows it to revive even the duller colors, but only at a certain distance. What happens with sunlight also happens with a flashlight. As mentioned earlier, colors are absorbed as a function of the amount of water the light passes through. It does not matter which direction the light comes from; what matters is the distance the light travels underwater (Figure 2).

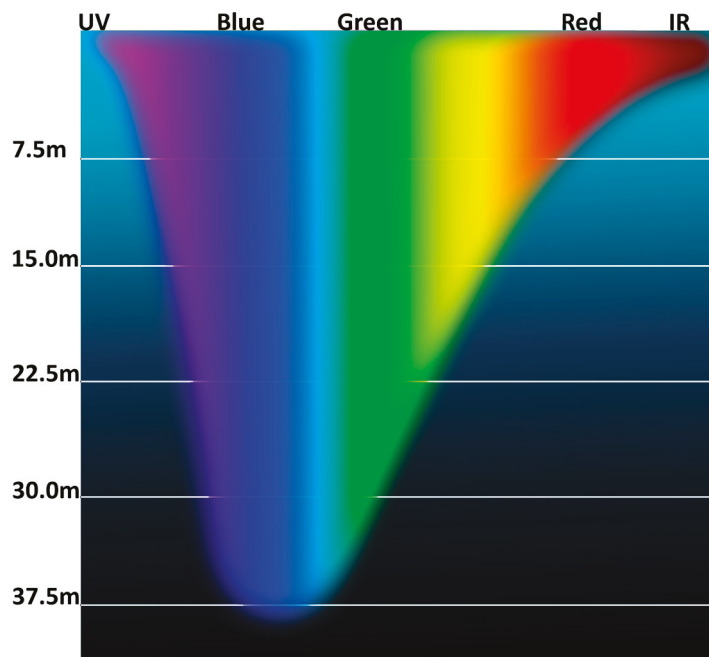


Figure 2. The colorful rainbow bands that make up white light are absorbed/attenuated by liquid water at different rates. This graph attempts to approximate how deep certain colors of light penetrate. According to this graph, blue light penetrates deepest, while ultraviolet, red, and infrared are rapidly absorbed near the surface. Source: Wikimedia Commons; Author: Tomemorris, License: CC-BY-SA-4.0.

Another factor to be considered is the depth to the bottom. If we are in the middle of the ocean, the light will not be able to penetrate for more than a few hundred meters, so—in other words—we will not have any reflection of the bottom, and we will see the water as a dark and intense blue. If, on the other hand, we are close to the coast, we will see the water as a brilliant blue-turquoise due in part to the reflection of the seabed.

2.2.2. Diffusion and Backscattering

Diffusion is another important phenomenon that must be kept in mind, and it is related to the presence of suspended materials in the water. Microorganisms, such as plankton, are always present; in tropical areas, the period of coral reproduction is characterized by large numbers of eggs dispersed in the water, but the real issue is the sand. Whether raised from the seabed due to rough seas or carried, for example, by rivers, sand, more than anything else, can make an underwater panorama appear as if it were shrouded in fog. The light hitting the suspended materials is reflected in every direction so that everything appears blurred and lacks details. This phenomenon is, however, always present since the presence of suspended elements in water is a common factor.

Backscatter, or backscattering, is usually a diffuse reflection due to scattering. It refers to the light from a flash or strobe reflected from particles in the lens' field of view, causing specks of light to appear in the photo. This gives rise to what are sometimes referred to as orb artifacts. Photo backscatter can result from snowflakes, rain, fog, or, in specific cases, suspension in a water medium [28]. Due to the size limitations of modern compact and ultra-compact cameras, especially digital cameras, the distance between the lenses and the built-in flash has decreased, thereby reducing the angle of reflection of light on the lenses and increasing the likelihood of reflection of the light from normally subvisible particles (Figure 3).

Backscatter can be reduced by compensating for the strobing direction of the photo as far away from the corner of the lens as possible. This is normally done by placing the light source high and to one or both sides by placing the strobes on extendable arms. As

the light comes from the sides, the reflected light is mainly in the direction of the strobe instead of the camera lens (Figure 4).

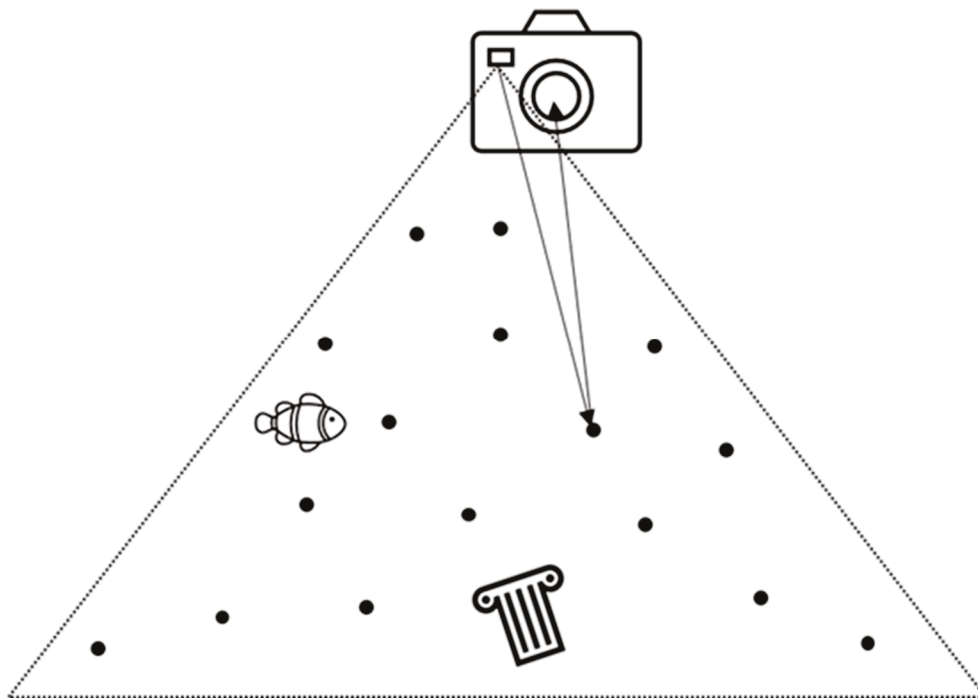


Figure 3. Backscatter from a strobe near the lens.

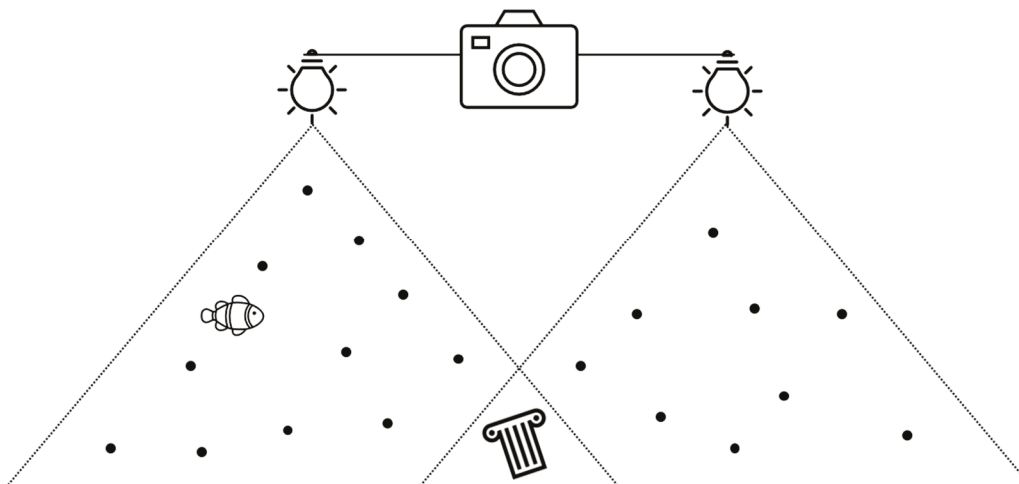


Figure 4. Backscatter can be minimized by moving the strobe away from the lens.

To overcome the reduction in the details and sharpness of distant objects related to diffusion, it is necessary to work at a very short distance, thus photographing the object of interest while being close to it. However, an important fact remains: in normal cases, all lenses increase their focal length, thus reducing the FOV and forcing them to shoot from greater distances than for a land survey (to comply with the required overlap).

2.2.3. Reflection and Refraction of Light in Water

Refraction is the bending of light as it passes from one medium to another with a different refractive index. The refractive index of water is higher than the refractive index of air, so when light travels from air to water, it slows down. Depending on the angle at which the light hits the water's surface, a greater or lesser part of the light will reach the

bottom. According to the Snell–Descartes law, if the light arrives at a different inclination, only a part penetrates towards the bottom, while a part is reflected (Figure 5).

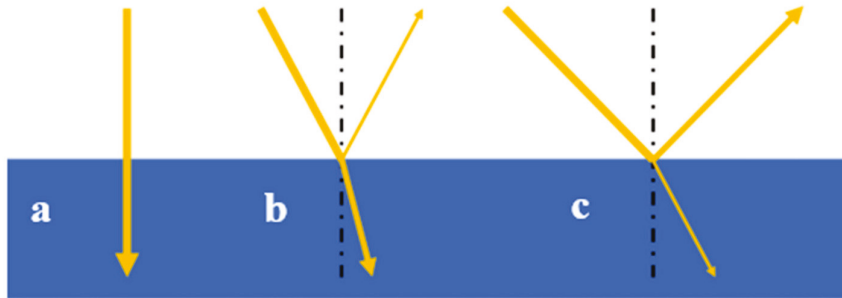


Figure 5. Refraction of light at the water surface: perpendicular incidence (a); inclined incidence (b); and low sun angle (c).

It should also be noted that rays of light that do not reach the water’s surface vertically undergo a deviation. In fact, due to the lower speed of light in the water, they tend to change direction, approaching the line perpendicular to the surface that passes through the point where the rays hit the surface. When light rays passing from the air to the water are deflected, their direction becomes closer to the normal, and the opposite occurs when light passes from the air to the water. In that case, there is a deviation from the normal.

Light rays traveling from water to air tend to move away from the perpendicular line that passes through the point where the rays hit the surface. The law of refraction, generally known as the Snell–Descartes law, governs the deviation undergone by light rays when they pass through a distinct interface between air and water. It is described by the following Equation (1).

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \quad (1)$$

where:

- θ_1 = the angle of incidence;
- θ_2 = the angle of refraction;
- n_1 = the refractive index of the first medium (approximately 1 for air);
- n_2 = the refractive index of the second medium (comprised between 1.3330 and 1.3721, depending on the salinity of the water [29]).

It is important to consider that the random effect of surface ripples generates unpredictable a priori refractions and, therefore, is not modellable without considering a degree of approximation.

It has been said that objects appear closer; to determine the distance at which they appear (called apparent distance), knowing the real one, the value of this is divided by the refractive index of the medium.

2.2.4. Refraction in UW Photogrammetry: Flat and Dome Ports

The influence of refraction is also felt in underwater photogrammetry; everything, regarding human sight, appears closer or larger when underwater, and in the same way, this also happens for digital and traditional cameras. In this case, the most disadvantaged cameras, even if it is possible to implement countermeasures, are the DSLRs.

When a camera is used in a terrestrial environment, it has a characteristic field of view (FOV), and this does not undergo any variation. The focal length of the lens, together with the sensor size, determines the FOV. As previously discussed, when light encounters a water surface, it refracts or bends closer to the line perpendicular to the boundary between the water and the air at the glass surface.

This behavior will also occur when photographing, resulting in a lower FOV. Decreasing the FOV transforms the behavior of the lens, making it more similar to that of a telephoto lens (Figure 6).

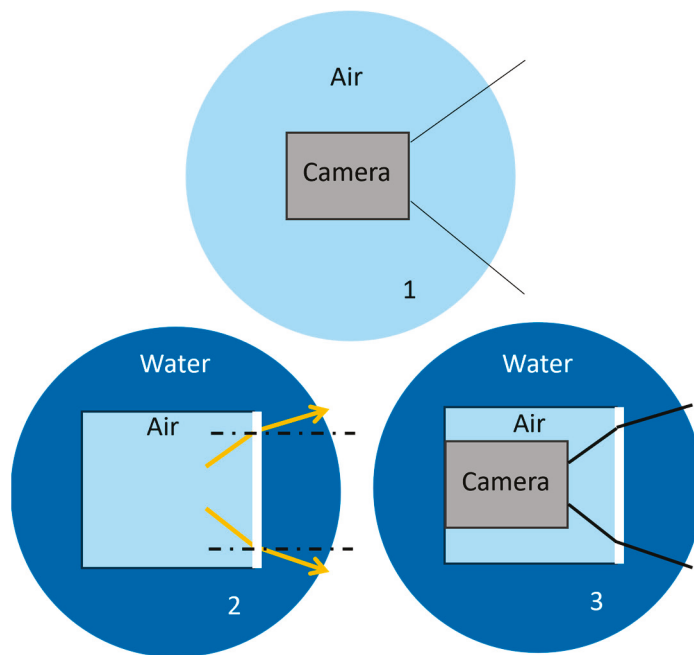


Figure 6. When cameras are employed underwater, the light passing through the medium interface of water undergoes refraction effects. The result is a smaller FOV than that obtainable with the same lens used in a terrestrial environment (1 FOV in the air, 2 camera housing in the water and connected FOV, 3 FOV reduction in the water when camera is enclsed in a camera house). Reproduced from [30].

Dome ports are specialized underwater housings that utilize a hemispherical glass or acrylic structure to provide a wide field of view for cameras. They are commonly used in underwater photogrammetry applications to capture overlapping images that can be used to reconstruct 3D models of underwater objects or scenes [31]. Dome ports also have the advantage of being able to image more of a scene in a single photograph, which can save time and effort during the photogrammetry process. (Figure 7). It is always of great benefit, even if the qualitative improvement is more noticeable than for a flat port in combination with pushed wide-angle lenses (5). Each objective lens must also correspond to a specific type of porthole. Its curvature must be suitable for the focal length of the lens, and the center of the sphere of which the port is a part must coincide with the optical center of the lens, which is not necessarily in correspondence with the outermost lens. Therefore, a different porthole for each focal length is necessary (at least in theory). The same port is used for multiple lenses of different focal lengths.

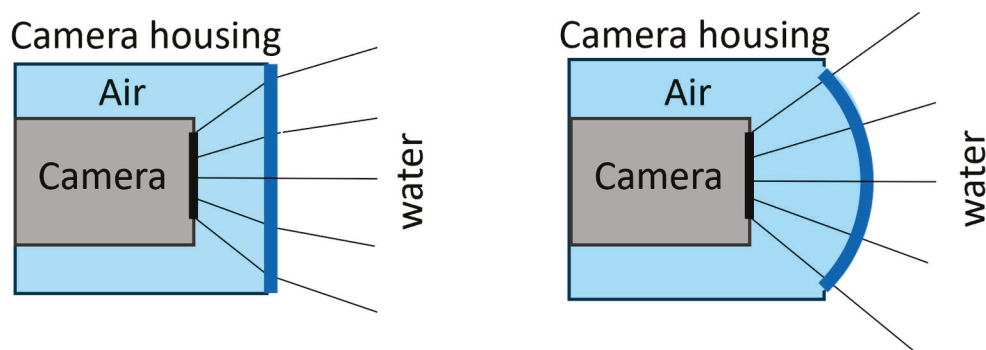


Figure 7. Comparison between a case with a flat port and one with a dome port. Examining the behavior of the light rays that pass through the glass and the window, it is evident that they do not undergo deviations when they pass through perpendicular to the surface. The shooting angle and the underwater focal length do not vary. Reproduced from [30].

There are glass or acrylic glass portholes on the market, including plexiglass with particular optical characteristics, and there are pros and cons for each of the two. Those in crystal (glass) are generally more robust, given the hardness of the material. The optical characteristics of the two materials are still excellent, but there are economic and practical differences. If glass portholes are more resistant, the difference in density between glass and water makes any scratches more evident than with plastic portholes. Thanks to their density similar to that of water and, therefore, their similar optical behavior, these materials can mask those small scratches produced on the external surface with use. It should be considered that a plastic porthole, given its simpler workability, is generally cheaper than glass ones.

2.3. Optical and Physics Issues Related to Underwater Photogrammetry

2.3.1. Geometric Aspects of Underwater Imaging and Stereo Reconstruction

Stereo reconstruction involves studying the mathematical principles governing acquiring and interpreting 3D information from underwater environments [32]. Underwater imaging systems, such as cameras and sonars, capture distorted and noisy data due to the unique properties of light and sound propagation in water [33]. To overcome these challenges and reconstruct accurate 3D models, it is essential to understand the geometric distortions and noise characteristics that affect underwater data (Figure 8).

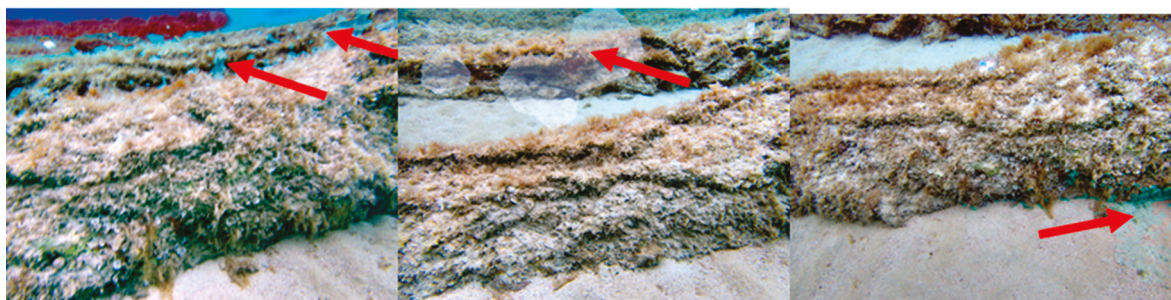


Figure 8. Examples of artifacts (indicated by the red arrows) due to poor model quality and inaccurate range maps.

The propagation of light and sound in water introduces several distortions that can significantly impact underwater imaging and stereo reconstruction. In addition to distortions, noise is another major challenge in underwater imaging and stereo reconstruction. One of the main causes of noise in underwater photogrammetry is light attenuation. Light travels less efficiently in water than in air, so the amount of light reaching the camera decreases with depth (Figure 9). This can make capturing sharp images difficult and introduce noise into the image data [34].

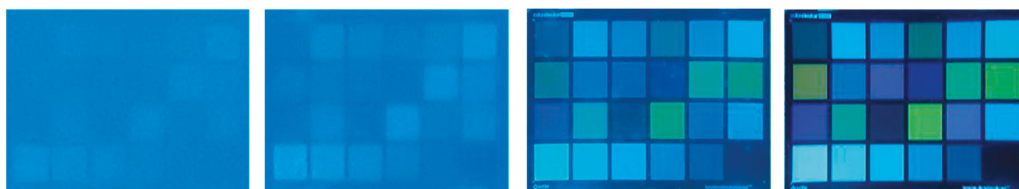


Figure 9. An example of light attenuation, which is related to the camera-to-object distance. The same calibration chart is photographed from left to right, increasing the camera's proximity to the chart.

Another major source of noise in underwater photogrammetry is scattering. When light passes through water, it can be scattered by particles suspended in the water, such as plankton and suspended sediment. This scattering can cause the image to become hazy and introduce noise into the image data [35].

In addition to light attenuation and scattering, several other factors can cause noise in underwater photogrammetry. These include the following:

- Camera motion: Any camera movement, underwater or on the surface, can cause blur and noise in images. This is particularly important for underwater photogrammetry, as the water can make it difficult to keep the camera steady.
- Waves and currents: Waves and currents can cause underwater objects to move, leading to blurring in underwater photographs. This can also make it difficult to stitch together multiple photographs to create a complete 3D model.
- Reflections: Underwater surfaces can reflect light, creating distracting photograph artifacts. These reflections can also make identifying features in the image data difficult (Figure 10).

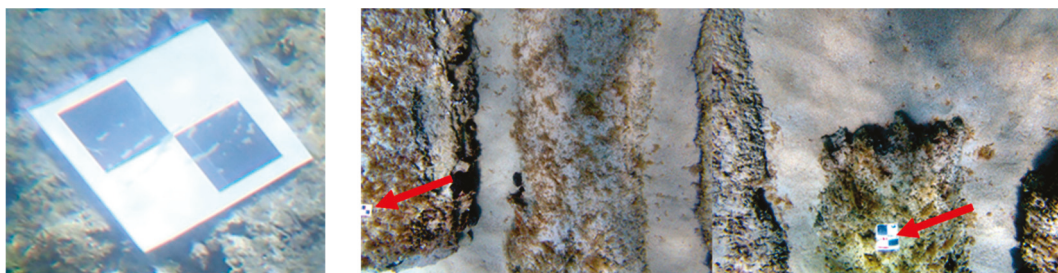


Figure 10. Examples of artifacts (indicated by the red arrows) due to reflections caused by the albedo of artificial objects.

Another relevant issue concerning the geometric aspect of underwater imaging, especially when operating in shallow waters, is the presence of caustics. Caustics are bright, localized patterns that occur when a curved surface reflects or refracts light rays. They are a common phenomenon in underwater photogrammetry and can be a major challenge in creating accurate 3D models (Figure 11).



Figure 11. An example of caustics (indicated by the red arrows), which are often present in underwater imagery acquired at shallow depths.

Caustics can be difficult to remove from underwater photogrammetry images because they can be very similar to real features of the object or scene. However, several techniques can be used to reduce their impact [36].

Lens aberrations are another common problem in underwater photogrammetry and can significantly impact the accuracy and quality of 3D models [37]. They occur when light rays passing through a lens do not converge perfectly in the image plane, which results in distortions in the image.

Despite the challenges posed by distortions and noise, geometric principles can be applied to mitigate these effects and achieve accurate underwater 3D reconstruction. These principles include the following:

- Calibration: The accurate calibration of underwater imaging systems is essential to account for geometric distortions and ensure the correct alignment of images or signals from multiple sensors [38].
- Dewarping: Dewarping algorithms can correct refraction and other geometric distortions in underwater images or signals [39].
- Noise reduction: Various noise reduction techniques, such as filtering and averaging, can be applied to reduce the impact of electronic and environmental noise on underwater data [40].
- Stereo reconstruction: Stereo reconstruction algorithms can fuse images or signals from multiple underwater sensors to reconstruct a 3D model of the scene [41].

To ensure metric consistency and obtain reliable 3D metric products, it is essential to follow photogrammetric principles, especially in underwater photogrammetry. The proper geometric calibration of the employed optics is essential with the widespread use of low-cost and non-metric sensors.

2.3.2. Camera Calibration

Calibration identifies geometric distortions in final images caused by the lens materials, shapes, and construction characteristics of the cameras and optics used in the survey.

Camera calibration for photogrammetry is a well-known practice [42] and is an essential preliminary step for accurate 3D object reconstruction. It allows for obtaining intrinsic camera parameters (f , c_x , c_y , k_1 , k_2 , k_3 , k_4 , b_1 , b_2 , p_1 , p_2) that describe the interior orientation and lens distortion. Knowing these parameters is essential for generating images as close as possible to central perspectives, which are necessary for metric purposes.

The following calibration parameters can be determined:

- f —the focal length.
- c_x and c_y —the principal point coordinates, i.e., lens optical axis intersection coordinates with sensor plane.
- b_1 and b_2 —the affinity and non-orthogonality (skew) coefficients.
- k_1 , k_2 , k_3 , and k_4 —the radial distortion coefficients.
- p_1 and p_2 —the tangential distortion coefficients.

Various methods and strategies exist for calibrating digital cameras in photogrammetry. The most common approach is to use computer vision algorithms to perform camera self-calibration [43]. This approach can substantially improve accuracy [44], even with non-metric and non-conventional low-cost photogrammetric sensors [45].

Pre-calibration can be used when the conditions do not change significantly between the calibration and the survey. In pre-calibration, the camera is calibrated in a controlled environment (using a calibration polygon) or with ad hoc procedures (using calibration panels with checkerboard or dot patterns). This provides a set of intrinsic parameters that can be used as an initial guess during the self-calibration phase performed before or during the bundle block adjustment (BBA) in a typical photogrammetric workflow.

While self-calibration is the most common approach in data acquisition situations, especially in archaeology [46], it is still possible to observe a significant gain in survey accuracy whenever a robust self-calibration procedure is conducted [47]. This is especially important for underwater photogrammetric surveys, where additional distortions are introduced due to the different refractive indexes of water and air and the geometric characteristics of the flat or dome port that may be used [31].

2.4. Radiometric Correction of Images

Underwater image color correction is an important area of research for disciplines such as underwater archaeology and marine biology. Domain experts and scientists need images with colors that are consistent with the real-world scene. Automatic and semi-automatic color correction methods and algorithms have been developed to meet this need and are mainly used in the pre- or post-processing phases of photogrammetry [19,27,48–51].

Image enhancement and restoration methods have been proposed for many years. This section will provide an overview of these methods and their relevance to the investigated topic.

Water absorption and scattering coefficients have been a topic of scientific interest for many years. In 1951, Jerlov classified waters into three oceanic and five coastal types based on these coefficients [52]. Since then, various methods have been developed to determine the inherent optical properties of Jerlov water types [53,54].

A mathematical model for the spectral analysis of water characteristics was proposed in 2014 [55]. This model can be used to determine the inherent optical properties of water, which can then be used for underwater image color correction [54]. Natural water bodies were used to determine the positions of all physically important RGB attenuation coefficients. They showed that the range of wideband attenuation coefficients in the ocean is limited and that the transition from wavelength-dependent attenuation $\beta(\lambda)$ to wideband attenuation $\beta(c)$ is more complex than previously thought. A simple fusion-based approach for enhancing underwater images was proposed in [56]. This method uses a single input image and blends multiple well-known filters to improve the image quality. The authors showed that this method effectively improves the underwater footage of dynamic scenes.

A first proposal for the color correction of UW images using the $\lambda\alpha\beta$ color space is presented in [49]. This method white-balances the chromatic components and performs histogram cut-off and stretching of the luminance component to increase image contrast. The method works well under the assumption of a gray world and homogeneous lighting of the scene, which is acceptable only for close-range acquisition in a downward direction, such as seabed mapping or UW photography, and in situations with slight light changes.

Bryson et al. [48] proposed an automated underwater image color correction method using a gray-world color distribution. This means that surface reflectance has a gray-scale distribution independent of scene geometry. This approach is particularly useful for imaging large-scale biological environments, where the use of color charts is prohibited due to the sensitivity of marine ecosystems to seabed disturbances.

Another underwater image color correction approach is to develop a physically based image formation model. This model considers the optical properties of water, such as absorption and scattering, to calculate the true color of a scene. In 2016, researchers proposed a formation model for calculating the true color of scenes taken from an underwater automated vehicle with strobes. This model required a unique camera setup and strobes, but it allowed the authors to create and propose a unique image formation model that could restore the true color of the images.

Akkaynak et al. [57] proposed a revised underwater image formation model that takes into account these differences. They derived the physically valid space of backscatter using oceanographic measurements and validated their model using in situ underwater experiments.

The revised model is more physically accurate than the current one but contains more parameters and can be challenging. However, the researchers also implemented a pipeline called Sea-thru [19] that uses the revised model to correct the colors of underwater images.

In 2021, Valchos et al. [58] proposed a mathematical method to color-correct underwater images by modeling light backscattering and absorption variation according to the distance of the surveyed object.

Another iteration of the latter is SeaThru-NeRF [59], a new rendering model for NeRFs in scattering media, which is based on the SeaThru image formation model and suggests a suitable architecture for learning both scene information and medium parameters¹. In 2023, Jamieson et al. proposed DeepSeeColor [60]. This novel algorithm combines a state-of-the-art underwater image formation model with the computational efficiency of deep learning frameworks. In their experiments, they show that DeepSeeColor offers comparable performance to the popular “Sea-Thru” algorithm while being able to rapidly process images at up to 60 Hz, thus making it suitable for use onboard AUVs as a preprocessing step to enable more robust vision-based behaviors².

3. The Use of Drones in Underwater Photogrammetry

3.1. UAS Photogrammetry in Very Shallow Water

To plan an effective archaeological survey campaign, it is essential to understand the topographic situation of a site, both to obtain an overview of the area and to comprehend the relationships between the surrounding territory and the underwater heritage itself. A hybrid approach integrating total stations and GNSS equipment for land surveys remains fundamental [61].

Aerial photography is an important tool for this purpose, as it can be used for both land surveys and the shallow water mapping of archaeological evidence. This is important not only to identify the presence of archaeological sites but also to better understand the layout of structures. Aerial photogrammetry, including legacy data, represents a cartographic basis for drafting an overall plan for the site.

For sites with assets halfway between water and land or with emerged and submerged portions, it is particularly important to study the relationship between the coast and the land to identify elements that may suggest continuity, or continuation. Here again, aerial photogrammetry plays an important role in understanding the limits of archaeological structures on land and underwater, which is essential for better planning subsequent surveys.

UAS (Unmanned Aerial System) photogrammetry has emerged as a powerful tool for archaeological surveys in very shallow water, offering a cost-effective and efficient way to perform bathymetric surveys [62]. However, the unique characteristics of shallow water environments pose several challenges for UAS photogrammetry, particularly the effects of refraction and waves [63].

In the case of UAS photogrammetry in shallow water, the difference in refractive index between air and water causes light rays to bend towards the water's surface, leading to distortion in the captured images. This distortion can result in errors in the reconstructed 3D models, affecting the accuracy of archaeological interpretations.

Waves on the water surface introduce additional challenges for UAS photogrammetry. The movement of waves can cause blurry or distorted images. Additionally, the rippling effect of waves can create artifacts in the reconstructed 3D models, affecting the visual interpretation of the archaeological site.

To mitigate the effects of refraction and waves, Partama [64] developed geometric modeling techniques specifically tailored for UAS photogrammetry in shallow water. These techniques involve incorporating the refractive index of water and wave characteristics into the photogrammetry software. This allows the software to compensate for the distortion caused by refraction and waves, resulting in more accurate 3D reconstructions [65]. Other solutions are represented by bathymetric mapping from UAS imagery based on machine learning [66] to automatically compensate for water refraction and wave motion.

Overall, these studies have demonstrated the effectiveness of geometric modeling in mitigating the effects of refraction and waves, leading to more accurate and reliable 3D reconstructions of underwater archaeological sites in very shallow waters.

3.2. Remotely Operated Vehicles (ROVs) in Underwater Photogrammetry

Remotely operated vehicles (ROVs) have emerged as powerful tools for underwater exploration and surveying, particularly in the context of underwater photogrammetry. Their ability to navigate underwater environments and acquire high-resolution imagery has transformed our ability to study underwater structures, habitats, and ecosystems. Unlike human divers, ROVs can operate in hazardous or inaccessible environments, providing a safer and more efficient means of data collection.

ROVs come in various sizes and configurations, catering to specific applications and depths. Smaller ROVs, known as mini ROVs, are typically used for shallow-water operations, while larger ROVs can venture into deeper waters. Some ROVs are designed for specific tasks, such as inspecting and maintaining underwater infrastructure, while others are more versatile for a wider range of applications.

ROVs offer several advantages over traditional underwater photogrammetry methods such as scuba diving and towed cameras:

- Enhanced safety: ROVs eliminate the risks associated with human divers, such as decompression sickness, entanglement, and hazardous marine life encounters.
- Deeper reach: ROVs can operate at depths beyond the reach of human divers, providing access to a wider range of underwater environments.
- Increased flexibility: ROVs can navigate complex underwater structures and environments with greater maneuverability than towed cameras.
- Automated data acquisition: ROVs can be programmed to follow predetermined paths and capture images autonomously, reducing operator fatigue and increasing efficiency.

ROVs have found widespread applications in underwater photogrammetry for various purposes, including documenting underwater shipwrecks, submerged settlements, and archaeological sites [67]; assessing coral reef health, studying marine habitats, and monitoring the impact of human activities [68]; and examining pipelines, dams, and other underwater structures for cracks, corrosion, or other damage [69].

4. Discussions

Underwater cultural sites are among the most difficult-to-reach heritage sites due to their intrinsic nature. The difficulty of operating in water environments is further compounded by the operator's reduced stay time on the site and environmental conditions that can affect the survey, such as light conditions and water turbidity.

Geomatics provides sensors and techniques that allow scientists and professionals to record, process, and efficiently present data related to underwater archaeological sites. While the potentialities and problems of these techniques have already been addressed in the past [70], new emerging sensors and applications necessitate the continued investigation and evaluation of different approaches. The adoption of low-cost sensors is becoming more common [71], and the possibility of processing and quickly obtaining photogrammetric point clouds cannot be separated from the need for high metric accuracy, which is necessary for a trustworthy survey in cultural heritage documentation [72]. As such, multi-image photogrammetry has proven to be an affordable methodology, supporting underwater archaeological activities with reliable results [73].

An important outcome of an accurate metric survey is the production of thematic maps relative to materials, conservation status, and so forth, with a methodology like the one adopted on land. Developing appropriate surveys is the basis for scheduling conservative restoration actions [74]. Such restoration activities must consider that biological colonisations also endanger underwater ruins (in the short term). For this reason, it is important to take action through an initial survey and constant monitoring over time, which is functional to conserving heritage.

Over the years, some research has tried to provide a suitable methodology for satisfying the required metric accuracy and fieldwork surveys in the archaeological domain. Despite consolidated methodologies and standards in terrestrial surveys, some gaps and shortcomings exist in the underwater environment. Firstly, there is a lack of solutions for providing an easy-to-deploy workflow for expert domains (archaeologists) with no proficiency in geomatics to conduct further research on the acquired data, for example, 3D model inspection and the multitemporal analysis of excavated sites and their contents. By investigating accuracy, fidelity, and interpretive biases inherent in digital reconstructions, Ref. [11] underscores the importance of maintaining a nuanced perspective when utilizing digital tools in archaeological research. This work contributes significantly to ongoing discussions within the field, offering valuable insights for archaeologists and scholars grappling with the challenges of integrating digital technologies into underwater archaeological practice. Moreover, it is crucial to evaluate different strategies for dissemination using tools for 3D model sharing and visualization, not only for scientists but also for the general public. Nevertheless, it is currently possible to speed up and make UCH metric

documentation more cost-effective, guaranteeing safety conditions during underwater operations simultaneously, thanks to underwater photogrammetry integrating various types of cameras and sensors.

Even if an accurate survey is important for underwater archaeology, it must link the archaeological knowledge to the surveyed geometry. So, not only must computer science be involved, but it is always fundamental to insert archaeological knowledge into the process [75].

Innovative monitoring and surveying procedures can promote underwater tourism, which combines single-activity leisure, sport, culture, and ecology, which makes it very profitable and highly sustainable, and the remote enjoyment of archaeological contexts. The exploitation of 3D reconstruction, remote visits, and virtual explorations serves as a tool for managing the cultural–natural heritage of underwater archaeological findings and maps areas from a new perspective (as an ethical obligation) based on the participatory approach of all the local stakeholders.

5. Conclusions

The take-home message is that photogrammetry is increasingly used in underwater archaeology to document, reconstruct, and restore underwater assets virtually [76]. When correctly adopted, this technology can make underwater sites more accessible to more people. It can also be used to track changes in the conditions of these sites over time, as well as foster the dissemination and promotion of UCH.

Photogrammetry can measure distances, areas, and volumes of objects and features in a marine environment. These data can be used to assess the conditions of marine structures, track changes over time, and develop conservation plans. For example, photogrammetry can measure the size and shape of coral reefs, track changes in coral cover, and assess the impact of human activities on coral reefs. Photogrammetry can also be used to record the appearance and condition of marine features. These data can be used to document marine sites' historical and cultural significance, assess the impact of human activities, and develop educational resources. For example, photogrammetry can be used to record shipwrecks' appearance, assess underwater pipelines' condition, and document the diversity of marine life.

Increasing knowledge is the basis for every act of protection and valorization of archaeological and natural heritage. When facing the complex study of the conservation of underwater heritage and the coastal landscape, it is important to develop investigation and survey techniques (such as bathymetry, photogrammetry, and so forth) that require the integration of several disciplines, not only for the evaluation of the causes of the submersion but also for the definition of the important relations between underwater archaeological remains and those on the shore, taking into account the historical and chronological data available and always considering natural and anthropic factors. The objectives above go towards the efficient and effective protection and valorization of heritage.

However, some challenges still need to be addressed to make photogrammetry more effective for underwater archaeology. These challenges include developing more accurate and user-friendly workflows for archaeologists, integrating archaeological knowledge into the photogrammetry process, and overcoming the limitations of topographic surveys underwater. Another of those limits is related to the constraints of topographic surveys underwater; topographic measurement operations are often difficult and expensive to conduct, and the results can be inaccurate and limited by time, depth, and environmental conditions. During the integration of both direct and indirect survey data, it is crucial to gather and structure all the information in a way that can be understood and managed not only by geomatics but also by domain experts (archaeologists, marine biologists, etc.). Underwater cameras and dome ports specifically made for marine environments are essential for lowering geometric errors related to the presence of two mediums, which might affect the reconstruction results.

Despite these challenges, photogrammetry is a promising tool that has the potential to revolutionize underwater archaeology. With further development, this technology could lead to a better understanding of underwater heritage and a more effective approach to its preservation.

Author Contributions: Conceptualization, A.C. and F.C.; methodology, A.C.; investigation, A.C.; resources, A.C.; data curation, A.C.; writing—original draft preparation, A.C.; writing—review and editing, A.C. and F.C.; supervision, F.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Notes

¹ https://github.com/deborahLevy130/seathru_NeRF (accessed on 1 February 2024)

² <https://github.com/warplab/DeepSeeColor> (accessed on 1 February 2024)

References

1. Rissolo, D.; Blank, A.N.; Petrovic, V.; Arce, R.C.; Jaskolski, C.; Erreguerena, P.L.; Chatters, J.C. Novel Application of 3D Documentation Techniques at a Submerged Late Pleistocene Cave Site in Quintana Roo, Mexico. In Proceedings of the 2015 Digital Heritage, Granada, Spain, 28 September–2 October 2015; Institute of Electrical and Electronics Engineers (IEEE): Piscataway, NJ, USA, 2016; pp. 181–182.
2. Menna, F.; Agrafiotis, P.; Georgopoulos, A. State of the Art and Applications in Archaeological Underwater 3D Recording and Mapping. *J. Cult. Herit.* **2018**, *33*, 231–248. [CrossRef]
3. Violante, C. A Geophysical Approach to the Fruition and Protection of Underwater Cultural Landscapes. Examples from the Bay of Napoli, Southern Italy. In *La Baia di Napoli. Strategie per la Conservazione e la Fruizione del Paesaggio Culturale*; Editori Paparo: Napoli, Italy, 2023; pp. 66–73.
4. Ricca, M.; Alexandrakis, G.; Bonazza, A.; Bruno, F.; Davidde Petriaggi, B.; Elkin, D.; Lagudi, A.; Nicolas, S.; Novák, M.; Papatheodorou, G.; et al. A Sustainable Approach for the Management and Valorization of Underwater Cultural Heritage: New Perspectives from the TECTONIC Project. *Sustainability* **2020**, *12*, 5000. [CrossRef]
5. Ricci, R.; Francucci, M.; De Dominicis, L.; Ferri de Collibus, M.; Fornetti, G.; Guarneri, M.; Nuvoli, M.; Paglia, E.; Bartolini, L. Techniques for Effective Optical Noise Rejection in Amplitude-Modulated Laser Optical Radars for Underwater Three-Dimensional Imaging. *EURASIP J. Appl. Signal Process.* **2010**, *2010*, 958360. [CrossRef]
6. Bartolini, L.; De Dominicis, L.; de Collibus, M.F.; Fornetti, G.; Guarneri, M.; Paglia, E.; Poggi, C.; Ricci, R. Underwater Three-Dimensional Imaging with an Amplitude-Modulated Laser Radar at a 405 Nm Wavelength. *Appl. Opt.* **2005**, *44*, 7130–7135. [CrossRef] [PubMed]
7. Skarlatos, D.; Agrafiotis, P.; Balogh, T.; Bruno, F.; Castro, F.; Petriaggi, B.D.; Demesticha, S.; Doulamis, A.; Drap, P.; Georgopoulos, A.; et al. Project iMARECULTURE: Advanced VR, iMmersive Serious Games and Augmented REality as Tools to Raise Awareness and Access to European Underwater CULTURAL heritage. In *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*; Ioannides, M., Fink, E., Moropoulou, A., Hagedorn-Saupe, M., Fresa, A., Liestøl, G., Rajcic, V., Grussenmeyer, P., Eds.; Lecture Notes in Computer Science; Springer International Publishing: Cham, Switzerland, 2016; Volume 10058, pp. 805–813. ISBN 978-3-319-48495-2.
8. Opdebeeck, J. *Shipwrecks and Amphorae: Their Relationship with Trading Routes and the Roman Economy in the Mediterranean*; University of Southampton: Southampton, UK, 2005.
9. Aurimemma, R.; Quiri, E. Importazioni Di Anfore Orientali Nell’Adriatico Tra Primo e Medio Impero. In *Transport Amphorae and Trade in the Western Mediterranean*; J. Eiring e J. Lund: Athens, Greece, 2004.
10. Marín-Buzón, C.; Pérez-Romero, A.; López-Castro, J.L.; Ben Jerbania, I.; Manzano-Agugliaro, F. Photogrammetry as a New Scientific Tool in Archaeology: Worldwide Research Trends. *Sustainability* **2021**, *13*, 5319. [CrossRef]
11. McAllister, M. The Problem with “digital Realism” in Underwater Archaeology: Photogrammetric Digital 3D Visualization and Interpretation. *J. Marit. Archaeol.* **2021**, *16*, 253–275. [CrossRef]
12. Skarlatos, D.; Agrafiotis, P. Image-Based Underwater 3D Reconstruction for Cultural Heritage: From Image Collection to 3D. Critical Steps and Considerations. In *Visual Computing for Cultural Heritage*; Springer: Cham, Switzerland, 2020; pp. 141–158.

13. Abate, N.; Ronchi, D.; Vitale, V.; Masini, N.; Angelini, A.; Giuri, F.; Minervino Amodio, A.; Gennaro, A.M.; Ferdani, D. Integrated Close Range Remote Sensing Techniques for Detecting, Documenting, and Interpreting Lost Medieval Settlements under Canopy: The Case of Altanum (RC, Italy). *Land* **2023**, *12*, 310. [CrossRef]
14. Ceccarelli, S.; Guarneri, M.; Ferri de Collibus, M.; Francucci, M.; Ciaffi, M.; Danielis, A. Laser Scanners for High-Quality 3D and IR Imaging in Cultural Heritage Monitoring and Documentation. *J. Imaging* **2018**, *4*, 130. [CrossRef]
15. Di Stefano, F.; Torresani, A.; Farella, E.M.; Pierdicca, R.; Menna, F.; Remondino, F. 3D Surveying of Underground Built Heritage: Opportunities and Challenges of Mobile Technologies. *Sustainability* **2021**, *13*, 13289. [CrossRef]
16. Pulido Mantas, T.; Roveta, C.; Calcinai, B.; di Camillo, C.G.; Gambardella, C.; Gregorin, C.; Coppari, M.; Marrocco, T.; Puce, S.; Riccardi, A.; et al. Photogrammetry, from the Land to the Sea and Beyond: A Unifying Approach to Study Terrestrial and Marine Environments. *J. Mar. Sci. Eng.* **2023**, *11*, 759. [CrossRef]
17. Calantropio, A.; Chiabrando, F.; Seymour, B.; Kovacs, E.; Lo, E.; Rissolo, D. Image Pre-Processing Strategies for Enhancing Photogrammetric 3d Reconstruction of Underwater Shipwreck Datasets. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2020**, *43B2*, 941–948. [CrossRef]
18. Doležal, M.; Vlachos, M.; Secchi, M.; Demesticha, S.; Skarlatos, D.; Liarokapis, F. Understanding Underwater Photogrammetry For Maritime Archaeology through Immersive Virtual Reality. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **2019**, *XLII-2-W10*, 85–91. [CrossRef]
19. Akkaynak, D.; Treibitz, T. Sea-Thru: A Method for Removing Water from Underwater Images. In Proceedings of the 2019 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), Long Beach, CA, USA, 15–20 June 2019; pp. 1682–1691.
20. Balletti, C.; Beltrame, C.; Costa, E.; Guerra, F.; Vernier, P. Underwater photogrammetry and 3d reconstruction of marble cargos shipwreck. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *XL-5/W5*, 7–13. [CrossRef]
21. Costa, E. Survey and Photogrammetry in Underwater Archaeological Contexts at Low Visibility in the Venice Lagoon. *Digit. Appl. Archaeol. Cult. Herit.* **2022**, *24*, e00215. [CrossRef]
22. Sapirstein, P.; Murray, S. Establishing Best Practices for Photogrammetric Recording during Archaeological Fieldwork. *J. Field Archaeol.* **2017**, *42*, 337–350. [CrossRef]
23. McCarthy, J.; Benjamin, J. Multi-Image Photogrammetry for Underwater Archaeological Site Recording: An Accessible, Diver-Based Approach. *J. Marit. Archaeol.* **2014**, *9*, 95–114. [CrossRef]
24. Livanos, G.; Zervakis, M.; Chalkiadakis, V.; Moirgiorgou, K.; Giakos, G.; Papandroulakis, N. Intelligent Navigation and Control of a Prototype Autonomous Underwater Vehicle for Automated Inspection of Aquaculture Net Pen Cages. In Proceedings of the 2018 IEEE International Conference on Imaging Systems and Techniques (IST), Krakow, Poland, 16–18 October 2018; pp. 1–6.
25. Hu, K.; Wang, T.; Shen, C.; Weng, C.; Zhou, F.; Xia, M.; Weng, L. Overview of Underwater 3D Reconstruction Technology Based on Optical Images. *J. Mar. Sci. Eng.* **2023**, *11*, 949. [CrossRef]
26. Jaffe, J.S. Computer Modeling and the Design of Optimal Underwater Imaging Systems. *IEEE J. Ocean. Eng.* **1990**, *15*, 101–111. [CrossRef]
27. Bryson, M.; Johnson-Roberson, M.; Pizarro, O.; Williams, S.B. True Color Correction of Autonomous Underwater Vehicle Imagery. *J. Field Robot.* **2016**, *33*, 853–874. [CrossRef]
28. Van Damme, T. Computer vision photogrammetry for underwater archaeological site recording in a low-visibility environment. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *XL-5/W5*, 231–238. [CrossRef]
29. Lide, D. *Handbook of Chemistry and Physics*, 86th ed.; CRC: Boca Raton, FL, USA, 2005.
30. Borri, E.M. *Fotografia Subacquea per Turisti Digitali*; Edizioni FAG Srl: Assago, Italy, 2005; ISBN 978-88-8233-433-8.
31. Menna, F.; Nocerino, E.; Remondino, F. Flat Versus Hemispherical Dome Ports in Underwater Photogrammetry. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *42W3*, 481–487. [CrossRef]
32. Bruno, F.; Bianco, G.; Muzzupappa, M.; Barone, S.; Rationale, A.V. Experimentation of Structured Light and Stereo Vision for Underwater 3D Reconstruction. *ISPRS J. Photogramm. Remote Sens.* **2011**, *66*, 508–518. [CrossRef]
33. Telem, G.; Filin, S. Photogrammetric Modeling of Underwater Environments. *ISPRS J. Photogramm. Remote Sens.* **2010**, *65*, 433–444. [CrossRef]
34. Karpouzli, E.; Malthus, T.; Place, C.; Chui, A.M.; Garcia, M.I.; Mair, J. Underwater Light Characterisation for Correction of Remotely Sensed Images. *Int. J. Remote Sens.* **2003**, *24*, 2683–2702. [CrossRef]
35. Cheng, H.; Chu, J.; Zhang, R.; Tian, L.; Gui, X. Turbid Underwater Polarization Patterns Considering Multiple Mie Scattering of Suspended Particles. *Photogramm. Eng. Remote Sens.* **2020**, *86*, 737–743. [CrossRef]
36. Agrafiotis, P.; Skarlatos, D.; Forbes, T.; Poullis, C.; Skamantzari, M.; Georgopoulos, A. Underwater photogrammetry in very shallow waters: Main challenges and caustics effect removal. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2018**, *XLII-2*, 15–22. [CrossRef]
37. Menna, F.; Nocerino, E.; Remondino, F. Optical Aberrations in Underwater Photogrammetry with Flat and Hemispherical Dome Ports. In Proceedings of the Videometrics, Range Imaging, and Applications XIV, Munich, Germany, 25–29 June 2017; SPIE: St Bellingham, WA, USA, 2017; Volume 10332, pp. 28–41.
38. Lavest, J.M.; Rives, G.; Lapresté, J.T. Underwater Camera Calibration. In *Computer Vision—ECCV 2000*; Vernon, D., Ed.; Springer: Berlin/Heidelberg, Germany, 2000; pp. 654–668.

39. Simple Algorithm for Correction of Geometrically Warped Underwater Images—Halder—2014—Electronics Letters—Wiley Online Library. Available online: <https://ietresearch.onlinelibrary.wiley.com/doi/full/10.1049/el.2014.3142> (accessed on 22 December 2023).
40. Jian, M.; Liu, X.; Luo, H.; Lu, X.; Yu, H.; Dong, J. Underwater Image Processing and Analysis: A Review. *Signal Process. Image Commun.* **2021**, *91*, 116088. [CrossRef]
41. Queiroz-Neto, J.P.; Carceroni, R.; Barros, W.; Campos, M. Underwater Stereo. In Proceedings of the Proceeding. 17th Brazilian Symposium on Computer Graphics and Image Processing, Curitiba, Brazil, 20 October 2004; pp. 170–177.
42. Remondino, F.; Fraser, C. Digital Camera Calibration Methods: Considerations and Comparisons. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2006**, XXXVI, 266–272. [CrossRef]
43. Fraser, C.S. Digital Camera Self-Calibration. *ISPRS J. Photogramm. Remote Sens.* **1997**, *52*, 149–159. [CrossRef]
44. Gruen, A.; Beyer, H.A. System Calibration Through Self-Calibration. In *Calibration and Orientation of Cameras in Computer Vision*; Gruen, A., Huang, T.S., Eds.; Springer Series in Information Sciences; Springer: Berlin/Heidelberg, Germany, 2001; pp. 163–193. ISBN 978-3-662-04567-1.
45. Perfetti, L.; Polari, C.; Fassi, F. Fisheye multi-camera system calibration for surveying narrow and complex architectures. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **2018**, XLII–2, 877–883. [CrossRef]
46. Rodríguez-Martín, M.; Rodríguez-González, P. Suitability of Automatic Photogrammetric Reconstruction Configurations for Small Archaeological Remains. *Sensors* **2020**, *20*, 2936. [CrossRef] [PubMed]
47. Fryer, J.G.; Fraser, C.S. On the Calibration of Underwater Cameras. *Photogramm. Rec.* **1986**, *12*, 73–85. [CrossRef]
48. Bryson, M.; Johnson-Roberson, M.; Pizarro, O.; Williams, S.B. Colour-Consistent Structure-from-Motion Models Using Underwater Imagery. *Robot. Sci. Syst.* **2013**, *8*, 33–40. [CrossRef]
49. Bianco, G.; Muzzupappa, M.; Bruno, F.; Garcia, R.; Neumann, L. A New Color Correction Method for Underwater Imaging. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.—ISPRS Arch.* **2015**, *40*, 25–32. [CrossRef]
50. Wu, M.; Luo, K.; Dang, J.; Li, D. Underwater Image Restoration Using Color Correction and Non-Local Prior. In Proceedings of the OCEANS 2017—Aberdeen, Aberdeen, UK, 19–22 June 2017; pp. 1–5. [CrossRef]
51. Roznere, M.; Li, A.Q. Real-Time Model-Based Image Color Correction for Underwater Robots. In Proceedings of the 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Macau, China, 3–8 November 2019.
52. Jerlov, N.G.; Koczy, F.F. *Photographic Measurements of Daylight in Deep Water*; Reports of the Swedish Deep-Sea Expedition, 1947–1948; Volume 3: Physics and Chemistry; Elanders boktr.: Gothenburg, Sweden, 1951.
53. Solonenko, M.G.; Mobley, C.D. Inherent Optical Properties of Jerlov Water Types. *Appl. Opt.* **2015**, *54*, 5392. [CrossRef] [PubMed]
54. Akkaynak, D.; Treibitz, T.; Shlesinger, T.; Tamir, R.; Loya, Y.; Iluz, D. What Is the Space of Attenuation Coefficients in Underwater Computer Vision? In Proceedings of the 2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), Honolulu, HI, USA, 21–26 July 2017; pp. 568–577. [CrossRef]
55. Blasinski, H.; Breneman IV, J.; Farrell, J. A MODEL FOR ESTIMATING SPECTRAL PROPERTIES OF WATER FROM RGB IMAGES. In Proceedings of the 2014 IEEE International Conference on Image Processing (ICIP), Paris, France, 27–30 October 2014; pp. 610–614.
56. Ancuti, C.; Ancuti, C.O.; Haber, T.; Bekaert, P. Enhancing Underwater Images and Videos by Fusion. In Proceedings of the 2012 IEEE Conference on Computer Vision and Pattern Recognition, Providence, RI, USA, 16–21 June 2012; pp. 81–88. [CrossRef]
57. Akkaynak, D.; Treibitz, T. A Revised Underwater Image Formation Model. In Proceedings of the 2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition. Salt Lake City, UT, USA, 18–23 June 2018; pp. 6723–6732. [CrossRef]
58. Vlachos, M.; Calantropio, A.; Skarlatos, D.; Chiabrando, F. Modelling colour absorption of underwater images using sfm-mvs generated depth maps. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2022**, *43*, 959–966. [CrossRef]
59. Levy, D.; Peleg, A.; Pearl, N.; Rosenbaum, D.; Akkaynak, D.; Korman, S.; Treibitz, T. SeaThru-NeRF: Neural Radiance Fields in Scattering Media. In Proceedings of the 2023 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), Vancouver, BC, Canada, 17–24 June 2023.
60. Jamieson, S.; How, J.P.; Girdhar, Y. DeepSeeColor: Realtime Adaptive Color Correction for Autonomous Underwater Vehicles via Deep Learning Methods. In Proceedings of the 2023 IEEE International Conference on Robotics and Automation (ICRA), London, UK, 29 May–2 June 2023.
61. Hybrid Survey Networks: Combining Real-Time and Static GNSS Observations for Optimizing Height Modernization | Journal of Surveying Engineering | Vol 144, No 1. Available online: [https://ascelibrary.org/doi/abs/10.1061/\(ASCE\)SU.1943-5428.0000244](https://ascelibrary.org/doi/abs/10.1061/(ASCE)SU.1943-5428.0000244) (accessed on 22 December 2023).
62. Del Savio, A.A.; Luna Torres, A.; Vergara Olivera, M.A.; Llimpe Rojas, S.R.; Urdy Ibarra, G.T.; Neckel, A. Using UAVs and Photogrammetry in Bathymetric Surveys in Shallow Waters. *Appl. Sci.* **2023**, *13*, 3420. [CrossRef]
63. Remote Sensing | Free Full-Text | Methodology for Combining Data Acquired by Unmanned Surface and Aerial Vehicles to Create Digital Bathymetric Models in Shallow and Ultra-Shallow Waters. Available online: <https://www.mdpi.com/2072-4292/14/1/105> (accessed on 22 December 2023).
64. Partama, I.G. A Simple and Empirical Refraction Correction Method for UAV-Based Shallow-Water Photogrammetry. *Int. J. Environ. Chem. Ecol. Geol. Geophys. Eng.* **2017**, *11*, 254–261.
65. Partama, I.G.Y.; Kanno, A.; Ueda, M.; Akamatsu, Y.; Inui, R.; Sekine, M.; Yamamoto, K.; Imai, T.; Higuchi, T. Removal of Water-Surface Reflection Effects with a Temporal Minimum Filter for UAV-Based Shallow-Water Photogrammetry. *Earth Surf. Process. Landf.* **2018**, *43*, 2673–2682. [CrossRef]

66. Agrafiotis, P.; Skarlatos, D.; Georgopoulos, A.; Karantzalos, K. Shallow Water Bathymetry Mapping From Uav Imagery Based On Machine Learning. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2-W10*, 9–16. [CrossRef]
67. Drap, P.; Seinturier, J.; Hijazi, B.; Merad, D.; Boi, J.-M.; Chemisky, B.; Seguin, E.; Long, L. The ROV 3D Project: Deep-Sea Underwater Survey Using Photogrammetry: Applications for Underwater Archaeology. *J. Comput. Cult. Herit.* **2015**, *8*, 1–24. [CrossRef]
68. Hovland, M.; Vasshus, S.; Indreeide, A.; Austdal, L.; Nilsen, Ø. Mapping and Imaging Deep-Sea Coral Reefs off Norway, 1982–2000. *Hydrobiologia* **2002**, *471*, 13–17. [CrossRef]
69. Ho, M.; El-Borgi, S.; Patil, D.; Song, G. Inspection and Monitoring Systems Subsea Pipelines: A Review Paper. *Struct. Health Monit.* **2020**, *19*, 606–645. [CrossRef]
70. Ballarin, M.; Costa, E.; Piemonte, A.; Piras, M.; Teppati Losè, L. Underwater photogrammetry: Potentialities and problems results of the benchmark session of the 2019 sifet congress. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2020**, *XLIII-B2-2020*, 925–931. [CrossRef]
71. Capra, A.; Dubbini, M.; Bertacchini, E.; Castagnetti, C.; Mancini, F. 3D Reconstruction of an Underwater Archaeological Site: Comparison between Low Cost Cameras. *Int. Soc. Photogramm. Remote Sens.* **2015**, *40*, 67–72. [CrossRef]
72. Capra, A.; Castagnetti, C.; Dubbini, M.; Gruen, A.; Guo, T.; Mancini, F.; Neyer, F.; Rossi, P.; Troyer, M. High Accuracy Underwater Photogrammetric Surveying. In Proceedings of the 3rd IMEKO International Conference on Metrology for Archeology and Cultural Heritage, Lecce, Italy, 23–25 October 2017.
73. Balletti, C.; Beltrame, C.; Costa, E.; Guerra, F.; Vernier, P. 3D Reconstruction of Marble Shipwreck Cargoes Based on Underwater Multi-Image Photogrammetry. *Digit. Appl. Archaeol. Cult. Herit.* **2016**, *3*, 1–8. [CrossRef]
74. Salvatori, M. *Archeologia sommersa nel Mediterraneo*; Restauro Consolidamento; Edizioni Scientifiche Italiane: Napoli, Italy, 2010; ISBN 978-88-495-2080-4.
75. Drap, P.; Merad, D.; Seinturier, J.; Mahiddine, A.; Peloso, D.; Boi, J.-M.; Chemisky, B.; Long, L.; Garrabou, J. Underwater Programmetry for Archaeology and Marine Biology: 40 Years of Experience in Marseille, France. In Proceedings of the 2013 Digital Heritage International Congress (DigitalHeritage), Marseille, France, 28 October–1 November 2013; Volume 1, pp. 97–104.
76. Bandiera, A.; Alfonso, C.; Auriemma, R. Active and passive 3D imaging technologies applied to waterlogged wooden artifacts from shipwrecks. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *XL-5/W5*, 15–23. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

Article

Revisiting the Serçe Limanı Sail Plan

Nathan Helfman ¹, Josef Rott ² and Deborah Cvikel ^{1,*}

¹ Leon Recanati Institute for Maritime Studies, University of Haifa, Haifa 3103301, Israel; nathan.helfman@gmail.com

² Marine Engineering, Yosearott Office for Naval Architecture, Yuvalim 2014200, Israel; yosearott@gmail.com

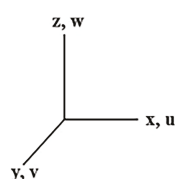
* Correspondence: dcvikel@research.haifa.ac.il

Abstract: The reconstruction of the Serçe Limanı ship proposed a double-masted rig consisting of two sails with a total combined area of 100 m². That proposal considered provenance evidence and appraised hydrodynamic and hydrostatic conditions. The current paper proposes an alternative rig consisting of a single sail. By applying computational fluid analysis and hydrostatic stability software to evaluate hull resistance, sail propulsion, and heeling moments, it has been demonstrated that a sail of no less than 150 m² was suited to propel the Serçe Limanı. One of the two suitable alternative sails tested has been selected.

Keywords: computational fluid dynamics; hydrostatic stability testing; sail plan; Serçe Limanı shipwreck

1. Introduction

The Serçe Limanı ship was discovered in the Serçe Limanı Bay, on the southwest coast of Turkey, opposite Rhodes, and excavated in 1977–1979 by an expedition of the Institute of Nautical Archaeology and Texas A&M University, headed by George F. Bass. The ship, also known as the ‘Glass Wreck’ because of the large quantities of broken glassware visible on the site, was dated to 1025 CE [1]. Until recent years, it was considered the first ship to have been constructed purely skeleton-first. Its reconstructed dimensions were 15.66 m long and 5.2 m wide, with an estimated burden of 35 tons [2], and it was a small two-masted vessel with lateen sails. This article aims to revisit and re-evaluate the reconstructed sail plan of the Serçe Limanı shipwreck [3]. The locomotion of a sailboat in water is a study in fluid mechanics, a dynamic interplay between hull resistance to water and the propulsive capacity of wind to supply forward thrust on a sail. By examining the hull and sail reconstruction plans of the Serçe Limanı, a numerical analysis was conducted, applying the disciplines of computational fluid dynamics (CFD) based on the Navier–Stokes equations (Equations (1)–(4)). The CFD software platforms were Orca3D[®] V3, a Rhinoceros 8 plug-in, and SolidWorks[®] 2023 Flow Simulation. The governing Navier–Stokes equations implemented for the numerical calculation of incompressible flow with constant viscosity (real viscous fluids) describe all the actions and forces acting upon a fluid. The fluid is assumed to be Newtonian, meaning that the linear shear stress is directly related to the velocity gradient. Both the pressure force and the viscous force are those which act at the surface of a fluid particle. The partial differential equations are given with the following coordinate system:



- Continuity equation (conservation of mass), expressed in a differential volume in the flow:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) \quad (1)$$

- Navier–Stokes Equations (conservation of momentum)

x-momentum:

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho g_x \quad (2)$$

y-momentum:

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial y} + \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + \rho g_y \quad (3)$$

z-momentum:

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + \rho g_z \quad (4)$$

where: g = gravity, ρ = density, p = pressure, μ = dynamic viscosity, the x component of velocity is u , the y component of velocity is v , and the z component of velocity is w .

In Volume 1 of the Serçe Limanı shipwreck final report [1], in Chapter 11 by S. Matthews dealing with the rigging reconstruction, it was noted that the absence of a full-length keelson and rigging attachments impeded the ability to establish a plausible rigging plan in the Serçe Limanı shipwreck [3]. If only an exemplary remnant of the keelson had been revealed, it would have sufficed to locate the recess into which the mast heel would have resided to reconstruct a sail plan. Matthews, however, relied on indirect evidence consisting of the provenance of halyard blocks and sheaves: the two-sail rigging plan was hence devised. Provenance evidence is indeed essential in developing maritime reconstructions. However, in heeding Bass's guidance in the same volume describing site documentation, "readers should exercise caution before concluding the seemingly anomalous location of any single object on the site" [1]. As required, Matthews then proceeded to calculate the hydrostatics and resistance properties, from which the geometry of a double sail propulsion system was conceived (Figure 1). However, these findings, as the authors indicated, "cannot discount the possibility that Serçe Limanı ship carried only one mast" [3].

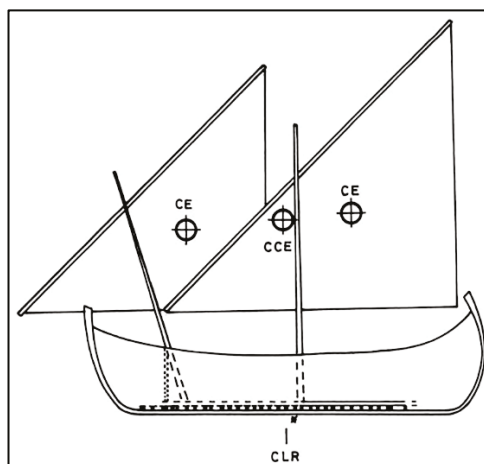


Figure 1. The reconstructed sail plan (S. Matthews [3], p. 185, Figure 11-11. Published with permission of publisher).

In deriving an alternative sail plan, the authors resourced the archaeological reconstructions of the hull, keelson, and keel [1]. Hence, the mast step was assumed to be located vertically aligned with the center of least resistance (CLR), slightly forward of the center of effort (CE). This fundamental design concept, which ensured minimal weather helm, has been employed by ancient shipwrights and contemporary marine architects alike [4,5]. This basic architectural principle served the authors in locating the mast step.

2. Methodology

2.1. Serçe Limanı's Architectural and Nautical Specifications

The analyses conducted on the Serçe Limanı ship were based on a model developed from a line drawing provided by Steffy [6]. Applying the 'lofting' functionality provided in the CAD software SolidWorks® 2023, a framing shell was developed upon which the hull skin was swept. Ignoring surface friction, the hull was faired and then imported into the Orca3D V3 Marine Design for Rhinoceros® 8 program for CFD hull resistance and hydrostatic stability analyses. In its simplest terms, CFD processes a physical flow problem while applying the basic Newtonian equations of conservation of mass and the second law of motion. The Orca3D® marine design software provides an interface dedicated to generating the mass properties and floated ship properties used in the CFD ship hull analysis. The results of this preprocessing closely matched the data presented by Steffy [6] (Table 1).

Table 1. Mass and floated properties of the Serçe Limanı ship.

Source	Displacement at Waterline (Metric Tons)	Length at Load Waterline (LWL) (m)
Steffy	57.27	14.93
Orca3D®	57.24	14.94

2.2. Hull Resistance

CFD and hydraulic stability analyses require specific dimensional and physical input data generated by the preprocessor and applied to governing fluid dynamics equations. The prevailing Eastern Mediterranean maritime conditions between the months of April and October determined wind velocity when computing lift and drag sail forces.

When possible, an analytical methodology was implemented. This involved initially solving a given formula or equation to arrive at a calculated value. This was indeed valuable in setting orders of magnitude and a generalized direction to complex problems of fluid dynamics. The solution was verified by applying numerical analysis, which iteratively 'converges' on the solution of a fixed value [7]. This method was particularly useful in modeling the CFD aerodynamic analysis of the sail forces where more detailed and specific aerodynamic input parameters were required [8]. The forward movement sailing vessel, rigged with a single lateen sail, is dependent on the forward thrust propulsion system of the vessel. The forward thrust of the vessel relies on the capacity of the sail to develop the power to overcome the wave and hull-side resistance forces, as illustrated in Figure 2.

The choice of a single sail the length of the ship was supported by CFD resistance testing of the Serçe Limanı, which compared 'with-keel' and 'without keel' configurations [9]. It was demonstrated that the keel of the Serçe Limanı, as reconstructed, provided enough side-force and yawing moment, which increased the proximity between the center of effort (CE) and the center of least resistance (CLR). Thus, the vessel without the keel would have necessitated a sail that would extend forward beyond the bow, similar to Nile dhows [9].

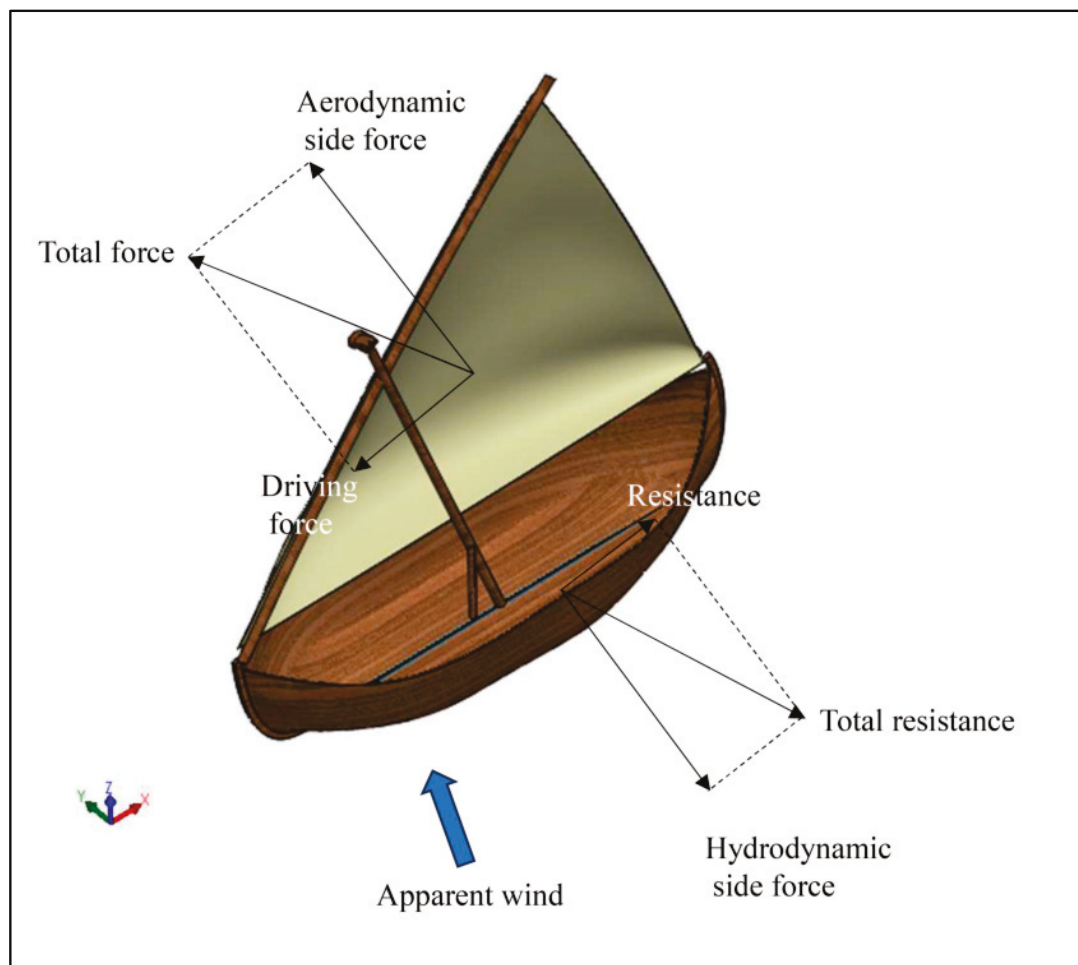


Figure 2. The forward thrust of the vessel is dependent on the capacity of the sail to develop the power to overcome the wave and hull-side resistance (Illustration: N. Helfman).

Hence, the CFD analysis simulated a vessel being towed directly through the water while the software continuously sampled and iteratively calculated the development of the resistant forces on the hull, while heeling and yawing angles were neglected as not being relevant to the research. The simulation was a generalized symmetrical system of resistance and thrust regimes upon which the geometry of the sail was configured (Figure 3). The validity of this approach has been demonstrated in a study that revealed that the primary factor influencing resistance on the hull of the Serçe Limanı was its forward velocity through the water [9]. The system essentially emulated a hydraulic towing tank. The CFD setup parameters were set at the following:

- Hull type: displacement;
- Forward velocity: 3.08 m/s;
- Mesh type: 3D; number of cells—3,513,022; number of faces—10,816,738; number of nodes—3,760,396;
- Analysis type: Resistance/Powering;
- Time definition: Time steps with five iterations; 800 times steps; frequency-200;
- Dynamic option: Pitch and heave;
- Wave: no wave.

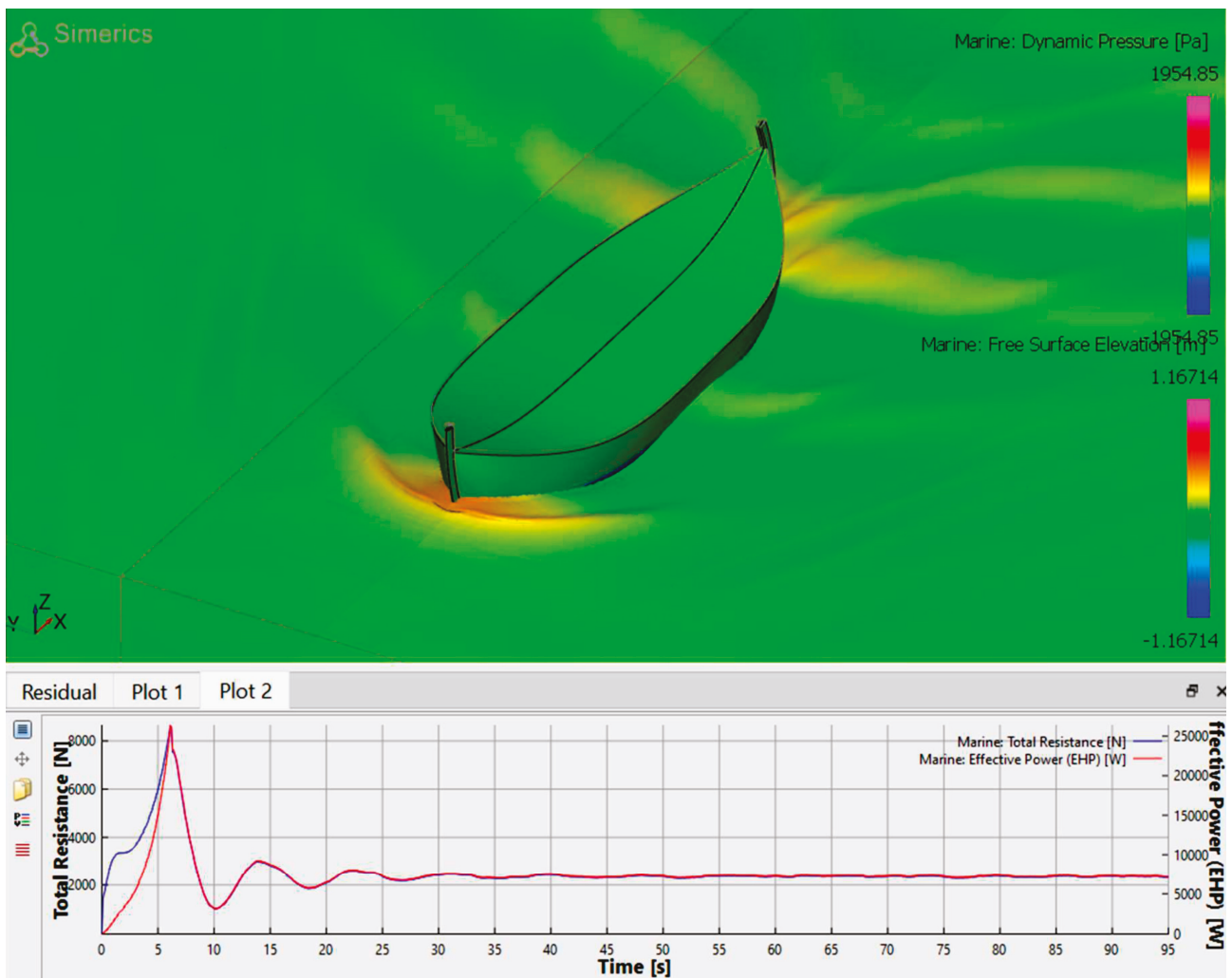


Figure 3. Computational fluid dynamics (CFD) analysis: resistance evaluation upon which the geometry of the sail was configured (Orca3D®/SimericsMP).

There is a direct relationship between the speed of a displacement boat and the length of the wave the hull generates [10], p. 10. Resistance to the water on the hull increases to the square of the hull's velocity. The Serçe Limanı, a displacement ship, moves through the water while creating small waves that progress towards the aft along the side of the ship. As the speed of the vessel increases, the waves generated at the bow increase their wavelengths (the distance from crest to crest) until only one wave is created, the length of the entire watercraft. With any additional increase in speed, the wave becomes longer, driving the stern of the vessel into a trough and causing the vessel to 'climb an inclined plane'. Forward motion is resisted until the vessel reaches its natural limit [10]. This is designated as the 'hull speed', a parameter required for the calculation of hull resistance. The velocity value for a displacement vessel can be calculated using the equation:

$$v = \sqrt{\frac{g\lambda}{2\pi}} \quad (5)$$

where v = velocity, g = gravitational acceleration, λ = wavelength at the waterline (14.93 m). Hence, based on Equation (5), the hull speed of the Serçe Limanı equals approximately 4.8 m/s or 9.3 knots under maximum conditions. The velocity on the simulations was held at 6.0 knots (3.08 m/s) under the assumption that a sail that would overcome resistance at 6.0 knots would be sufficient to propel the vessel at lower hull speeds.

A related input value when calculating the resistance on the hull is the generation of waves caused by the longitudinal motion of the vessel in the water. This can be simplified by assuming that the water is moving and that the hull is stationary. The flow around the hull would be the same as if it were moving over still water [5]. As the speed increases, the resistance increases exponentially (Figure 4). Longer wavelengths are generated along the hull, while concomitantly, the phenomenon of wave interference occurs. If the crests of the bow and stern coincide, large waves result. If the bow wave crests coincide with the troughs of the stern, wave attenuation occurs [11]. This is expressed in the Froude number (Equation (2)), which was employed when conducting a resistance analysis on the digital model of the Serçe Limanı. The resistance was relative to diverging hull wave amplifications and attenuations; the ‘humps and hollows’ are indicative of this phenomenon (Figure 5). The dimensionless value is expressed in Equation (6)

$$F_n = \frac{v}{\sqrt{gL_{WL}}} \quad (6)$$

where F_n = Froude number, v = velocity (m/s), g = gravity, and L = wavelength at waterline (m).

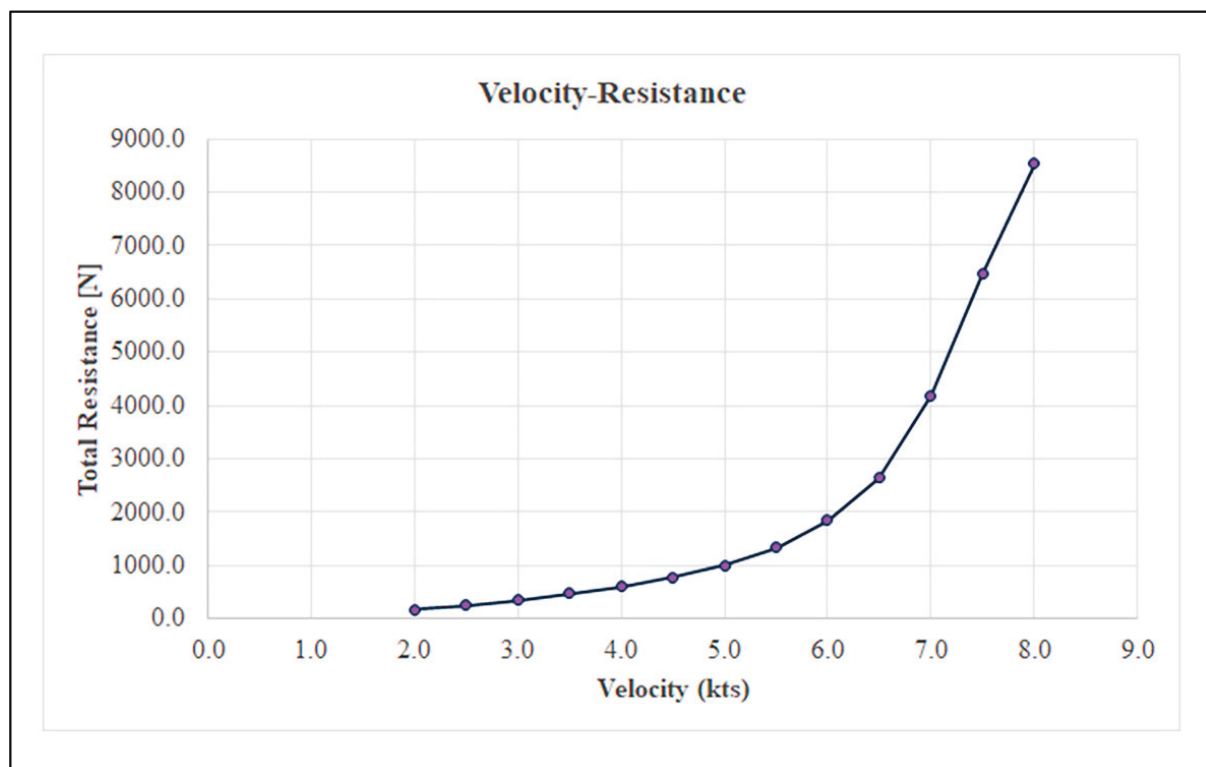


Figure 4. Velocity–resistance graph: as the velocity increases, the resistance increases exponentially (generated by Orca3D®, N. Helfman).

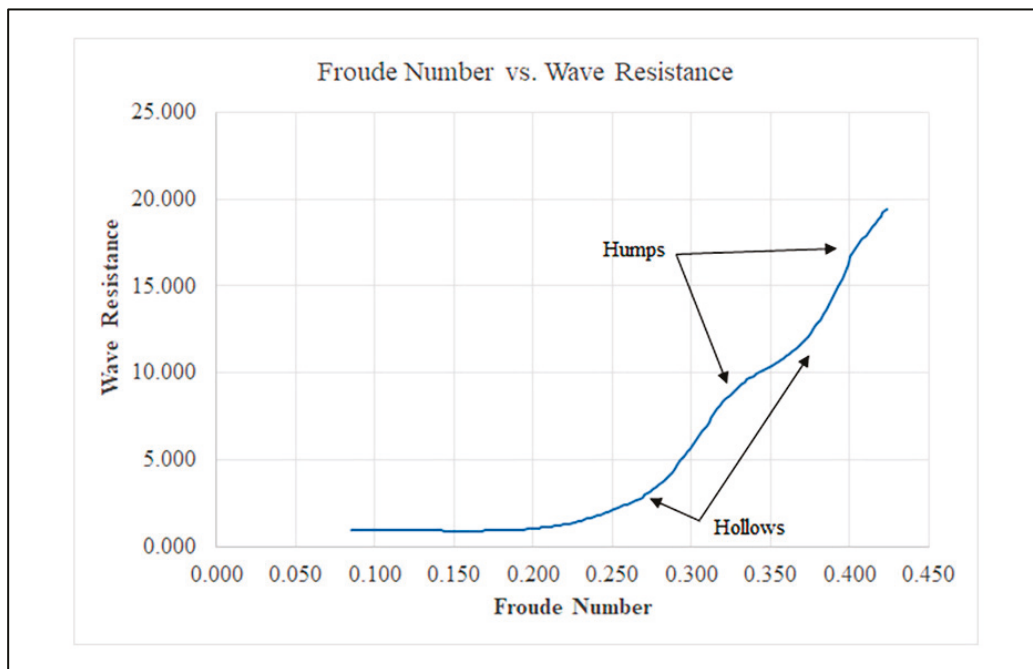


Figure 5. Resistance–Froude number analysis of the Serçe Limanı, which was amplified and attenuated: humps and hollows (generated by Orca3D®, N. Helfman).

Further, it can be demonstrated that there is a relationship between wavelength and traveling speed. Given the relationship wave speed in Equation (7):

$$\sqrt{\frac{g\lambda}{2\pi}} = 1.25 \sqrt{\lambda} \quad (7)$$

where λ = wavelength, an 8 m long wave will have a speed of 3.5 m/s. The wave travels longitudinally with the ship; hence, the length of the waves generated depends on the ship's speed. As per Equation (3), if the speed is 1.25 times the square root of the water line length, a vessel with wave crests simultaneously at the bow and the stern will have a speed of 3.5 m/s. As per Equation (2), the Froude number is 0.39.

2.3. Sail Power

2.3.1. The 11th Century Prevailing Wind Speed

The Eastern Mediterranean experienced a warm phase in the period between 1000 and 1200 CE, otherwise known as the 'Medieval Climate Anomaly' [12], a fact that would necessarily impact wind velocity regimes. This period overlaps and is inclusive of the period when the Serçe Limanı ship plied the seas. Adding to the complexity of adjusting current wind conditions to the 11th-century prevailing winds, demonstrated that there have been significant warming episodes over the last 150 years. Thus, the complexity of gauging the 11th-century conditions to contemporaneous wind velocities prevented a reliable extrapolation. Assuming a tolerable range of error, the authors opted to apply the current prevailing conditions to the Serçe Limanı ship.

The determination of the driving force generated by the sail is directly dependent on the sail area and wind velocity. Pre-CFD analytical calculations to determine orders of magnitude and range were evaluated by applying Equation (8):

$$F_D = C_R \times \rho \times v^2 \times A \quad (8)$$

where F_D = driving force, C_R = aspect ratio coefficient, ρ = air density, v = velocity, A = area [5]. Other relevant parameters include shape and cloth roughness. Preprocessing fluid CFD parameters were set at the following:

- Flow type—both laminar and turbulent;
- Surface roughness—12 μm ;
- Wind velocity 3.08 (m/s);
- Angle of attack—25° (0.436 radians);
- Semi-dense meshing regime;
- Sail canvas roughness—12.0 μm ;
- Wind velocities were based on the survey conducted by the Turkish National Committee of the World Energy Council, as the average offshore wind speed was measured in wind classes higher than 4.0 m/s [12], p. 34. Wind velocities were set as a variable parameter at 6.0 knots (3.08 m/s).

Sail propulsive force was determined by employing aerodynamical CFD SolidWorks® 2023 Flow Simulation. The preprocessor was set to evaluate both the lift (F_Y) and the drag forces (F_X) on the sail samples, yielding the total force, F_T . The product of the F_T and wind velocity yields power in terms of Watts in Equation (9):

$$P = v \times F_T \quad (9)$$

where P = Power [W], v = velocity [m/s], and F = force [N], where the force is the product of the sail area pressure multiplied by its projected area.

Determining the shape of a medieval sail is problematic [2]; hence, as a single sail configuration, two different triangular-shaped sails were proposed for CFD aerodynamic velocity-pressure simulations: one resembling a right-angle triangle and the other, a scalene triangle. In rigging the sails, care was taken in the design of the sails to place the CE forward of the CLR to reduce weather helm (Figure 6).

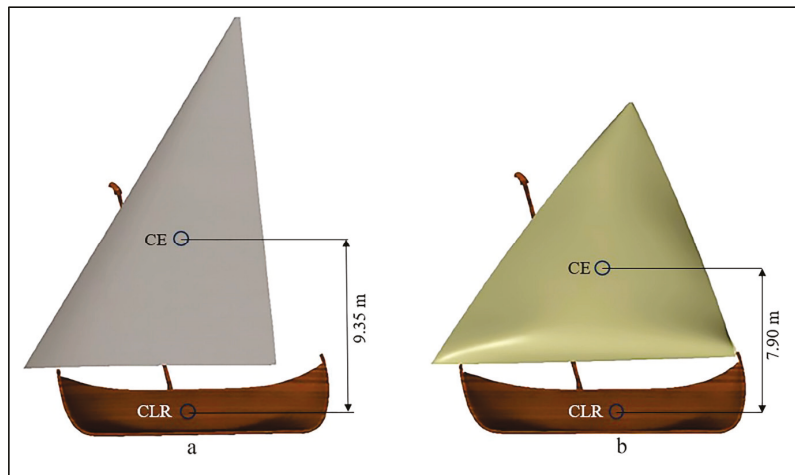


Figure 6. The design of the two suggested sails the center of effort (CE) forward of the center of least resistance (CLR) to reduce weather helm: (a) a right-angle triangle and (b) a scalene triangle (Illustration: N. Helfman).

A sampling of 100 m², 150 m², and 200 m² triangular sails was processed as airfoils, such that the apparent wind velocity was kept constant at 6.0 knots (3.08 m/s) at an attack angle of 25° (Figure 7). The F_{Total} , the resultant of the drag and crosswind forces, was subsequently converted to a power-based equation Equation (9). The results were compared to the effective hull power (resistance) [W] derived from the CFD Orca3D® V3: The sail power had to be greater than the hull resistance. In both sail types, the yard was removed, thereby ignoring turbulence eddies developed along the luff.

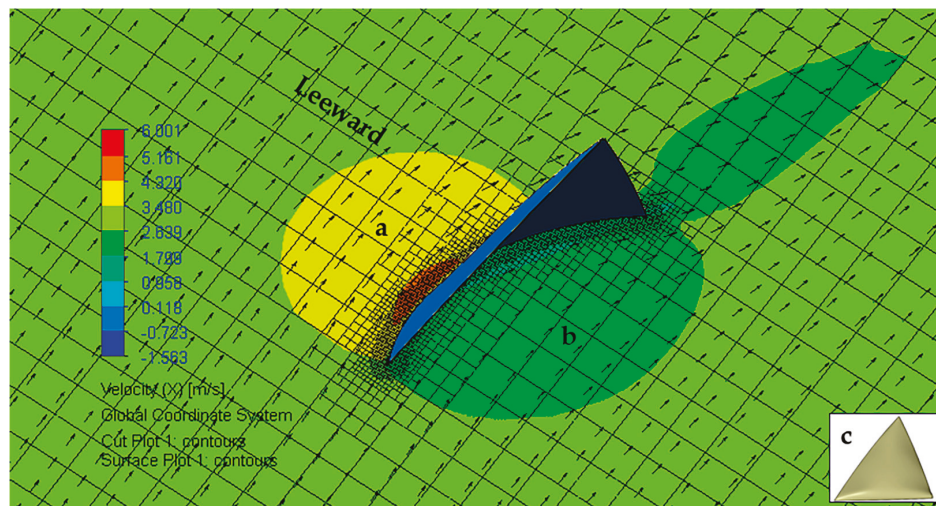


Figure 7. Power analysis of the scalene triangle sail displaying mesh and pressure differentials consistent with forward propulsion: (a) high velocity (low pressure); (b) low velocity (high pressure); (c) thumbnail of scalene triangle sail (Illustration: N. Helfman).

2.3.2. Optimizing Mesh: Convergence Analyses

Verification of CFD results involves an iterative process of optimizing meshing refinement until differences between the results are reduced and converge to an optimal value. The process begins at a base line to which subsequent runs are compared. The integrity of the analysis is enhanced with the addition of finite elements, their specific type, and the number of time-steps and iterations. The objective of the analysis is to achieve maximum result consistency at minimal analysis run-time.

A convergence process was conducted on the aerodynamic analysis of the scalene triangle sail by repetitively evaluating a force–power scenario; the sail was fixed in its domain while refining the meshing. The ‘global mesh’, which is a relatively coarse foundational mesh, was kept constant while the ‘equidistance refinement’, which builds layers of increasingly refined ‘local mesh’, was varied. The number of elements can be increased on a sliding-scale functionality known as ‘maximum equidistant level’. Up to three variable offset distances can be manipulated. The convergence was achieved at a foundation layer of 0.5 m offset from the surface of the sail and 0.8 m offset for the less refined layer. The results of the convergence are presented in Table 2.

Table 2. Computational fluid dynamics (CFD) convergence values.

No.	Base Offset [m]	Secondary Offset [m]	Refinement Value	Number of Elements	Iterations	Total Force Result [N]	Time [s]
1.	0.061	0.0244	4	116,968	146	834.92	395
2.	0.2	0.4	4	374,993	157	1004.70	1016
3.	0.2	0.4	4	274,792	144	1003.20	880
4.	0.5	0.8	5	4,254,403	181	1010.62	22,881

There was an appearance of convergence between analyses 1, 2, and 3. Upon significantly raising the refinement level and run time in analysis number 4, it was apparent that any refinement of the mesh beyond level 3 did not contribute to the convergence. The analysis appearing in Figure 7, which was run at level 3, is the analysis of the scalene triangle sail displaying the wind velocity differential between the windward and leeward sides. The windward side has characteristically higher pressure and an attack angle of 25°, providing forward propulsion.

2.4. Stability

If a ship returns to its initial position after heeling, the condition of equilibrium is stable. If the ship continues to heel, the equilibrium is unstable, causing it to capsize [13]. Matthew noted that the two-sail design was constructed such that the CE was lowered to prevent large heeling motions and stability [3]. This was, however, difficult to verify due to the lack of quantitative data: height and fore-aft positioning. To perform the calculation, several quantities must be known, among others:

- The estimated displacement of the ship, which included its cargo and distribution;
- The ship's dimensions: length, beam, overall depth, heeling arm;
- Sail dimensions;
- Forces on the sail resulting from wind velocity.

The stability of the vessel under beam wind conditions is governed by the critical value known as the vertical center of gravity (VCG), otherwise known as the keel gravity (KG). The basic equation for identifying the VCG is Equation (10):

$$VCG = \frac{W_{hull} \times d_{hull} + W_{cargo} \times d_{cargo}}{W_{hull} + W_{cargo}} \quad (10)$$

where W_{hull} = weight of the hull, d_{hull} = the distance of the gravity of the reference point, W_{cargo} = cargo weight, d_{cargo} = cargo weight. d_{cargo} = the distance of the cargo's center of gravity from the same reference point. This calculation resulted in a value of 1.2 m, applying the sinkage, as reported by the Orca3D® CFD application, as 1.21 m. Lacking any evidence otherwise, it is assumed that the cargo was evenly distributed over the length of the ship at a depth of 1.2 m.

The VCG is an axis about which a heeling moment, caused by the wind on the sail, tends to roll the ship. The heeling moment is countered by the righting moment, which is dependent on the distance between the center of buoyancy and the center of gravity [5], p. 338. This calculation assumes a static condition where dynamic factors such as wave action and wind can affect stability, requiring highly complex computation. When evaluating the stability of a vessel, its righting arm is calculated over a range of heeling angles. Figure 8 is a generalized 'stability curve', which shows two graphs of static equilibrium where point A is the angle of the steady heel or angle equilibrium, point B is the point of maximum stability, and point C is the angle of vanishing stability. Hence, the plots display the relationship of the righting moment to the heeling moment where positive stability persists from 0° to 80°.

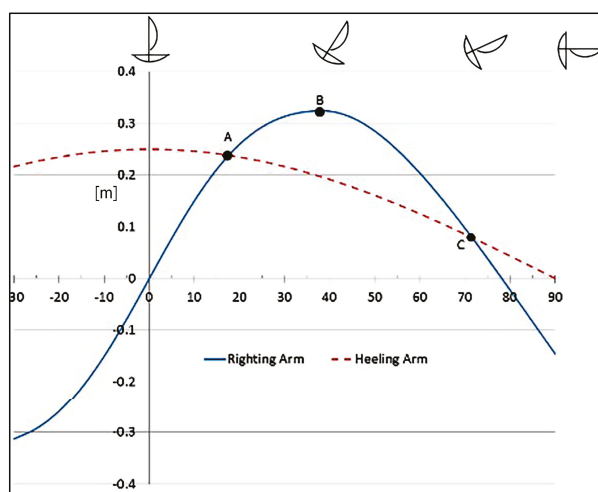


Figure 8. A generalized 'stability curve' plots the righting moment opposed to the heeling moment where positive stability persists from 0° till 80° where point A is the angle of equilibrium, point B is the point of maximum stability, and point C is the angle of vanishing stability (published with permission of Orca3D®).

The calculation of the heeling arm relates to force $F_y = p_y A_y$, where p_y is the wind pressure, and A_y is the area of the sail (Figure 9). The force F_y tends to heel and drift the ship but is opposed by force R , which is equal to F_y . R acts at the half-draft $T/2$, where torque is developed until the heeling moment equals the righting moment. The heeling arm varies with the heeling angle where the area exposed to the wind varies proportionally to $\cos\phi$ parallel to the inclined plane $W_\theta L_\theta$ and is expressed in the Equation (11):

$$L_y(\phi) = \frac{P_y A_y \left(h_y + \frac{T}{2} \right)}{g \Delta} \cos^2 \phi \quad (11)$$

where L_y = wind heeling arm, h_y = height of sail area centroid above $W_0 L_0$ [13]. This is the governing equation, in addition to a set of criteria for sea and structural conditions, which are set before running a stability analysis (Figures 10 and 11).

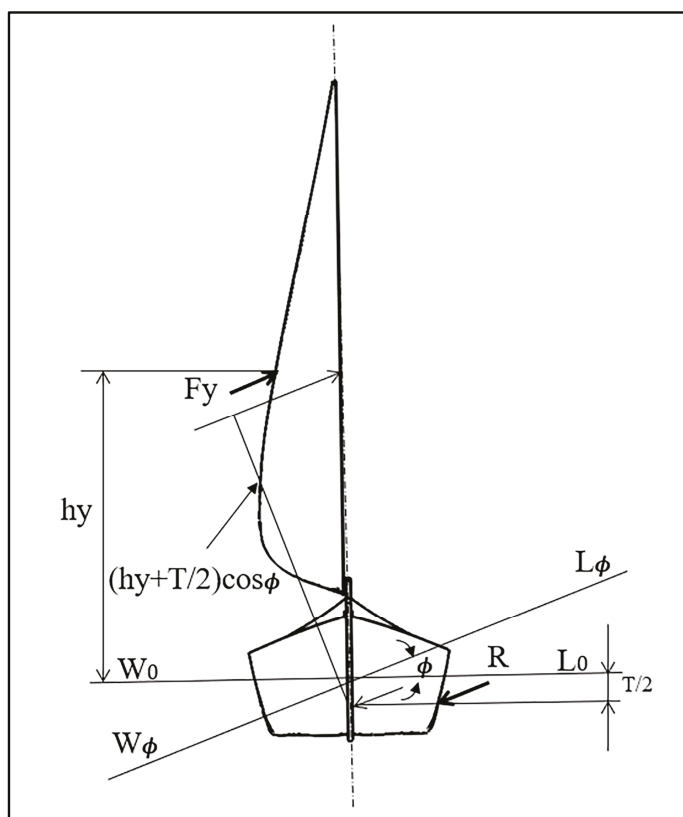


Figure 9. Wind heeling arm at beam wind perpendicular to the centerline: F_y = heeling force; R = righting force; h_y = height of the sail area centroid above water line $W_0 L_0$ (Illustration: N. Helfman).

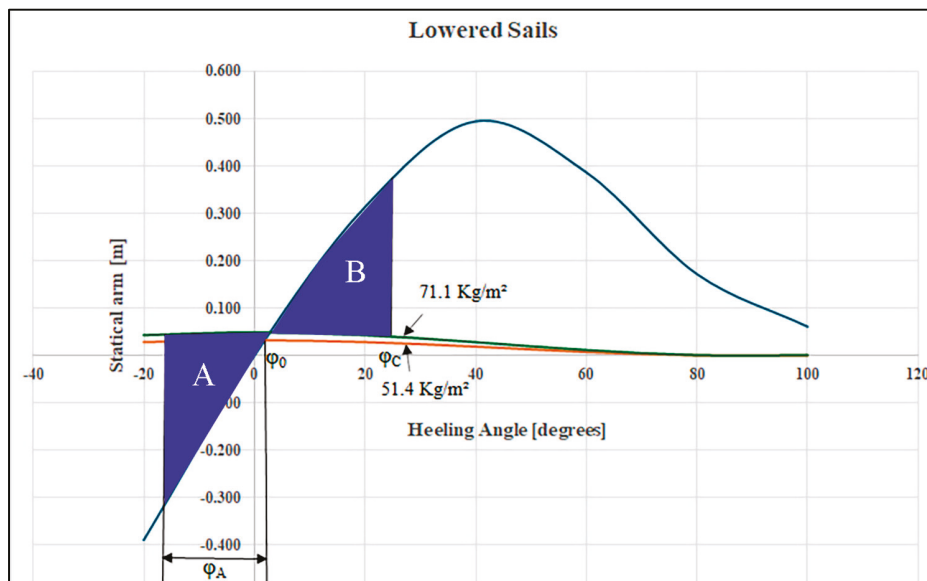


Figure 10. Lowered sails calculation results of the ‘Acute-angle’ sail—mast height = 7.9 m; the values 51.4 Kg/m² and 71.1 Kg/m² represent a stationary wind load and a gust load, respectively (Graph by N. Helfman; calculations confirmed by J. Rott, Marine Engineer).

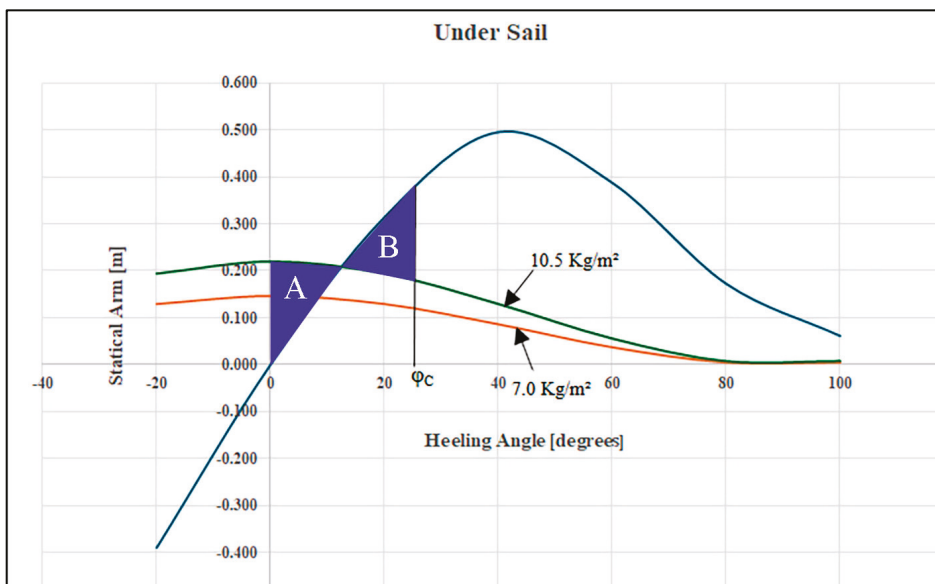


Figure 11. The under-sail calculation results of the ‘acute-angle’ sail—mast height = 7.9 m; the values 10.5 Kg/m² and 7.0 Kg/m² represent a stationary wind load and a gust load, respectively (Graph by N. Helfman; calculations confirmed by J. Rott, Marine Engineer).

3. Results and Discussion

The objective of this study was to offer an alternative solution to the sail plan of the Serçe Limanı ship based on the results applying rigorous methodologies of computational fluid dynamics and hydrodynamics stabilities software. This kind of research is not experimental in the sense of collecting populations or samples of statistical data to be tested for significance, averaged, or trend tested. The results rely on the intense iterative computations of complex partial differential equations partitioned into time steps, which generate moving averages. Each hydrodynamic and aerodynamic result was unique and verified by repeating the computations at least twice. Care was taken, when possible, to precede numerical solutions with analytical methods by calculating governing equations.

The results were sufficient to generate range and orders of magnitude, providing direction and continuity.

The computational results were from three categories: analysis of hull hydrodynamic resistance, aerodynamic sail propulsion, and wind-heeling stability. The hull and sail results were translated into power values [W], while the heeling results were given in degrees of heeling as a function of a statical arm [m].

The values displayed in Table 3 present the resistance force and, hence, the effective power of the ship's hull. This served as a baseline for the minimum power required by a given sail to propel the ship forward to a velocity of 3.08 m/s (6.0 knots). Tables 4 and 5 present the results of triangular lateen sails of two different geometries: an acute angle and a right-angle sail, comparing the propulsion capacities of each by varying their projected area. Each sail type was re-scaled to 100 m², 150 m², and 200 m², analyzed for forward thrust power, and then compared to the effective hull resistance power. The scalene triangle sail, although performing slightly better than the right-angle sail, was selected as the most suitable single sail configuration due to its shorter 'hy' distance (Figure 9), which would provide greater stability. The oversized 200 m² sail, which produced twice the power required, was dismissed.

Table 3. Hydrodynamic computational fluid dynamics (CFD) simulation evaluating the resistance force translated to power (Orca3D[®]/SimericsMP).

Simulation Speed [m/s]	Resistance Force [N]	Power [W]
3.08	712.76	2195.31

Table 4. Aerodynamic computational fluid dynamics (CFD) simulations evaluating propulsion power of a scalene triangle sail (SolidWorks[®] Computational Fluid Dynamics).



Sail Area	Velocity-Apparent Wind [m/s]	Total Force [N]	Power [W]
100 m ²	3.08	682.4	2101.8
150 m ²	3.08	1004.7	3094.5
200 m ²	3.08	1341.7	4132.4

Table 5. Aerodynamic computational fluid dynamics (CFD) simulations evaluating propulsion power of a right-angle lateen sail.



Sail Area	Velocity-Apparent Wind [m/s]	Total Force [N]	Power [W]
100 m ²	3.08	627.2	1931.8
150 m ²	3.08	893.4	2751.6
200 m ²	3.08	1218.4	3752.7

The single sail concept gains credence based on the excavated finds of the Ma'agan Mikhael B shipwreck (7th–8th century CE) found off the coast of Israel in 2005. This 25-m-long merchantman possessed unequivocal evidence of a hook-shaped masthead fitting with sheaves, a single mast step, and mast support indicative of a single lateen sail rig [14]. A digital 3D model of the Ma'agan Mikhael B ship was developed by resourcing excavation data, iconographic representations, and relevant documentation. A standard maritime engineering analysis of stability and strength, and CFD analyses were performed on the digital model to evaluate hull resistance and the power of the ship's single lateen sail. The simulations demonstrated that the fully loaded merchantman was seaworthy and made satisfactory speed over the ground with a sail area of 200 m² [15].

Stability Results

The aerodynamic results, as displayed in Tables 3 and 4, demonstrated almost identical power output [W] for both sail configurations. The mast heights CLR to CE of the ‘right angle’ and the ‘acute angle’ sails were 9.35 m and 7.90 m, respectively. Agreeing with Matthews that a lower center of gravity would provide greater heeling stability [3], the stability analysis was conducted on the ‘acute angle’ sail. The method of calculation conformed to the standards set by the Netherlands Regulatory Framework (NeRF)—Maritime [16] for vessels exceeding 12 m. As per the standard, two basic qualifying tests were performed: stability with struck sails (Figure 9) and stability under sail (Figure 10). The equations prescribed by NeRF for calculating both heeling moment conditions are as follows:

For vessels with struck sails: stationary wind load = 51.4 kg/m^2 ;
gust = 77.1 kg/m^2

$$\text{Moment 1} = 51.4 \times (\text{Orl} \times \text{Arl} + \text{Otuig} \times \text{Atuig})$$

$$\text{Moment 2} = 77.1 \times (\text{Orl} \times \text{Arl} + \text{Otuig} \times \text{Atuig})$$

For a ship under sail (basic rigging): stationary wind load = 7.0 kg/m^2 ;
gust = 10.5 kg/m^2

$$\text{Moment 1} = 7.0 \times (\text{Orl} \times \text{Arl} + \text{Osail} \times \text{Asail})$$

$$\text{Moment 2} = 10.5 \times (\text{Orl} \times \text{Arl} + \text{Osail} \times \text{Asail})$$

where Orl = lateral surface of the hull (m^2), Arl = distance between the center of gravity of Orl (m), Otuig = total rigging (m^2), Atuig = one-half the height of the highest mast to the lateral point (m), Osail = the total area of the sails (m^2), Asail = distance of composed center of effort to the lateral point (m).

In both evaluations, area ‘A’ must be equal to area ‘B’, where φ_0 = the vessel’s angle of heel under the influence of the stationary wind load with lowered sails, φ_A = the roll amplitude due to a resonant roll movement caused by the wave load, and φ_C = the vessel angle of heel due to a gust [16]. The calculations performed demonstrated a high degree of stability based on the NeRF standards, such that $\varphi_A = 17.68^\circ$, $\varphi_0 = 2.00^\circ < 20^\circ$, $\varphi_C = 23^\circ < 45.00^\circ$, $\varphi_C = 25.6^\circ < 50.00^\circ$.

4. Conclusions

Matthews proposed a dual sail rigging configuration with a combined sail area of 100 m^2 for the Serçe Limanı ship. In this paper, an alternative single lateen sail rig has been proposed while analyzing the power required to propel the Serçe Limanı ship. Applying Orca3D V3 CFD software to evaluate the resistance of the ship’s hull at 6.0 knots, it became apparent that a sail area of 100 m^2 was incapable of propelling the vessel.

Two lateen sail options were selected for inquiry: a right-angle and an acute-angle sail. Both sails, though markedly different in their appearance, demonstrated that, to generate the power to propel the Serçe Limanı, at least 150 m^2 was required. Both sails could be rigged within the boundaries of the ship’s hull, their only difference being their heights: 7.9 m (acute angle) versus 9.35 m (right angle). The 7.9 m long mast was selected for testing, assuming a lower center of gravity and, therefore, less vulnerability to capsizing. Applying hydrostatic stability testing, it was thus demonstrated that the single sail Serçe Limanı, with a 7.9 m mast, faired extremely well, even under gust conditions.

It was demonstrated that the acute angle sail configuration robustly produced sufficient power to propel the Serçe Limanı while meeting standard stability criteria. Thus, a single acute triangular sail met the challenge of the dual sail rigging as proposed by Matthews. In the spirit of further research, a challenge is welcome.

In the strictest sense, CFD results should be validated either by employing towing tanks or wind tunnels. These types of validations were not performed, but their absence provides an opportunity for future research in other variable parameters, such as hull shape

and construction methods. Further, in addition to towing tanks and wind tunnels, future research should involve the application of a Velocity Prediction Program (VPP), a program used in yacht design that predicts heel, speed, leeway, and apparent wind quantities.

Author Contributions: Conceptualization, N.H.; methodology, N.H.; software, N.H.; validation, N.H. and J.R.; formal analysis, N.H. and J.R.; investigation, N.H. and D.C.; resources, D.C.; data curation, N.H.; writing—original draft preparation, N.H. and D.C.; writing—review and editing, N.H. and D.C.; visualization, N.H. and D.C.; funding acquisition, D.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Sir Maurice Hatter Fellowship and the Dov Shafir Fellowship.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors are grateful to B. Doron for the English editing and to the anonymous reviewers for their valuable comments and suggestions.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Bass, G.F.; Van Doornink, F.H. Discovery, Excavation and Conservation. In *Serçe Limani: An Eleventh-Century Shipwreck, the Ship and Its Anchorage, Crew, and Passengers*; Bass, G.F., Matthews, S.D., Steffy, J.R., Van Doorninck, F.H., Eds.; Texas A&M University Press: College Station, TX, USA, 2004; pp. 53–70.
2. Pomey, P.; Kahanov, Y.; Rieth, E. Transition from Shell to Skeleton in Ancient Mediterranean Ship-Construction: Analysis, problems, and future research. *Int. J. Naut. Archaeol.* **2012**, *41*, 235–314. [CrossRef]
3. Matthews, S.D. Evidence for the Rig of the Serçe Limani Ship. In *Serçe Limani: An Eleventh-Century Shipwreck, the Ship and Its Anchorage, Crew, and Passengers*; Bass, G.F., Matthews, S.D., Steffy, J.R., Van Doorninck, F.H., Eds.; Texas A&M University Press: College Station, TX, USA, 2004; Volume 1, pp. 171–187.
4. Roberts, O.T. An explanation of ancient windward sailing—Some other considerations. *Int. J. Naut. Archaeol.* **1995**, *24*, 307–315.
5. Marchaj, C.A. *Sailing Theory and Practice*; Dodd, Mead & Company: New York, NY, USA, 1964.
6. Steffy, J.R. Construction and Analysis of the Vessel. In *Serçe Limani: An Eleventh-Century Shipwreck, The Ship and Its Anchorage, Crew, and Passengers*; Bass, G.F., Matthews, S.D., Steffy, J.R., Van Doorninck, F.H., Eds.; Texas A&M University Press: College Station, TX, USA, 2004; Volume 1, pp. 153–170.
7. Thomson, D.B. *Numerical Methods 101-Convergence of Numerical Models*; SGS Staff—Published Research: Yokohama, Japan, 1992; p. 115.
8. Dassault Systemes Corporation. *SolidWorks Simulation Training Manual*; Dassault Systemes Corporation: Vélizy-Villacoublay, France, 2015.
9. Helfman, N. The Keelson: A Marine Architectural-Archaeological Analysis in the Context of the Transition in Ship Construction. Ph.D. Thesis, University of Haifa, Haifa, Israel, 2023, unpublished.
10. Anderson, B.D. *The Physics of Sailing Explained*; Sheridan House, Inc.: Dobbs Ferry, NY, USA, 2003.
11. Eliasson, R.; Larsson, L.; Orych, M. *Principles of Yacht Design*, 3rd ed.; International Marine/McGraw Hill Camden: New York, NY, USA, 2014.
12. Lüning, S.; Garcés-Pastor, S.; Danladi, I.B.; Galka, M. The Medieval climate anomaly in the Mediterranean region. *Paleoceanogr. Paleoclimatol.* **2019**, *34*, 1625–1649. [CrossRef]
13. Biran, A.B. *Ship Hydrostatics and Stability*; Butterworth Heinemann: Oxford, UK, 2003; pp. 36–109.
14. Cohen, M.; Cvikel, D. Rigging of the Ma’agan Mikhael B shipwreck (7th–8th centuries AD): New finds. *Int. J. Naut. Archaeol.* **2020**, *49*, 291–302. [CrossRef]

15. Helfman, N.; Cohen, M.; Rott, J.; Creisher, M.; Cvikel, D. From Shipwreck to Seaworthy: A Digital Reconstruction of the Ma'agan Mikhael B Ship. *Digit. Appl. Archaeol. Cult. Herit.* 2024; *in press*.
16. Netherlands Regulatory Framework (NerF)—Maritime: Rules for Commercial Cruising Vessels, Chapter 04-Stability. Available online: https://puc.overheid.nl/nsi/doc/PUC_2054_14/1/#31272 (accessed on 16 March 2024).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

Article

Identifying Anthropogenic Versus Natural Submerged Prehistoric Landscapes: Two Case Studies from the Sicilian Channel

Ehud Galili ^{1,2,*}, Liora Kolska Horwitz ³, Ilaria Patania ⁴, Amir Bar ⁵ and Isaac Ogloblin Ramirez ^{6,7}

¹ The Zinman Institute of Archaeology, University of Haifa, Haifa 3498838, Israel

² Recanati Institute of Maritime Studies, University of Haifa, Haifa 3498838, Israel

³ National Natural History Collections, The Hebrew University, Jerusalem 9166100, Israel; lix1000@gmail.com

⁴ Department of Anthropology, Washington University in St. Louis, St. Louis, MO 63130, USA; ilariap@wustl.edu

⁵ Department of Marine Geosciences, Leon H. Charney School for Marine Sciences, University of Haifa, Haifa 3498838, Israel; beachrock.israel@gmail.com

⁶ Laboratory for Environmental Micro-History, Department of Maritime Civilizations, School of Archaeology and Maritime Cultures, University of Haifa, Haifa 3498838, Israel; ogloblinisaac@gmail.com

⁷ Institute of Archaeology, Tel Aviv University, Tel Aviv 6997801, Israel

* Correspondence: galilish@netvision.net.il; Tel.: +972-4-9841976

Abstract: In submerged landscapes, distinguishing anthropogenic features versus natural ones is often challenging. We have developed a set of criteria to validate the identification of submerged anthropogenic remains that include examining the geological context, sea-level considerations, associated archaeological finds (including coastal survey), and documenting the broader archaeological context. Furthermore, our experience demonstrates that, while progress has been made in applying remote-sensing technologies to detect anthropogenic features on the seabed, there is no substitute for direct, visual assessment by an underwater archaeologist for verification of their anthropogenic status. We have applied these criteria to examine two published case studies detailing suspected anthropogenic stone features on the seabed in the Sicilian Channel. Our examination has led us to conclude that both localities are not anthropogenic features. The Pantelleria Vecchia Bank features represent natural outcrops on a submerged paleo-landscape that were shaped by depositional and erosional processes during transgression and regression periods. The suspected Lampedusa cultic site comprises natural features that are located on a submerged neo-landscape formed due to erosion and retreat of the coastal cliff since the mid-Holocene, when the sea level reached its present level.

Keywords: submerged prehistory; sea-level change; underwater archaeology; beach deposits; inundated settlements

1. Introduction

The post-glacial rise in sea level (ca. 20,000 to 5000 years BP) inundated large regions of previously dry coastal plains, resulting in submerged areas of the continental shelf [1,2]. These included areas that had been occupied by people since the Early Paleolithic period, e.g., [3–6]. As early as 1937, A.C. Blanc, who studied the west coast of Italy [7], hypothesized that prehistoric materials and terrestrial landscapes could be preserved on the submerged continental shelf, and indeed, in the past 80-plus years, thousands of prehistoric sites have been found underwater, representing a unique environmental and cultural record [8–13]. However, identification of submerged anthropogenic sites is often challenging since underwater features of natural origin can sometimes be misconstrued as human-made (i.e., pseudo-archaeological). Stone features, created by erosional or depositional processes, frequently exhibit symmetrical or repetitive forms whose origin can be misleading. Notable examples of suspected submerged anthropogenic sites are the localities of Yanuguni and

Kerama, in southern Japan [14,15]: See the figure on page 595. These are two submerged rock formations identified as anthropogenic by amateur archaeologists but never confirmed as such by professional scholars. Conspicuously, neither site has yielded *in situ* diagnostic archaeological fingerprints (e.g., tool marks, tools or other archaeological remains), raising suspicions that they are just impressive natural structures.

Establishing a set of validation parameters based on archaeological considerations, in combination with studies of factors related to earth sciences, is crucial to ensuring the accurate and correct identification of submerged anthropogenic sites and features. Factors to be considered in the verification process include identifying distinct patterns of deliberate material selection (such as slabs or elongated stones) to exclude those that can occur naturally, determining the provenance of the stones (local or non-local), and analyzing the arrangement patterns of rocks and stones [10,16–19]. Critically, finds should never be studied in isolation. Characterization of the geological substrate establishes the age of the rock formations in the research area and their relation to the suspected anthropogenic remains, while observations of sea-level and tectonic activities that may have affected the area at the time of the proposed human occupation are also necessary in order to understand site formation processes. Additionally, geomorphological observations can reconstruct depositional and erosional processes and indicate signatures that are anthropogenic versus those that are natural. Natural agents (e.g., rivers, waves, tsunamis) or anthropogenic ones (e.g., ships) may have been responsible for transporting artifacts found on the seabed and depositing them in their find location, while sedimentation, erosion, and abrasion processes may generate anthropogenic-like features, or cover or destroy sites [12,13,19]. It should be noted that by themselves, none of these earth science datasets are enough to unambiguously establish the anthropogenic origin of a site. The presence of indicators clearly linked to human activity (e.g., artifacts made of stone, bone, or organic materials; flint tools; production waste; charcoal; or faunal and floral remains), is the key element needed to confirm an anthropogenic origin [10,16–19], as establishing that such finds are *in situ*.

In recent years, remote-sensing technologies have been commonly used to explore and map currently submerged paleo-landscapes in search of prehistoric sites. Remote-sensing techniques applied to submerged prehistory can be divided into devices scanning the surface/sea bottom (e.g., side scan sonar, multibeam sonar, remote-operated vehicle), devices scanning the sub-bottom (e.g., sub-bottom profiler), and devices scanning shallow water from the air (e.g., aerial photography, LIDAR). In the field of submerged prehistory, remote-sensing techniques are efficient when there is a need to scan wide areas of sea bottom that otherwise will require many days of scuba diving, and thus identify the most promising sectors on which research should focus. Moreover, such techniques are also useful when searching for submerged landscapes and sites covered with sediments [19]. Although these methods provide unique and useful information, as will be detailed below, they still face problems of precision and accuracy in discerning anthropogenic from natural features and identifying archaeological finds of material culture, such as those listed above. For example, based on geo-acoustic experiments of knapped flint using sub-bottom profiling, Gron and colleagues [20,21] have been able to identify human-altered lithics in some submerged contexts, but have demonstrated difficulty in distinguishing cultural layers from the surrounding natural geologic ones. Although such studies show promise, their findings need to be corroborated by direct observation, survey, and/or excavation of material on the sea bottom by underwater archaeologists. Thus, in submerged prehistory, remote-sensing techniques can serve as a valuable complement to archaeological studies, but is not a replacement.

In this study, we discuss two published examples that deal with stone features that are suspected to be anthropogenic in origin. Both are located on the seabed of the Sicilian Channel: (i) the Pantelleria Vecchia Bank stone ridges and monolith, and (ii) stone arrangements situated off Lampedusa Island (Figure 1). In each instance, the features were first studied (without the aid of professional archaeologists) by geologists and recreational divers using

remote-sensing technologies and interpreted as anthropogenic in origin. In this study, we want to test the hypotheses proposed through the application of the archaeological and geoarchaeological validation methodologies outlined above.



Figure 1. Location of the two studied sites depicted by red circles, water depth isobaths in m. (Map: Sara Elettra Zaia, Esri, CGIAR, Source: Esri, USGS.)

In order to evaluate whether these submerged localities are natural or anthropogenic, we have analyzed the data presented by the discoverers, and complemented these data with underwater and coastal surveys at the suspected site off Lampedusa (carried out by two of the authors). Although the Pantelleria Vecchia Bank was not surveyed by us due to accessibility limitations, the published data are critically assessed here. We present our findings, which serve as an example of the inadequacy of relying only on remote-sensing technologies, and the need for complementary, hands-on examination of suspected anthropogenic sites by experienced underwater archaeologists.

1.1. Brief History of Submerged Prehistory

The field of submerged prehistory emerged following finds of faunal and lithic remains that were dredged up in trawler nets in the North Sea [22], while terrestrial forests were identified in various intertidal areas of the United Kingdom and France [23–26]. Additionally, sporadic finds by recreational divers helped to trigger interest in this research. For example, in the 1960s, the first reports of finds of Neolithic objects from the submerged locality of Tel Hreiz, situated off the Mediterranean coast of Israel [27,28], then led to the discovery of more than 16 concentrations of submerged Neolithic sites and the test excavation of the coastal sector of the submerged Pottery Neolithic site of Neve Yam [9,19,28–30]. These discoveries contributed to the development of pioneering excavation methods of

submerged prehistoric Mediterranean settlements (e.g., Neolithic sites of Atlit-Yam and Kfar Samir) [19,31], complemented by multidisciplinary studies of the archaeological finds (e.g., sediments, flint, stone and bone tools, and pollen, floral, faunal, and human remains). The methods used were later consolidated as the Israeli Model for the detection, identification, and investigation of submerged prehistoric remains [19,32]. Parallel to this, similar processes were taking place in other parts of the world. One early example from the 1970s, was the use of a systematic methodology to study the sub-bottom and seabed in search of possible prehistoric remains, following extensive industrial work on the sea bottom of the Gulf of Mexico [33]. To do so, remote-sensing methods were applied to produce bathymetric and sub-bottom profiles. These data were corroborated by sediment samples, which helped to reconstruct the terrestrial paleoenvironment. Paleo-environment and identifiable land identifiable landforms were correlated with known archaeological features on land to generate predictive models. If a possible site was identified, further sediment samples, underwater documentation, and diver investigations were undertaken [33,34]. Another model, developed by Fisher [35–37], aimed at locating submerged prehistoric sites by identifying submerged landforms similar to terrestrial counterparts known to be rich in archaeological remains. The basic methodologies used in the Gulf of Mexico, have since benefitted from technological improvements. These include remote-sensing studies that are undertaken in deep water and sediment-covered areas, as well as intensive work in the field of underwater survey [25], with direct-contact diving surveys usually conducted in shallow areas, where snorkeling and scuba diving is possible. The need to investigate areas currently covered by thick layers of sediment, has guided researchers to look for anthropogenic signatures beyond the presence of human-made artifacts, often using sediment coring, to recover finds related to paleo-environmental proxies such as faunal remains, charcoal and pollen, some detected by using sedDNA analysis [26,38–41].

In sum, the accumulation of more than 40 years of experience since the first conference (1981) and publication of the first book relating to the topic of submerged prehistoric sites and landscapes [3], has resulted in general models and recommendations for the investigation of submerged landscapes and prehistoric sites, offering innovative and robust protocols for their detection/identification, investigation, and preservation, as detailed below.

1.2. Citizen Sources

Despite the extensive work that has been undertaken to produce efficient models and research strategies, most often submerged prehistoric remains are reported based on citizen observations—with the naked eye, or found by a fisherman's net [19,35,36,42]. Thus, gathering data from citizen sources like industrial, military, and recreational divers, and fisherfolk, is essential. In this regard see also Archaeology, Wessex. "Protocol for Reporting finds of archaeological interest, Annual Report to BMAPA 2005–2006". 2006.

1.3. Depth-Dependent Likelihood of Detecting Prehistoric Sites

The inundation and drying (terrestrial conditions) of a submerged landscape is generally conditioned by Pleistocene and Holocene sea levels. Analyzing the available global sea-level curves suggest that in a given region, areas situated at greater depths on the seabed experienced shorter periods of exposure during low sea-level phases. This statement is based on the simple logic that, if a point at a certain depth was situated on dry land, all points above it must be dry as well. Thus, the deeper a site is, the less time it was dry land. This has been explained in some detail in two previous publications [17,19]. Thus, statistically, the likelihood of encountering submerged prehistoric sites diminishes in currently deeper locations. Additionally, the last time the continental shelf was exposed beyond a depth of 50 m dates back to 13,000 years BP. These landscapes would have been inhabited by hunter-gatherer communities whose sites lacked substantial architecture and whose ephemeral activities are less likely to be preserved or found [17,19]. Consequently, the likelihood of discovering submerged prehistoric deposits and significant architecture increases in shallow waters, as these areas were exposed for longer periods of time and could

have been occupied by both Paleolithic hunter-gatherers, sedentary Neolithic and later communities. Regrettably, modern human activities (development, building, quarrying) and consequent marine erosion pose great threats to these areas, leading to their heightened destruction. Moreover, when excavating in extremely shallow water the intertidal and surf zones (0–5 m) present extremely difficult working conditions due to changing sea conditions, rapid erosion, and sedimentation of the excavated area [10,12,13,17,19,43].

1.4. Models for Detecting Sites

Generating models for prehistoric site detection mainly focuses on producing a comprehensive picture of the paleo-landscape by applying sea-level considerations and using remote-sensing technologies enabling high-resolution reconstruction of prehistoric landscapes. However, choosing the most appropriate method for detecting, surveying, and researching sites is crucial, and often the use of simple, low-tech methods is no less effective than costly and sophisticated remote-sensing technologies. Both methods, together with archaeological information from adjacent terrestrial areas (site distribution patterns, site layout, chrono-cultural entities, etc.) and geological data of the studied region (river outlets, raw material sources, detection of cultural or biological relics relating to ancient sea levels, etc.) will enable production of models to detect areas of potential interest [18,19,33–35,37,44–48]. Additionally, current research efforts have seen the development of methods that explore a broad range of anthropogenic signatures aside from the presence of items of material culture, and this includes investigation of finds related to paleo-environmental proxies such as charcoal, faunal remains, and pollen [26,38–41,49].

1.5. The Utilization of Paleosols and Rocky Coastal Areas by Prehistoric Populations

In the Mediterranean Basin, submerged remains of early agropastoral societies (Neolithic–Chalcolithic) are generally associated with paleosols that developed under terrestrial environments. Paleosols and other submerged landscapes may be affected by high sediment input that covers sites and makes them difficult to detect and access [10,12,13,19,49]. Rocky coastal areas were generally less sustainable for agro-pastoral human occupation due to the lack of arable land. However, such areas were frequently used for various economic and cultic purposes rather than agriculture (e.g., as demonstrated in Australia) [48]. Intense abrasion that affects submerged landscapes during inundation and periods of high-stand sea levels have probably destroyed much of the archaeological deposits [10,12,13,19].

1.6. The Importance of Archaeological Investigations to Corroborate the Anthropogenic Nature of a Site

Acquisition of submerged landscape data by remote-sensing and geophysical technologies has developed extraordinarily quickly. Using innovative and sophisticated technologies provides crucial physical and sedimentary details, and often helps to detect and document in great detail underwater features and reconstruct the paleo-landscape that is currently submerged [26]. However, these techniques do not provide information on a site's archaeological setting and stratigraphy. Such archaeological data, in addition to finds of material culture (e.g., stone, bone and wood artifacts, flint tools, architecture elements, stone arrangements) and anthropogenic-associated finds (charcoal, dung, ash, human remains, faunal remains with butchery marks), can only be obtained by archaeological survey and excavation [17–19,50–52]. Such data are crucial for establishing whether a site is anthropogenic in origin or not.

2. Materials and Methods

The sites discussed and re-evaluated in this article were investigated by us using different research strategies. In assessing the Pantelleria Vecchia features, we could only use material available in publications, since field survey was not possible because access to the area where the site is located, is restricted. In contrast, we were able to access and survey for ourselves the submerged Lampedusa site (for survey methods, see below, in

Section 3.2. The Lampedusa Site). In both sites, sea-level and tectonic considerations were assessed, deposits from the MIS5e isotopic stage were checked to gauge tectonic stability (at Lampedusa), and data regarding the dating of geological and archaeological features were considered. The published data from the petrography and thin sections from the Pantalleria Vecchia site were checked, and the availability of human-made finds and traces (charcoal, faunal and floral remains, as well as flint, bone, and stone artifacts) in the suspected anthropogenic sites were considered. In addition, we tested the hypothesis that the Lampedusa site is situated on a submerged paleo-landscape that potentially could have been occupied by humans in prehistoric times, versus a submerged neo-landscape that is relatively young, and thus could not have been occupied during prehistoric times.

3. Results

3.1. The Pantelleria Vecchia Bank

- Archaeological setting:

The earliest signs of human habitation on the island of Pantelleria trace back to the Neolithic era around the eighth millennium BP. Archeological findings, such as a workshop for crafting obsidian located at Punta Fram near Pantelleria city's modern cemetery, suggest early human activity [53]. Various artifacts like tools, ornaments, and weapons crafted from Pantelleria obsidian, discovered across Sicily, Malta, Tunisia, Southern France, and other Mediterranean regions, indicate a sustained human presence and a vast exchange network during the Neolithic period [54]. Concrete evidence of permanent settlement emerges during the Bronze Age, particularly from the late fifth to late-fourth millennium BP, notably with the Mursia village and the Sesi necropolis [53]. Subsequently, Pantelleria's history reflects influences from various cultures, including the Phoenicians and the Romans [54,55].

- Geological setting:

The Pantelleria Vecchia Bank is situated on the Adventure Plateau, between western Sicily and Pantelleria island (Figure 1). It is a submerged landscape, currently at 35–40 m depth, which was connected to Sicily during the low sea stand of the glacial periods. During the Younger Dryas (ca. 11,500 years BP), when global sea level was ca. 55 m lower, the area was an archipelago of six dispersed islands located off the southwestern coast of Sicily, while at the end of the 1B Melt Water Pulses (ca. 11,200 years BP), the sea level was ca. 40 m lower than present SL and the islands were smaller [56]. Analyses of geomorphological markers, mainly MIS5e deposits [56,57], have shown that the northwestern Sicilian Channel has been tectonically stable at least since the Late Pleistocene (with an estimated vertical change of ± 0.04 mm/y). This was confirmed by independent measurements derived from semi-permanent GPS stations [58], which do not reveal significant present-day tectonic activity in this region.

- Past studies:

Two submerged enigmatic stone ridges and a stone monolith in the Pantelleria Vecchia Bank (NW Sicilian Channel) were studied by Lodolo and colleagues [59] and Lodolo and Ben Avraham [60]. In a third paper from 2024, Lodolo and colleagues describe a few ridges, in the form of a half-ring, on the Pantelleria Vecchia Bank (Figure 2D) [61]. The underwater features are located tens of kilometers offshore, between Pantelleria and Sicily, at a depth of ca. 35–40 m on the seabed (Figures 2 and 3). In their studies, the researchers used a multibeam swath bathymetry and high-resolution seismic reflection data, radiocarbon dates, and petrographic thin sections of rock samples taken from the ridges and the monolith. Documentation, photography, and sampling were carried out by technical divers. Radiocarbon ages for four rock samples, analyzed in two different laboratories, all fell within MIS3, i.e., the Late Pleistocene ($39,960 \pm 500$ years BP to $44,560 \pm 1270$ years BP) [60] and are close to the limit of radiocarbon [60] (p. 399) (Table S1). The ridges, in the form of a half-rings, were deposited during the Late Miocene (Tortonian) [61,62]. In the three articles, presumably based on chronology and patterns, the authors tentatively suggest that these features (Ridges 1 and 2, the monolith, and the

half-ring ridges) could be anthropogenic in origin and propose that they are, respectively, Neolithic and Mesolithic in age [60,61].

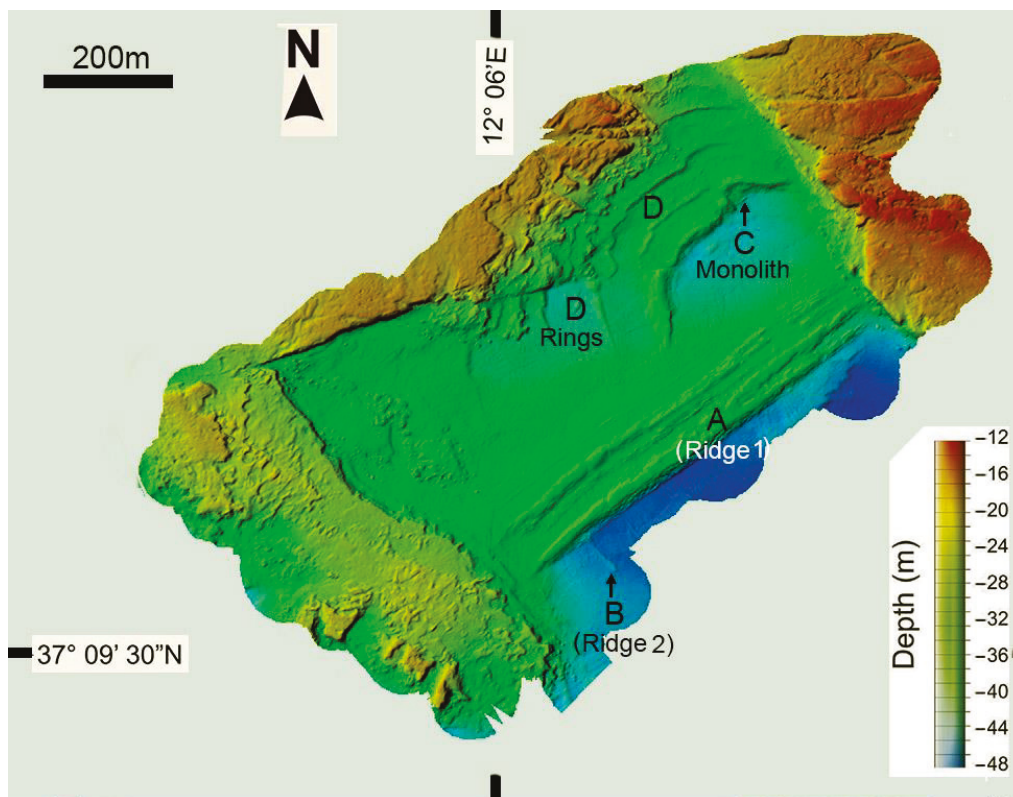


Figure 2. A multibeam image of the Pantelleria Vecchia Bank (modified after [60]).



Figure 3. Rock blocks on Ridge 1, modified after [60].

1. Ridge 1 is an 820 m-long stone ridge whose lower part is covered with unconsolidated sediment (sand), while the upper part comprises what Lodolo et al. [59] describe as “horizontally arranged” stone blocks 0.5 m thick, some rectangular in shape, with the largest measuring ~3.4 m (Figures 2A and 3). Based on thin-section petrography analysis of samples collected from the feature, their lithology was classified as bioclastic sandstone (Table S1). Based on chronological and morphological patterns (e.g., the orthogonal geometry, the blocky structure, and its stepped slopes on its seaward margins), the ridge was interpreted as having been initially embedded in coarse sand during a low sea-level stand some 40,000 years BP. Lodolo et al. [59]

suggest that later, ~9000 years BP, the natural deposit was modified and stone blocks were intentionally erected by prehistoric inhabitants of the region to serve as a coastal defense against sea-level rise.

2. Ridge 2 is an 82 m-long and 6–8 m-wide stone feature that lies perpendicular to and 100 m northeast of, the west end of Ridge 1 (Figures 2B and 4). It too is characterized by rectangular stone blocks that rise 1 m above the surrounding seafloor. It was dated to an earlier Late Miocene (Tortonian) era, similar to the half-ring ridges (see below).



Figure 4. Rock blocks on Ridge 2, modified after [59].

Based on thin-section petrographic analysis of samples collected from the stone features, their lithology was classified as bioclastic sandstone (Table S1). In their 2023 paper [59], Lodolo et al. suggested that “It seems unlikely that this concentration of peculiar and geometrically regular structures would develop by natural processes in this small (~0.5 km) study area. . . . In view of the above, it seems possible that the two ridges are associated with human occupation”.

3. The stone monolith is located at 35 m depth, some 300 m north of Ridge 1. It is described in a 2015 paper [60] as a ~12 m-long stone monolith that broke into three stone blocks that are now arranged in a line (Figures 2C and 5). Based on thin-section petrography analysis of samples collected from the features, its lithology was classified as bioclastic sandstone, similar to Ridge 1 described above (Table S1). In three different places on this rock, there are holes, one of which runs through the rock from side to side. Lodolo et al. suggest that the rock represents a broken human-made megalith, associated with a Mesolithic culture that occupied the Pantelleria Vecchia Bank during low sea level ~13,000 years BP, and was probably placed in an erect position. They therefore assume that people extracted the rock and transported it some 300 m from Ridge 1 and then erected it. The following features were offered by them to support the anthropogenic origin of the monolith: (1) It is made of the same rock and is the same age as Ridge 1, closing the submerged paleo-embayment; (2) it is of rather regular shape and has three regular holes of similar diameter at the top and on its sides; (3) there are no reasonable known natural processes that may have produced these elements; (4) the monolith is made of stones other than those that constitute the neighboring outcrops (this statement contradicts no. 1 above).
4. The half-ring features are a sequence of block (up to 3 m long and 0.5 m thick) accumulations forming parallel, curved ridges stretching a few hundred meters to the north of Ridges 1 and 2. Based on thin-section petrographic analysis of samples collected from the half-ring features (see Table S1), their lithology was classified as bioclastic limestone dated to the Late Miocene (Tortonian) [61]. According to the observations of Lodolo and colleagues, the rock type of the half-ring ridges is identical to the surrounding rocks forming the Pantelleria Vecchia Bank (dated to the Late Miocene). Nevertheless, based on analyses of their data and examination of their

geometry and structure, they excluded the possibility that the concentric half-rings were formed by natural processes and suggest that they were originally part of human-made structures functioning either as fortifications, anchorage, fishing installation, or used for ritual practices [61].



Figure 5. The isolated monolith, modified after [60] (Figure 4: lateral view from the SW).

3.2. The Lampedusa Megalithic Site

- Archaeological setting:

The initial occupation of the island of Lampedusa dates back to the Neolithic period, ca. 6000 years BP, with the earliest evidence of human presence from the site of Cala Pisana, excavated by the University of Pisa [62]. The island, which was investigated by Thomas Ashby in 1909 and by the Natural History Department of the University of Pisa in 1971, abounds in Late Prehistoric or Early Bronze Age architectural remains characterized by circular-shaped stone structures (See Figure S1). The period and purpose of these structures remain unclear, and they have been interpreted as agricultural installations or dwellings [63]. From 1000 BCE. until modern times, the island has been influenced by various cultures, including the Phoenicians, Greeks, Romans, and World War II events [64].

In publications from 2014 and 2019, Diego Ratti tentatively proposed that he had found a possible submerged prehistoric place of worship off the northwest coast of the island of Lampedusa [65,66].

- Geological setting:

The suspected megalithic installation was detected off the northwestern coast of Lampedusa at the foot of a cliff more than 100 m high (Figures 6 and 7). Grasso and Pedley [67] conducted a detailed geological survey of the elongated east–west-oriented island. They reported on a northwest–southeast trending Late Miocene fault (a monoclinical flexure) that divides the island into two morphological units. To the west, all strata are horizontal, with vertical cliffs up to 100 m high on the coast. The southern and southeastern shores are ria-type, with well-developed, drowned river valleys and small bays. While rapid headward erosion has destroyed much of the original pre-Tyrrhenian coastline in the western promontory and northern coasts, no such destruction has occurred at the southern and southeastern sides of the island [67]. Unlike the ria-like eastern and southeastern sectors of the island, this region is characterized by active coastal erosion creating coastal cliffs and numerous landslides. Erosion of the bedrock reveals two main geological units on the section of the coastal cliff: white chalkstone at the bottom of the cliff and darker yellow limestone at its top.

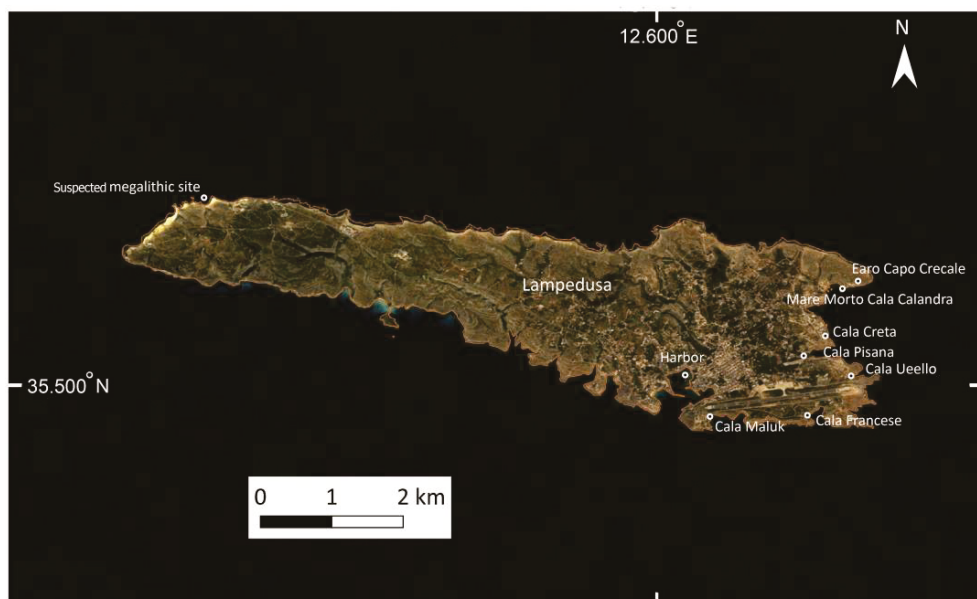


Figure 6. Lampedusa Island and the location of sites mentioned (map: modified after Sentinel-2 cloudless layer for 2023, with bright overlay layer by EOX—4326).

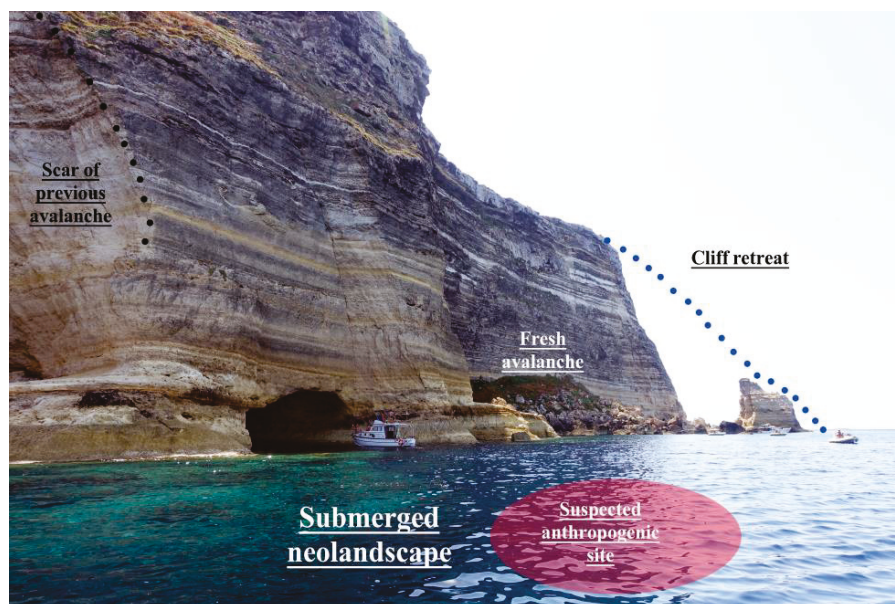


Figure 7. Photograph showing active cliff retreat in the studied locality creating caves, a sea stack and submerged neo-landscape, and the location of the suspected anthropogenic site (E. Galili).

- Past and present studies:

The suspected megalithic site at Lampedusa was initially explored by recreational divers [65] using multibeam images and aerial and underwater photography. In 2019, two of the authors (E.G. and I.O.R.) investigated the site and associated features, with the purpose of inspecting the submerged landscape and the suspected anthropogenic features in the site [68]. The underwater surveys were carried out using a diving boat, standard scuba 12 and 15 L air tanks, and underwater cameras—a Sony 100 III in housing and a GoPro. Measurements were taken using a rolled metric tape, while underwater drawing was carried out using a pencil on A4 plastic sheets. Rocks were sampled using a chisel and hammer, and shallow trenching of sediments was performed using hand fanning to expose underlying features. A complementary coastal survey was also carried out by E.G. and

I.O.R. with the aim of identifying possible parallel human-made structures on land, and archaeological and geological features that could be used as indicators of ancient sea levels and vertical tectonic changes.

In his publications, Diego Ratti described features made of stone boulders off the northwest coast of the island at an average depth of -11 m below sea level (Figures 8–10). His underwater surveys close to the foot of the cliff yielded two circular stone formations, bounded to the north by a bedrock plateau (Figure 10, no. 3). The size of the stones ranged from approximately 1.5 to 5 m. We carried out a 50 cm-deep probe into the carbonate sand within the circle installation (and tested it by hand fanning) with the aim of finding anthropogenic remains like stone tools, imported stones, charcoal, or bones, but it yielded no finds. Initially, Ratti had thought these structures were simply a random set of broken rocks that had rolled from the nearby cliff following natural coastal erosion. However, after various diving surveys and aerial photos, Ratti perceived that the rocks formed circular and elliptic enclosures, similar to those of a prehistoric place of worship with an area of rock-cut steps [65,66].

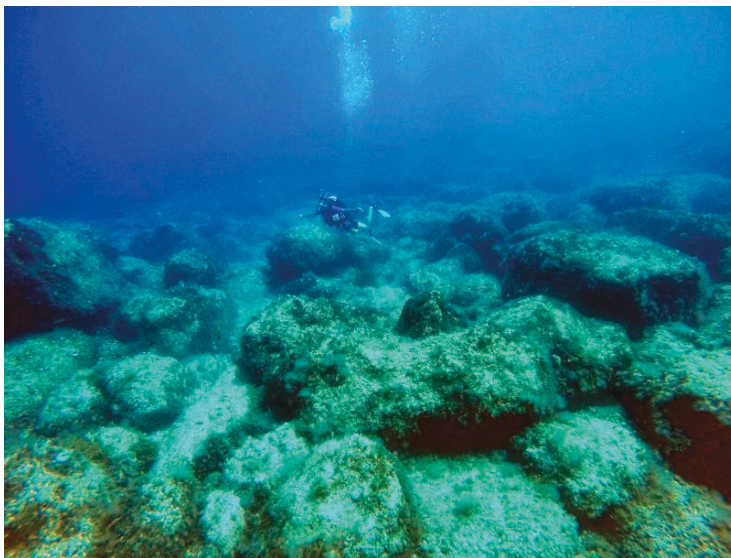


Figure 8. Boulders on the sea bottom at the suspected cultic site off Lampedusa (for location, see below in Figure 10, nos. 1,2) (E. Galili).

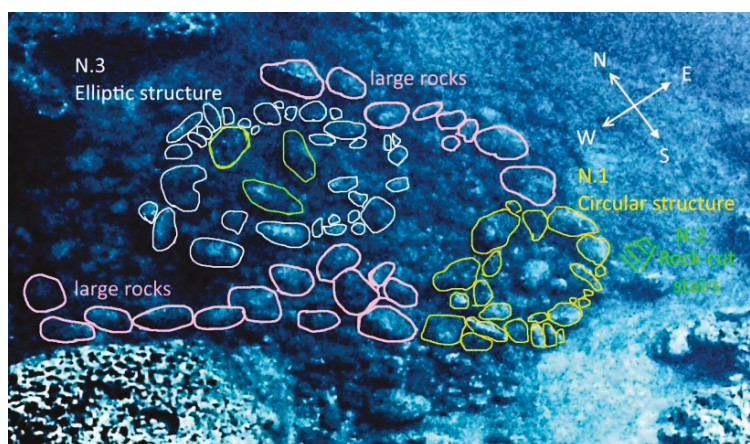


Figure 9. Plan of the suspected cultic site (courtesy of Diego Ratti, modified after Figure 2.88 in [63]).

Additionally, a protruding rock on the seabed located ~ 30 m northwest of the boulder concentrations was suspected to be a zoomorphic sculpture (Figure 10, no. 4, Figure 11).

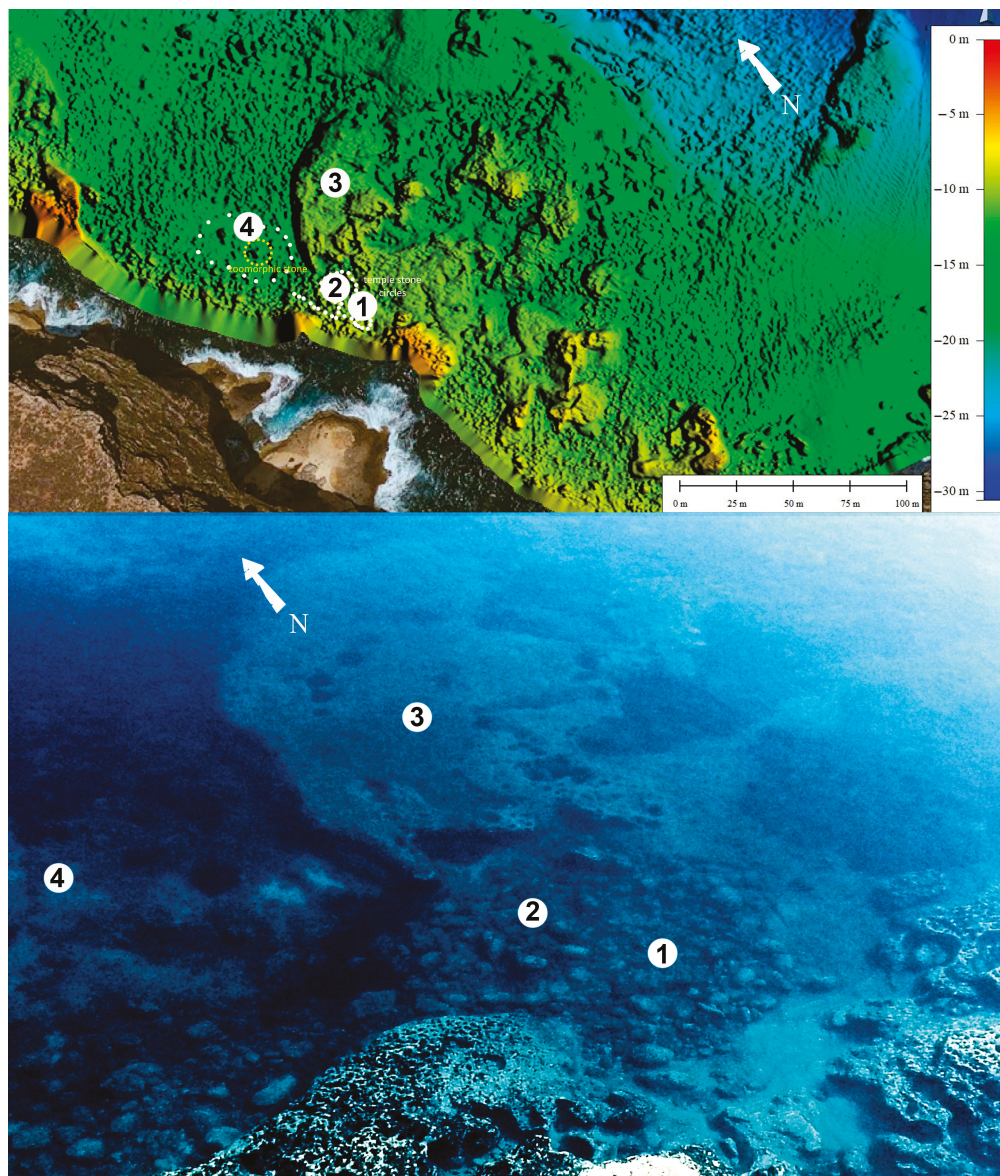


Figure 10. Above: multi-beam image of the site with the location of the main features: 1, 2—concentrations of boulders suspected to represent cultic circles, 3—flat surface of in situ eroded rock, 4—suspected zoomorphic feature or natural erosional feature (courtesy of Diego Ratti and CNR Centro Nazionale delle Ricerche). Below: aerial photo of the suspected site (courtesy of Diego Ratti).

South of the site, Ratti identified pits in a submerged cliff that he suspected represented rock-cut tombs, while west of the site were rocks that are zoomorphic in shape (Figure 11).

In 2019, the data collected by Diego Ratti were complemented by underwater and coastal surveys led by two of the authors (E.G. and I.O.R.) together with Diego Ratti, Pietro Ratti, Fabio Giovanetti, Anna Sardone, and Giuseppe Sorrenti. Samples were taken from the boulders, the sea bottom, and the supposed zoomorphic rock, and were examined with the naked eye. During the underwater surveys in and around the suspected anthropogenic site, two main rock features were identified on the sea bottom at ~10–15 m depth:

1. Clusters of boulders of various sizes and shapes, which had collapsed from the coastal cliff. These are scattered in a random pattern on the shallow (1–12 m deep) sea bottom, close to the foot of the coastal escarpment, as usually can be found in colluvial deposits and landslides (Figure 7). Of the hundreds of boulders found there (Figure 9), some stone clusters may resemble human-made “stone arrangements”.

2. Rock features protruding from the original in situ rocky deposit on the sea bottom. These are the remains of rock sections that were probably more resistant, and thus underwent less erosion and remained in their original location. Some of these are isolated, vertical protrusions (Figure 10, no. 4), while others are large rock surfaces (up to $50 \times 30 \times 3$ m) (Figure 10, no. 3). Galili and Ogloblin-Ramirez [68] summarized their research in an unpublished report, in which they noted that the boulder concentrations on the sea bottom are situated close (10 m or closer) to the foot of the coastal cliff, and that the numerous features identified on the sea bottom are typical products of a coastal escarpment under erosion (Figure 6).



Figure 11. Suspected zoomorphic feature or erosional feature at the Lampedusa site (for location, see Figure 10, no. 4) (E. Galili).

In their observations, they note that one boulder concentration comprises mainly local limestone from the upper stratum of the cliff, while the second concentration is a mix of chalk and limestone originating from both strata of the cliff (Figure 12). The proposed zoomorphic rock feature is composed of an in situ deposit of chalk. The underwater surveys in and around the site revealed no clear human traces, neither artifacts nor tool marks. Galili and Ogloblin Ramirez [68] concluded that the stones that make up the suspected ritual structure actually represent natural boulders that fell from the cliff, as initially suggested by Ratti. In 2022, Ratti published a new version of his 2015 book “Lampedusa Preistorica” [69] (pp. 182–204), accepting the natural origin of the suspected megalithic site, as proposed by Galili and Ogloblin Ramirez [68].

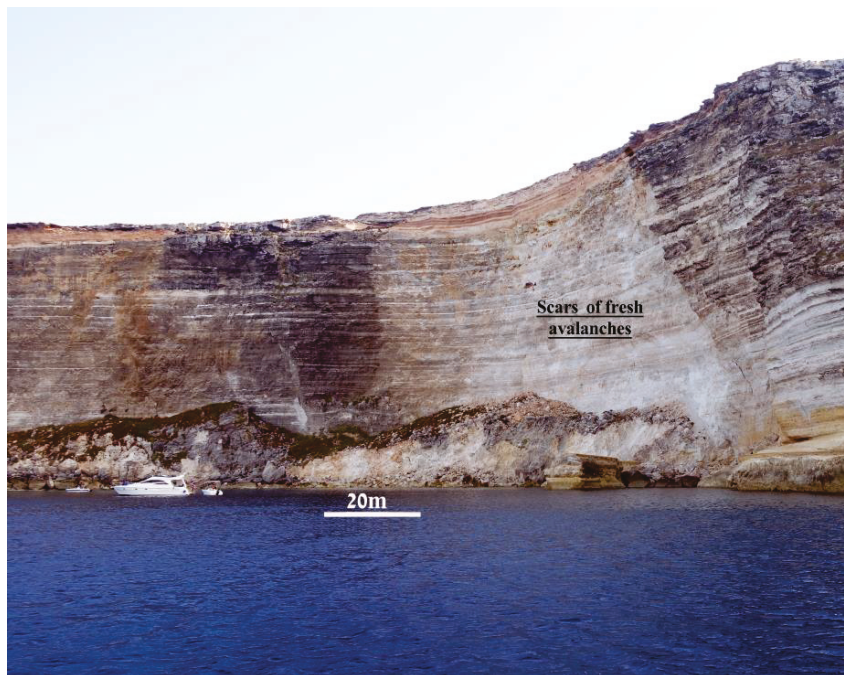


Figure 12. Typical landscape, fresh avalanches, and cliff retreat on the west and northwest coast of the Lampedusa site (E. Galili).

4. Discussion

4.1. The Pantelleria Vecchia Bank Site

In 2015, Tusa et al. [70] published a detailed rebuttal (in Italian) of the Lodolo and Ben-Avraham [60] paper, presenting extensive geomorphological, contextual, and archaeological data to refute their claim of having found a large anthropogenic megalith. However, Lodolo and Ben-Avraham were apparently unconvinced and presented the same arguments in two additional articles [59,61]. To avoid a possible “illusory truth” effect, [71] we felt compelled to re-examine the issues raised by Lodolo and colleagues relating to the anthropogenic nature of their finds. Using a comparative approach and examples from several other Mediterranean coastal areas, we explain why, in our view (and as previously noted by Tusa et al.) [70], the rock formations they describe on the Pantelleria Vecchia Bank do not support their claim that they are human-made constructions, but rather confirm that they are natural features.

- Geomorphological considerations:

Based on the thin sections shown in the publications of Lodolo and colleagues, they proposed that both Ridge 1 and Ridge 2 are composed of bioclastic rocks (either beachrock or consolidated beach deposits), and that the elongated Ridge 1 that blocks the submerged bay is probably a beachrock that was consolidated and embedded in the intertidal zone during a low sea stand some 45,000 to 50,000 years BP, as the ^{14}C dates indicate. This interpretation is supported by the sea-level curves [72–76], suggesting that the sea bottom in the Sicilian Channel was dry land between ca. 75,000 to 10,000 years BP. It is emphasized here that the dates presented by them reflect the timing of beachrock/beach deposit consolidation and not that of suspected anthropogenic activities. It is also worth noting that this date falls at the end of the range of radiocarbon, and thus its reliability is limited.

Beachrock is a common formation in the Mediterranean Sea and often forms on sandy coasts. As noted by Tusa et al. [70], beachrocks (our translation from Italian follows) “often detach from the rocky basin of origin due to coastal erosion, depositing themselves in the Mediterranean Sea between +1 and −5 m with respect to the coastline (they are known and dated up to a depth of 60 m in Sardinia, Turkey, Sicily, Greece, Croatia, and Liguria)”; for examples, see [77,78]. Thus, various features and patterns resulting from coastal erosion of

beachrock and beach deposits (e.g., chimneys, detached rectilinear blocks) are common in coastal environments.

- Sea level and tectonic considerations:

Vertical earth crust changes due to tectonic activity, isostasy, or structural changes may have changed the relative sea level in the research area. However, given that the area is considered relatively stable [57], such changes, if they occurred during the Holocene, would have only resulted in a displacement of a few meters. Thus, the height of the reported finds relative to sea level, and the deposition and erosion processes of the beachrocks under coastal/shallow marine conditions, have not changed considerably due to vertical changes in the earth's crust. Notably, according to the available sea-level curves for the last 80,000 years [72–78], the two stone ridges were exposed to coastal/intertidal/shallow marine conditions ca. 9000 years BP to 12,000 years BP and from 75,000 years BP to 85,000 years BP. We contend that during these events, the beachrock ridges most likely underwent significant erosion, resulting in the rectangular forms observed.

Ridge 1 is currently located in situ, at the site of its deposition. Thus, the most parsimonious explanation for the presence of the “horizontally arranged stone blocks” noted by Lodolo and colleagues is that these rectangular-shaped blocks are the result of post-depositional erosion of the stone, followed by the ridge cracking and settling on its southern sea side. The weathering and collapse of large sections of a beachrock ridge usually occur due to erosion and scoring of underlying sediments on its sea side, or due to a landslide (see Figures 1 and 11d in [79]). Such beachrock erosion is common in coastal environments and can be seen, for example, on the Israeli Mediterranean Sea coast at Ashkelon (on the seaward side of the beachrock outcrop—see Figure 3 in [79]) or at Akko on the landward side of the beachrock outcrop (Figures 13 and 14) as well as in other localities, e.g., Southeast Afric (see plate 13 in [80]) (see Figure 15).



Figure 13. Blocks of beachrock outcrop under coastal, landward erosion north of Akko (Israeli coast), looking north (E. Galili).



Figure 14. Blocks of beachrock outcrop under coastal, landward erosion north of Akko (Israeli coast), looking southwest (E. Galili).

Lodolo and colleagues suggest that these “block” features may be the result of human modification, although they cite the publication of Shinn [81], who outlined in some detail the “simple mechanism that can produce beach-rock geometries” similar to those characteristics observed on the seaward side of Ridge 1, namely, “Exposure to sunlight and constant wetting and drying break the rock down into individual slabs, like to a concrete road. The size of the individual slabs is determined by the thickness of the rock. Uncemented sand under the rock also promotes cracking as the rock settles, much like ice on a frozen pond”. Shinn [81] gives an entirely plausible, natural explanation for the shape as well as the location of stone blocks similar to those observed on the Pantelleria Vecchia Bank.

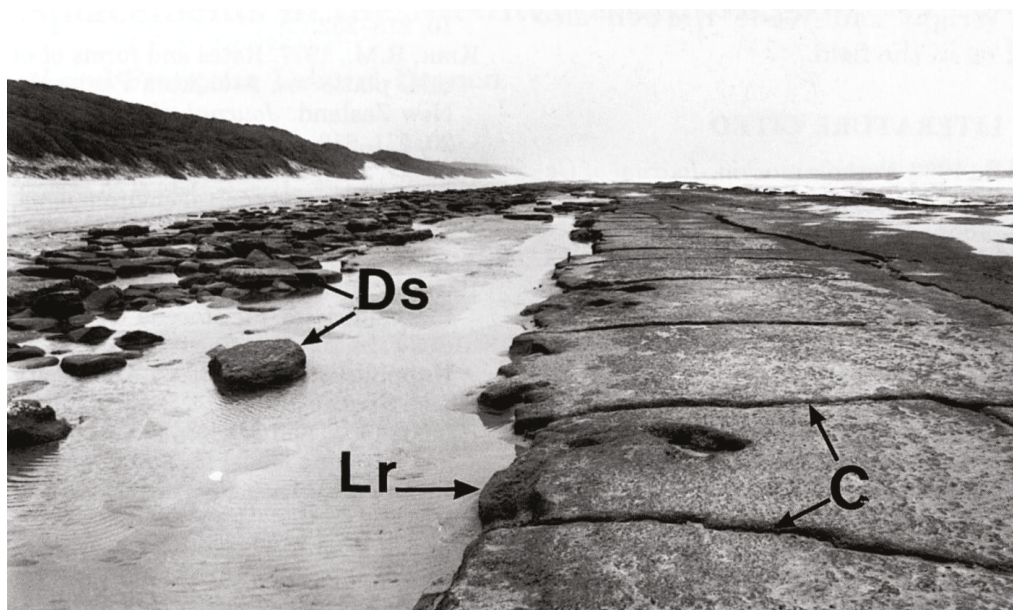


Figure 15. Lingoid ridge (Lr) developed on a Type 3 intertidal platform (C refers to transversal cracks in the beachrock plates; Ds refers to detached blocks of beachrock washed shoreward), modified after [81] (see plate 13 in [80]).

Likewise, the possibility of modification of Ridge 2 by people some 9500 years BP, i.e., the building of a wall-like structure with stone blocks, as proposed by Lodolo and Ben Avraham [60], is not supported by any archaeological or geoarchaeological information presented by the authors. A more parsimonious explanation is that Ridge 2 was deposited at an earlier stage, under different environmental and sea conditions than those prevailing during the deposition of Ridge 1, creating a different paleo-coastline. Thus, Ridge 2 may represent a natural relic of one of the half-ring ridges, rather than being a human-made feature.

Regarding the so-called monolith, Lodolo and Ben-Avraham [60] state that “the monolith is made from stone other than those which constitute all the neighboring outcrops . . .”, but they also state that “the lithology and age of the rock that makes up the monolith are similar to those that make up the blocks of the rectilinear ridge closing the embayment”. Thus, the monolith probably originated from the neighboring eroded beachrock Ridge 1, which is located some 300 m to the south. It is feasible that when the bay was flooded some 9500–9200 years BP [60] (their Figure 8), a large, elongated piece of rock broke off Ridge 1 and was washed inland (northward) by a tsunami or by storm waves. During the Neolithic period, the Pantelleria Vecchia site (an isolated island at the time) must have been exposed to violent coastal/shallow marine processes that affected the Early Holocene coast. For example, tsunami waves are known to transfer large masses hundreds of meters inland [82–85]. Conceivably, the elongated rock deriving from Ridge 1 could have weakened during such processes and subsequently broken up into three separate blocks.

As to the possibility that the half-ring ridges are anthropogenic in origin, as in the case of the other features discussed above, this statement is not supported by any archaeological or geoarchaeological information presented by the authors. These features are most likely the product of natural Late Miocene depositional processes (long before human presence) or natural post-deposition, coastal erosion processes.

- Holes and “chimney” features in an intertidal, rocky environment:

Lodolo and Ben-Avraham [60] state that “the monolith has three regular holes of similar diameter, one that crosses it completely on its top, and another two at two sides of the monolith”. We reiterate here the counterarguments first raised by Tusa et al. [70] concerning the holes in the rocks, since they appear to have gone unnoticed in the literature and by Lodolo and colleagues in their 2015 paper and subsequent papers. Tusa et al. rightly contended that they are typical products of coastal erosion of beachrock, either by plant or by water action when the rock was exposed in the highly energetic paleo-intertidal zone.

Careful observations of Figure 4 in the 2015 Lodolo and Ben-Avraham article [60] depicting the stones reveal that the statement made by Lodolo and Ben Avraham regarding the monolith (that it is of rather regular shape and has three regular holes of similar diameter at the top and on its sides) is to be reconsidered. It seems that although the monolith is an elongated feature, its regular shape is questionable and the holes differ from each other in size and form, and probably also the agent responsible for them. Indeed, one is a through perforation and two appear to be cavities. In the intertidal and supratidal zones, a variety of processes can cause the erosion of rock, such as physical or chemical erosion, bio-erosion, and algal induration [79,80,86]. Round holes, cavities, geyser chimneys (Figure 16), and craters are scoured and abraded by water under the influence of currents and waves, and are typical of high-energy, intertidal, rocky environments. In their rebuttal, Tusa et al. [70] also note that even perfectly cylindrical holes can be created by natural action. They further suggest that natural erosion, due to plant action, can create similar holes: “over 5 m long and with a section compatible with those shown in Lodolo and Ben-Avraham [60], and are found in large numbers along the coasts of the Black Sea, on lithologies similar to that of the “monolith” e.g., Erginal et al. [87]”.



Figure 16. Water emerging from a geyser chimney (pipe/hole) on a rocky (aeolianite sandstone—kurkar) section of the Israeli coast, near Kibbutz Neve Yam (E. Galili).

- Dating considerations:

The dates presented by Lodolo and colleagues for the monolith and the ridges (Table S1) are in fact taken from carbonate shells extracted from the samples. As such, they represent the period of deposition and consolidation of the bioclastic rocks, and so are not pertinent to the issue of whether these features are anthropogenic in origin or natural.

The proposed dating of the monolith, which is based purely on sea-level considerations and speculations, implies according to Lodolo and Ben-Avraham [60], an anthropogenic origin and the possible modification of the two beachrock/consolidated beach deposit ridges by humans [59]. The sea-level curves cited [72,73,75,76,88,89] suggest that some 9200–9500 years BP, the sea level in the Sicilian Channel was ca. 40 m lower than today and the Pantelleria Vecchia Bank was a small island between Pantelleria and the Sicilian coast. Thus, the ridges and monolith were under coastal/shallow marine conditions at the beginning of the Holocene. Lodolo and colleagues note that this paleo-coastal area would have been accessible to humans during certain prehistoric periods. However, this situation is also valid for thousands of other square kilometers of continental shelves around the globe, down to a depth of 40 m [90]. Consequently, basing human intervention on a speculative argument of possible accessibility to the area where the ridges and monolith were found cannot be considered scientific proof to support a Mesolithic anthropogenic origin for the monolith stone feature, as suggested by Lodolo and Ben-Avraham [60], nor for the modification of the ridges during the Early Neolithic, as proposed by Lodolo et al. [59,61].

- Archaeological considerations:

In their discussion of the rock formations of Pantelleria, Tusa et al. [70] detail why, on archaeological grounds, the presence of a monolith that can be compared or traced to the central Mediterranean megalithic tradition in these locations is not feasible. In addition, they also refute the proposed dating suggested by Lodolo and colleagues for Pantelleria Vecchia Bank (see details in Tusa et al. [70] and references therein). It should be noted here that Lodolo and colleagues did not involve a professional archaeologist, who may have related to the existence or nonexistence of anthropogenic fingerprints and finds of material culture.

In general, the possibility of finding unique stone structures in archaeological sites cannot be ruled out. However, usually the manner in which they were built have parallels in other contemporaneous sites in the same region. In the case of the Pantelleria Vecchia Bank features, we do not know of any contemporaneous (i.e., Mesolithic) terrestrial parallels

in Italy for structures that resemble the form of the submerged features documented by Lodolo and colleagues. It is also unlikely that such a monumental ancient structure would have been built on a remote offshore island, with no developed cultural center that could have supported such a project, leaving no anthropogenic fingerprints. Tusa et al. [70] refute the comparisons made by Lodolo and Ben Avraham [60] to the monolithic cultures of Malta and Gobekli Tepe in Turkey, which are both chronologically and culturally distant from Sicily. As Tusa et al. conclude, "...it is absolutely methodologically incorrect to compare distant and independent historical dynamics to justify the alleged presence of absolutely unjustifiable artifacts in their correct geographical reference context".

- The absence of human-made finds in the suspected anthropogenic site:

It is expected that a prehistoric culture capable of producing gigantic megaliths and mega-constructions would leave behind at least a few anthropogenic finds of distinctive material culture (e.g., flint implements, bones, wood, charcoal, ash, and pottery in the case of Pottery Neolithic, Chalcolithic, or later cultures). Admittedly, the absence of evidence is not evidence of absence. However, the absence of such finds in such a gigantic complex thought to be anthropogenic in nature is a strong argument against the anthropogenic nature of the ridges and monolith. For example, stone tools, faunal remains, and even a hearth feature were discovered adjacent to a Neolithic seawall made of large boulders off the Israeli coast, corroborating that this structure was definitely human-made [42]. In submerged prehistoric sites—both ephemeral and sedentary ones that were investigated off the Israeli coast—large quantities of both organic and non-organic items of material culture were recovered, clearly demonstrating the anthropogenic nature of these sites [9,19,31,42]. At the very least, flint artifacts that are highly resistant to erosion even in underwater conditions (as attested to at hundreds of submerged prehistoric sites discovered worldwide), e.g., [4,5,83], are expected to have been preserved and discovered in association with at least one of the features described at the Pantelleria Vecchia Bank. The feasibility of this is highlighted by the presence of human-made artifacts recovered underwater near Pantelleria Island [91]. This approach may be adopted by other research fields when access to suspected features is limited, e.g., sub-bottom remote-sensing research on land (for detecting buried architecture) or underwater (for detecting shipwrecks or buried human-made features). In the case of detecting a suspected buried feature, it should be treated as an "anomaly" that should be further investigated using direct-contact archaeological investigations (e.g., jet probes, cores, trenches, and excavations). However, the above approach may not be relevant for all fields of research, and there are cases in which an opposite approach has, and can be, adopted. For example, most of the suspected meteorites collected by amateur meteorite and mineral hunters are in fact items of anthropogenic origin. In this case, if an anthropogenic origin of a suspected meteorite is ruled out by a professional archaeologist, it can be considered to be natural.

4.2. The Lampedusa Site

- Possible parallel archaeological features on Lampedusa, Malta, and Sicily:

Megalithic constructions were not uncommon in the European Bronze Age. In fact, such structures can be found in the central Mediterranean islands of Malta and Sicily, with some smaller ones reported also on the central and eastern parts of Lampedusa Island [63,69] (and see Figure S1 here). This cultural connection has deep roots, as the two groups of islands shared cultural traces after the Neolithic (~5500 BCE), when the first attested colonists from Sicily established themselves in Malta [92–95]. The two groups kept cultural ties alive for millennia, as shown by parallels in their pottery traditions; the flint, obsidian, and other trades; as well as cultural and religious practices (see [73–75]). While these early cultural trends seem to have originated on the main island of Sicily and were introduced to Malta, scholars propose that the opposite is true for the Early Bronze Age megalithic traditions [96–98]. Megalithic building seems to have started in Malta ~3500 BCE and was connected to new ritual practices, including group burials. Only

later was it brought to Sicily (see [98]). Similar group burial practices are suggested in Sicily for the dolmen structures appearing in the third millennium in the Hyblean Plateau and in other scattered sites north and southwest of the main island of Sicily (see [98,99]). In his 2014 publication, Ratti ([65], p. 18) pointed out an oval stone structure located in Lampedusa on the top of the cliff above the suspected submerged cultic site, which has never been excavated or published: (our translation from Italian) “A stone structure of the same shape and dimensions of the underwater one can be seen on top of the cliff (110 m above sea level) exactly above the submerged one”. This structure is also depicted in his 2022 edition (see Figure 2.85 in [69]). During a field survey we conducted on top of the cliff, some stone arrangements and structures were identified. However, unlike the boulders found in the suspected submerged megalithic structure (the latter weighing up to a few tons each), the terrestrial structure is built of smaller stones arranged in patterns that differ markedly from the underwater feature. Thus, the yet unexcavated and undated stone structures on top of the cliff, and the other megalithic structures on the island, do not represent possible parallels to the submerged structures.

- The MIS5e deposits and the archaeological sea-level markers used for testing tectonic stability and sea-level changes:

To estimate changes in the local relative sea-level and possible tectonic uplift of Lampedusa, two sets of sea-level indicators were investigated. Marine Isotope Stage 5e (MIS5e) beach deposits dated to the last interglacial high stand (124 ka) were identified based on fossil indicators (mollusk species: *Strombus bubonius*, and possibly *Patella ferruginea* and *Arca noae*, identified by geologist Giuseppe Sorrenti personal communication). The find elevations of these mollusks relative to the modern sea level was documented for the methodology and examples (see [57,100–105]). This parameter was of use to reconstruct the relative sea level during the Last Interglacial, when the global sea level was ca. 6 to 12 m higher than today. It also facilitated evaluation of the long-term vertical changes of the island since the deposition of these beach deposits. The heights of coastal installations (e.g., rock-cut bollards to which boats were tied) relative to the sea level today provided rough information about the sea level during historical periods. These Late Pleistocene and Late Holocene geological and archaeological indicators enable a rough evaluation of the relative sea-level height and tectonic stability of the region during prehistoric and historic times, respectively.

Previously, Segre [106] and Grasso and Pedley [67] located Tyrrhenian terraces and MIS5e deposits while producing the geological map of Lampedusa. East of the monocline, on the ria coastline (from Cala Greca to Cala Creta [see Figure 2]), Tyrrhenian features consisting of beach deposits containing the mollusk *Strombus bubonius* lie at ca. +2 m above present sea level (see [106] (p. 138)). West of the monocline, prehistoric caves were identified by Segre (see pp. 145–147, Figure 7d in [106]) at an elevation of ca. 35 m above sea level. Grasso and Pedley [67] suggested that these caves are related to the same Tyrrhenian episode identified on the east side of the island, and that the tectonic movement associated with the monoclinical flexure was completed by Late Pleistocene times.

Following these studies, we rechecked the deposits in some key sites on the island of Lampedusa. In Cala Ucello Bay, a clear MIS5e beach deposit with at least four individuals of the index fossil *Strombus bubonius* in a good state of preservation were identified (Figure 17). The maximum elevation (the so-called inner edge) of this deposit was 2.20 m asl (at 6:30 pm on 3 August 2019). In Cala Maluk, a probable MIS5e beach deposit formation was identified on the western side of the bay. In this case, fossils of *Patella ferruginea* and *Arca noae* mollusks were observed. The maximum elevation of the deposit was 1.60 m asl (at 7:00 pm). Another MIS5e deposit at a similar elevation containing *Strombus bubonius* was identified in Cala Pisana. Overall, all the MIS5e/Tyrrhenian deposits studied do not display evidence of dramatic tectonic changes in the region during the time period of the formation of the coastal escarpment. According to Lambeck et al. (see Figure 6 in [107]), the average rates of vertical movements in the Linosa/Pantaleria region during the Holocene, and for the last glacial cycle, was ± 0.15 mm/y. Assuming that tectonic movement associated with the

monoclinical flexure on the island was completed by Late Pleistocene time, as suggested by [67], tectonics would have had very little impact on the erosion of the cliff above the suspected cultic site. It is reasonable to assume that the most significant erosion and retreat of the coastal cliff took place after the Mid-Holocene, when the sea level reached its present elevation. However, the possibility of initial coastal cliff erosion during the Last Interglacial (MIS5e isotope stage) cannot be ruled out. Thus, the sea bottom opposite the coastal cliff of Lampedusa may be a partly submerged paleo-landscape, as well as a partly submerged neo-landscape, depending on the distance from the cliff.



Figure 17. Left: Cala Ocello Bay and location of the MIS5e deposit, center and right: close-ups of *Strombus bubonius* mollusks (E. Galili).

- Mid- to Late Holocene sea-level indicators:

These were identified in Cala Pisana Bay, where a modern beachrock formation composed of modern materials (e.g., glass, and metal) was located on the shoreline at an elevation associated with the present sea level. Important archaeological indicators identified were rock-cut bollards that are reported here for the first time (Figure 18). Of the 16 bollards located, two were in Cala Pisana Bay, and the rest were in the Porto Vecchio (Cala Palme) and Porto Nuovo (Cala Salina). Other rock-cut features such as carved channels and square installations were also identified in the harbor area, and a large quarry site a few meters above current sea level was observed in Cala Calandro. In general, rock-cut installations are not easy to date [108]. Although such rock-cut bollards are hard to date and some of them are still being used (e.g., in Brucoli Sicily, lat. 37.2817° N, lon. 15.1862° E), similar installations found in well-documented archaeological sites [109,110] suggest that they date to the Roman/Byzantine periods. Some of those rock-cut installations were affected by sea erosion and modern coastal constructions; however, their elevation above sea level enables proper functioning, suggesting that the relative sea level has not changed dramatically since they were cut in the stone.

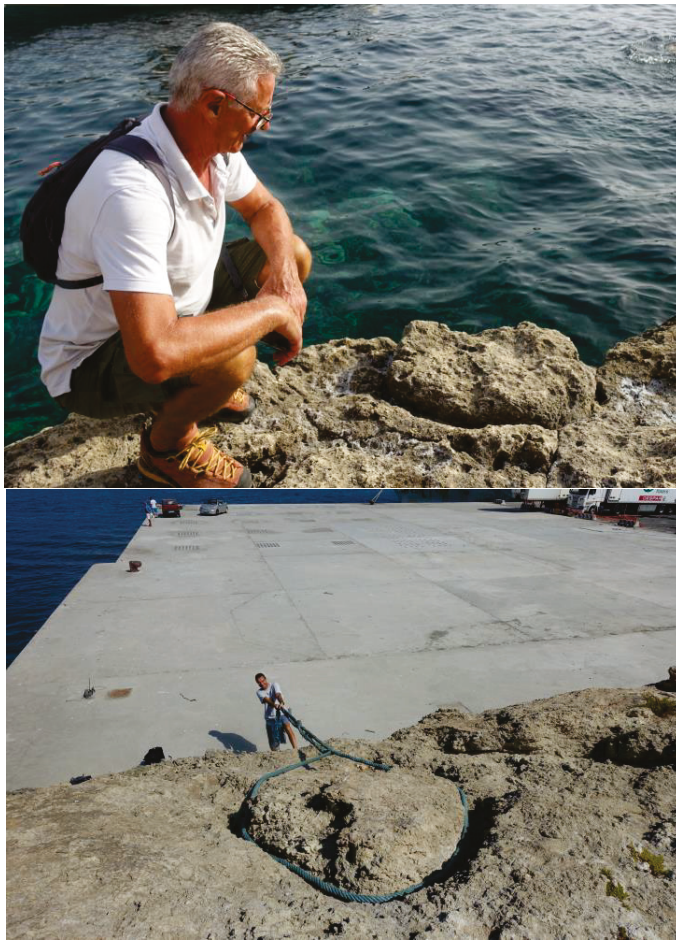


Figure 18. Top: ancient rock-cut bollard in the modern Lampedusa harbor, bottom: ancient rock-cut bollard in Cala Pisana Bay (E. Galili).

- Submerged paleo-landscape versus submerged neo-landscape:

In situ submerged prehistoric sites can be found on submerged landscapes inundated by post-glacial sea-level rise. However, some submerged landscapes are relatively new (post-prehistoric/post Mid-Holocene periods, hence the submerged neo-landscape). Examples for such submerged neo-landscapes may be at the foot of an active, retreating coastal escarpment (Figures 7 and 19), or on the surface of a consolidated lava flow that entered the sea. In situ finds discovered on such landscapes may then logically be attributed to a period later than the formation of the landscape. Thus, the date of the deposition of the natural rock may be used as a terminus post quem for the site deposited on it.

The erosion rate of the cliff and the proximity to the cliff were major arguments to rule out the possibility of the suspected Lampedusa site being anthropogenic in origin. Similar rapid erosion and retreat was identified in coastal cliffs composed of poorly consolidated aeolianite (*kurkar*) in central Israel [111]. An important geological indicator in the Lampedusa study area was a sea stack, probably part of the island in the past that had been separated from the present shoreline (Figures 7 and 19). The numerous fresh landslides on the coastal escarpment and its rapid active retreat suggest that the features in the studied site (the coastal cliff and caves and the adjacent sea bottom) are products of events that occurred during the second half of the Holocene sea-level rise.

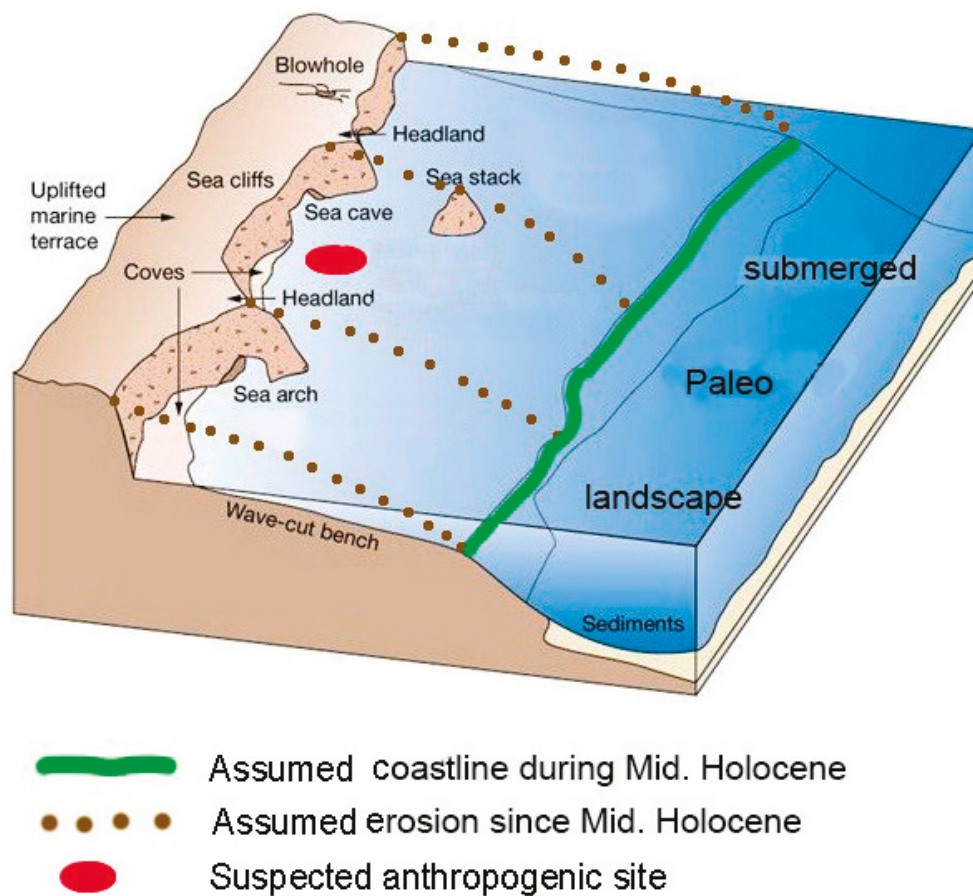


Figure 19. Coastal erosion, recent active retreat of the coastal escarpment, and creation of a submerged neo-landscape at the foot of the cliff schematic drawing, modified after Figure 5 in [112]).

5. Conclusions

Innovative remote-sensing technologies have been commonly used to explore and map currently submerged paleo-landscapes in search of prehistoric sites, providing unique and useful information. However, their findings need to be corroborated by detailed archaeological research, as there is no substitute for the knowledge and direct examination by an underwater archaeologist.

5.1. The Submerged Features on Pantelleria Vecchia Bank

Given all the data outlined above, we find that the suggestions for the possible anthropogenic origin of the discussed stone features, including the ridges and the elongated pierced monolith, to be unfounded. We feel that it is apt to repeat Tusa et al.'s excellent summary [our translation from Italian]: "multiple considerations both of a purely geological order, both intrinsic to the morphological characteristics of the object, both inherent to the immediate context of its position, and in reference to the broader chronological and geographical context, lead us to the natural conclusion that it is not a question of a manufactured, but rather a natural product". In addition, our study has shown the limitations of relying on high-tech remote-sensing techniques to identify anthropogenic sites, and confirms the need for complementary first-hand, professional archaeological documentation and research to provide a rigorous foundation for such determinations.

5.2. The Suspected Megalithic Feature in Northwestern Lampedusa

The shallow sea adjacent to (up to few tens of meters from the cliffs) western and northwestern Lampedusa can be considered a submerged neo-landscape (post-prehistoric

times) formed during the second half of the Holocene i.e., after the sea level reached its present elevation. It is suggested that the discussed submerged megalithic structures are natural features and represent boulders that collapsed from the adjacent cliff, while the adjacent zoomorphic-like feature are erosional features that developed on these rocks.

5.3. *In Case of Doubt, There Should Be No Doubt*

Generally speaking, the submerged landscapes and features described above are extremely interesting, and the geological and geomorphological formation processes that created them are worthy of investigation. We suggest that the rationale underlying the interpretation of features identified on submerged landscapes as anthropic should not be symmetrical. In other words, if it is suspected that a submerged feature is human-made, further archaeological investigations should be undertaken, and until such a verification has been made, the feature should be considered of natural origin. Moreover, we suggest that the rationale underlying the interpretation of features identified on submerged landscapes as anthropic should not be symmetrical. The reasoning behind this asymmetry is that, worldwide, there are only a small number of prehistoric megalithic stone features that are human-made. Statistically speaking, the probability for the existence of symmetrical and geometric rock features or stone arrangements on a submerged landscape that may be human-made (even if their formation processes are yet unclear) is slight. Most importantly, the presence of a symmetric or geometric feature in a given underwater site cannot by itself point to an anthropogenic origin. To determine the anthropogenic origin of such features, a detailed archaeological investigation yielding material finds that clearly connect the object to human manufacture should be presented. Thus, in cases where there is neither clear archaeological material evidence for an anthropogenic origin of a submerged site, e.g., artifacts, debris, charcoal, faunal remains, etc., nor use-marks, production marks, or signs of intentional shaping of the stone, the site should be considered of natural origin. In such unclear cases, instead of stating that “we cannot rule out the possibility of an anthropogenic origin,” it is strongly recommended to rule out such an origin until it is supported by solid archaeological evidence and to treat the site as an interesting natural feature that should be studied and preserved.

In the examples discussed in this paper, the application of remote-sensing techniques enabled the initial detection and mapping of submerged features, but the verification of their status as natural or anthropogenic relied upon their being surveyed and sampled firsthand, by an archaeologist who collected relevant data both underwater and on the adjacent coastal area. This study demonstrates that these two are complementary methods that can be successfully applied to identify submerged anthropogenic sites.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse12111981/s1>, Table S1: Details of published rock samples from the Pantelleria Vecchia Bank discussed in the text; Figure S1: Round undated structure made of stones in Cala Calandra, on the north-eastern coast of Lampedusa, looking south.

Author Contributions: Conceptualization, E.G., L.K.H., I.P., A.B. and I.O.R.; methodology, E.G., I.O.R.; investigation, E.G., L.K.H., I.P., A.B. and I.O.R.; writing—review and editing, E.G., L.K.H., I.P., A.B. and I.O.R.; visualization, E.G.; project administration, E.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: New data (mainly photos) resulting from the Lampedusa underwater and coastal surveys is held by E.G. and I.O.R., and will be provided upon request.

Acknowledgments: The authors wish to thank Diego Ratti and Pietro Ratti for their kind hospitality, for founding the research on the Lampedusa Island, and for providing Figures 9 and 10 and the permission to publish them. Thanks to Diego Ratti, Fabio Giovanetti, Anna Sardone, and Giuseppe Sorrenti for participating in the underwater and coastal research on Lampedusa Island; to geologist Giuseppe Sorrenti, who participated in the underwater and coastal research and identified the sediments, the beach deposits, and the index mollusk fossils; to Nino Taranto from the Lampedusa archive

for providing photos and information regarding the history of Lampedusa Island; to Emmanuel Lodolo and Tzvi Ben Avraham for providing Figures 2–5 and permission to publish them; to E.C.R. Luo, for the permission to publish Figure 19 depicting the formation of the beach profile; and to W.R. Miller, and T.R. Mason, for the permission to publish Figure 15 depicting the erosional features of the coastal beachrock and aeolianite outcrops in South Africa. We also wish to thank Sara Elettra Zaia for preparing the map of Figure 1 and the three anonymous reviewers for their useful remarks and suggestions, which considerably improved the article, including remarks concerning meteorites made by reviewer #2 which were incorporated in the article.

Conflicts of Interest: All authors declare that they have no conflicts of interest.

References

1. Lambeck, K.; Purcell, A. Sea-level change in the Mediterranean Sea since the LGM: Model predictions for tectonically stable areas. *Quat. Sci. Rev.* **2005**, *24*, 1969–1988. [CrossRef]
2. Lambeck, K.; Woodroffe, C.D.; Antonioli, F.; Anzidei, M.; Gehrels, W.R.; Laborel, J.; Wright, A.J. Paleoenvironmental records, geophysical modelling and reconstruction of sea level trends and variability on centennial and longer time scales. *Underst. Sea Level Rise Var.* **2010**, *1*, 61–121.
3. Master, P.M.; Flemming, N.C. *Quaternary Coastlines and Marine Towards the Prehistory of Land Bridges and Continental Shelves*; Academic Press: London, UK, 1983.
4. Benjamin, J.; Fischer, A.; Pickard, C.; Bonsall, C. *Submerged Prehistory*; Oxbow Book: Oxford, UK, 2011.
5. Evans, A.M.; Flatman, J.C.; Flemming, N.C. *Prehistoric Archaeology on the Continental Shelf: A Global Review*; Springer: New York, NY, USA, 2014.
6. Harff, J.; Bailey, G.N.; Lüth, F. Geology and archaeology: Submerged landscapes of the continental shelf: An introduction. *Geol. Soc. Lond. Spec. Publ.* **2016**, *411*, 1–8. [CrossRef]
7. Blanc, A.C. Low levels of the Mediterranean Sea during the Pleistocene glaciation. *Geol. Soc. Lond. Q. J.* **1937**, *93*, 621–625. [CrossRef]
8. Raban, A.; Galili, E. Recent maritime archaeological research in Israel—A preliminary report. *Int. J. Naut. Archaeol.* **1985**, *14*, 321–356. [CrossRef]
9. Galili, E.; Weinstein-Evron, M. Prehistory and paleoenvironments of submerged sites along the Carmel coast of Israel. *Paléorient* **1985**, *11*, 37–52. [CrossRef]
10. Bailey, G.N.; Flemming, N.C. Archaeology of the continental shelf: Marine resources, submerged landscapes and underwater archaeology. *Quat. Sci. Rev.* **2008**, *27*, 2153–2165. [CrossRef]
11. Flatman, J.C.; Evans, A.M. Prehistoric archaeology on the continental shelf: The state of the science. In *Prehistoric Archaeology on the Continental Shelf: A Global Review*; Evans, A.M., Flatman, J.C., Flemming, N.C., Eds.; Springer: New York, NY, USA, 2014; pp. 1–12.
12. Flemming, N.C.; Harff, J.; Moura, D. Non-cultural processes of site formation, preservation and destruction. In *Submerged Landscapes of the European Continental Shelf: Quaternary Paleoenvironments*; Flemming, N.C., Harff, J., Moura, D., Burgess, A., Bailey, G.N., Eds.; Wiley Blackwell: Hoboken, NJ, USA; Sussex, UK, 2017; pp. 51–82.
13. Flemming, N.C.; Harff, J.; Moura, D.; Burgess, A.; Bailey, G.N. Introduction: Prehistoric remains on the continental shelf—Why do sites and landscapes survive inundation? In *Submerged Landscapes of the European Continental Shelf Quaternary Paleoenvironments*; Flemming, N.C., Harff, J., Moura, D., Burgess, A., Bailey, G.N., Eds.; Wiley and Sons: London, UK, 2017; pp. 1–10.
14. Kimura, M. Ancient megalithic construction beneath the sea off Ryukyu islands in Japan, submerged by post glacial sea-level change. In *Proceedings of the Oceans’ 04 MTS/IEEE Techno-Ocean’04* (IEEE Cat. No. 04CH37600), Kobe, Japan, 9–12 November 2004; Volume 2, pp. 947–953.
15. Hancock, G. *Underworld: The Mysterious Origins of Civilization*; Crown: Chichester, UK, 2009; pp. 595–625.
16. Benjamin, J.; Hale, A. Marine, maritime, or submerged prehistory? Contextualizing the prehistoric underwater archaeologies of inland, coastal, and offshore environments. *Eur. J. Archaeol.* **2012**, *15*, 237–256. [CrossRef]
17. Galili, E. Prehistoric archaeology on the Continental Shelf: A global review. *J. Isl. Coast. Archaeol.* **2017**, *12*, 147–149. [CrossRef]
18. Missiaent, T.; Sakellariou, D.; Flemming, N.C. Survey strategies and techniques in underwater geoarchaeology research: An overview with emphasis on prehistoric sites. In *Under the Sea: Archaeology and Paleolandscapes of the Continental Shelf*; Bailey, G.N., Harff, J., Sakellariou, D., Eds.; Springer: Cham, Switzerland, 2017; pp. 21–37.
19. Galili, E.; Horwitz, L.K.; Rosen, B. The “Israeli Model” for the detection, excavation and research of submerged prehistory. *TINA-Marit. Archaeol. Period.* **2019**, *10*, 31–69.
20. Grøn, O.; Jørgensen, A.N.; Hoffmann, G. Marine Archaeological Survey by High-Resolution SBPs. *Nor. Sjøfar. Arbok* **2007**, 115–144.
21. Grøn, O.; Boldreel, L.O.; Boumda, R.T.; Blondel, P.; Madsen, B.; Nørmark, E.; Cvikel, D.; Galili, E.; Dell’Anno, A. Acoustic Detection and Mapping of Submerged Stone Age Sites with Knapped Flint. In *The Handbook of Cultural Heritage Analysis*; D’Amico, S., Venuti, V., Eds.; Springer: Berlin/Heidelberg, Germany, 2002; pp. 901–933.
22. Emery, K.O.; Edwards, R.L. Archaeological potential of the Atlantic continental shelf. *Am. Antiq.* **1966**, *31 Pt 1*, 733–737. [CrossRef]

23. Oakley, K.P. Note on the Late Post-Glacial Submergence of the Solent Margins. In *Proceedings of the Prehistoric Society*; Cambridge University Press: Cambridge, UK, 1943; Volume 9, pp. 56–59.
24. Steers, J.A. *The Coastline of England and Wales*; Cambridge University Press: Cambridge, UK, 1948.
25. Flemming, N.C. Survival of submerged Lithic and Bronze Age artifact sites: A review of case histories. In *Quaternary Coastlines and Marine Archaeology*; Master, P.M., Flemming, N.C., Eds.; Academic Press: London, UK, 1983; pp. 135–173.
26. Flemming, N.C. Preface. In *Prehistoric Archaeology on the Continental Shelf. A Global Review*; Evans, A.M., Flatman, J.C., Flemming, N.C., Eds.; Springer: New York, NY, USA, 2014; pp. I–IV.
27. Ronen, A.; Raban, A. Underwater State-Wide Survey. *Bimtzulot Yam* **1965**, 5, 3–4. (In Hebrew)
28. Raban, A. Submerged prehistoric sites on the Mediterranean coast of Israel. In *Quaternary Coastlines and Marine Archaeology*; Masters, P.M., Flemming, N.C., Eds.; Academic Press: Cambridge, MA, USA, 1983; pp. 215–232.
29. Wreschner, E.E. Neve Yam—A submerged late-Neolithic settlement near Mount Carmel. *Eretz-Israel* **1977**, 13, 260–271.
30. Wreschner, E.E. The submerged Neolithic village Neve Yam on the Israeli Mediterranean coast. In *Quaternary Coastlines and Marine Archaeology*; Master, P.M., Flemming, N.C., Eds.; Academic Press: London, UK, 1983; pp. 325–333.
31. Galili, E.; Weinstein-Evron, M.; HersHKovitz, I.; Gopher, A.; Kislev, M.; Lernau, O.; Lernaut, H. Atlit-Yam: A prehistoric site on the sea floor off the Israeli coast. *J. Field Archaeol.* **1993**, 20, 133–157. [CrossRef]
32. Galili, E.; Horwitz, L.K. Submerged prehistory in Israel: A relatively new discipline. *Strat. J. Anglo-Isr. Archaeol. Soc.* in press.
33. Faught, M.K.; Donoghue, J.F. Marine inundated archaeological sites and paleofluvial systems: Examples from a karst-controlled continental shelf setting in Apalachee Bay, northeastern Gulf of Mexico. *Geoarchaeology* **1997**, 12, 417–458. [CrossRef]
34. Pearson, C.E.; Weinstein, R.A.; Sherwood, M.G.; Kelley, D.B. Prehistoric Site Discover on the Outer Continental Shelf, Gulf of Mexico, United States of America. In *Prehistoric Archaeology on the Continental Shelf. A Global Review*; Evans, A.M., Flatman, J.C., Flemming, N.C., Eds.; Springer: New York, NY, USA, 2014; pp. 53–72.
35. Fisher, A. (Ed.) An entrance to the Mesolithic world below the ocean. Status of ten years' work on the Danish Sea floor. In *Man and Sea in the Mesolithic*; Oxbow Press: London, UK, 1995; pp. 371–384.
36. Fischer, A. *Man and the Sea in the Mesolithic: Coastal Settlement Above and Beyond Present Sea Level*, Oxbow Monographs in Archaeology; Oxbow Books: Oxford, UK, 1995.
37. Fischer, A. Drowned forests from the Stone Age. In *The Danish Storebaelt Since the Ice Age: Man, Sea and Forest*; Pedersen, L., Fischer, A., Aaby, B., Eds.; Danish National Museum: Copenhagen, Denmark, 1997.
38. Gagliano, S.M.; Pearson, C.E.; Wiseman, D.E.; McClendo, C.M. *Sedimentary Studies of Prehistoric Archaeological Sites: Criteria for the Identification of Submerged Archaeological Sites of the North Gulf of Mexico, Continental Shelf*; Prepared for the U.S. Department of the Interior; National Park Service, Division of the State Plans and Grants: Washington, DC, USA, 1982; Volume 3500379.
39. Murphy, E.L. 8SL17: *Natural Site-Formation Processes of a Multiple-Component Underwater Site in Florida—Submerged Cultural Resources*; Special Report; National Park Service: Santa Fe, NM, USA, 1990; pp. 29–36.
40. Smith, O.; Momber, G.; Bates, R.; Garwood, P.; Fitch, S.; Pallen, M.; Gaffney, V.; Allaby, R.G. Sedimentary DNA from a submerged site reveals wheat in the British Isles 8000 years ago. *Science* **2015**, 347, 998–1001. [CrossRef]
41. Skriver, C.; Borup, P.; Astrup, P.M. Hjarnø Sund: an eroding Mesolithic site and the tale of two paddles. In *Under the Sea: Archaeology and Paleolandscapes of the Continental Shelf*; Bailey, G.N., Harff, J., Sakellariou, D., Eds.; Springer: Cham, Switzerland, 2017; pp. 131–143.
42. Galili, E.; Rosen, B.; Evron, M.W.; HersHKovitz, I.; Eshed, V.; Horwitz, L.K. Israel: Submerged prehistoric sites and settlements on the Mediterranean coastline—The current state of the art. In *The Archaeology of Europe's Drowned Landscapes*; Bailey, G., Galanidou, N., Peeters, H., Jöhns, H., Mennenga, M., Eds.; Springer: Cham, Switzerland, 2020; pp. 443–481.
43. Bav'on, M.C.; Politis, G.G. The intertidal zone site of La Olla: early middle Holocene human adaptation on the Pampean coast of Argentina. In *Prehistoric Archaeology on the Continental Shelf. A Global Review*; Evans, A.M., Flatman, J.C., Flemming, N.C., Eds.; Springer: New York, NY, USA, 2014; pp. 115–130.
44. Marcus, L.F.; Newman, W.S. Hominid migrations and the eustatic sea level paradigm: A critique. In *Quaternary Coastlines and Marine Towards the Prehistory of Land Bridges and Continental Shelves*; Master, P.M., Flemming, N.C., Eds.; Academic Press: London, UK, 1983; pp. 63–85.
45. Faught, M.K. Remote sensing, target identification and testing for submerged prehistoric sites in Florida: Process and protocol in underwater CRM projects. In *Prehistoric Archaeology on the Continental Shelf: A Global Review*; Evans, A.M., Flatman, J.C., Flemming, N.C., Eds.; Springer: New York, NY, USA, 2014; pp. 37–52.
46. Jöns, H.; Harff, J. Geoarchaeological research strategies in the Baltic Sea area: Environmental changes, shoreline-displacement and settlement strategies. In *Prehistoric Archaeology on the Continental Shelf: A Global Review*; Evans, A.M., Flatman, J.C., Flemming, N.C., Eds.; Springer: New York, NY, USA, 2014; pp. 173–192.
47. Tizzard, L.; Bicket, A.R.; Benjamin, J.; DE Loecker, D. A Middle Palaeolithic site in the southern North Sea: investigating the archaeology and palaeogeography of Area 240. *J. Quat. Sci.* **2014**, 29, 698–710. [CrossRef]
48. Benjamin, J.; O'leary, M.; McDonald, J.; Wiseman, C.; McCarthy, J.; Beckett, E.; Morrison, P.; Stankiewicz, F.; Leach, J.; Hacker, J.; et al. Correction: Aboriginal artefacts on the continental shelf reveal ancient drowned cultural landscapes in northwest Australia. *PLoS ONE* **2023**, 18, e0287490. [CrossRef]
49. Ogloblin Ramirez, I.; Galili, E.; Shahack-Gross, R. Locating submerged prehistoric settlements: a new underwater survey method using water-jet coring and micro-geoarchaeological techniques. *J. Archaeol. Sci.* **2021**, 135, 105480. [CrossRef]

50. Fisher, A. Stone Age on the Continental Shelf: an eroding resource. In *Submerged Prehistory*; Benjamin, J., Bonsall, C., Pickard, C., Fisher, A., Eds.; Oxbow Book: Oxford, UK, 2011; pp. 298–310.
51. Flemming, N.C. Research infrastructure for systematic study of prehistoric archaeology of the European submerged continental shelf. In *Submerged Prehistory*; Benjamin, J., Bonsall, C., Pickard, C., Fisher, A., Eds.; Oxbow Books: Oxford, UK, 2011; pp. 287–297.
52. Gusick, A.E.; Faught, M.K. Prehistoric archaeology underwater: A nascent subdiscipline critical to understanding early coastal occupations and migration routes. In *Trekking the Shore: Changing Coastlines and Antiquity of Coastal Settlements*; Bicho, N.F., Haws, J.A., Davis, L.G., Eds.; Springer: New York, NY, USA, 2011; pp. 22–50.
53. Orsi, P. *Pantelleria, Risultati di Una Missione Archeologica*; Reprinted from Orsi, P. 1899, Pantelleria. Monumenti Antichi dei Lincei IX; Tipografia della R. Accademia dei Lincei: Palermo, Italy, 1991; pp. 449–540.
54. Tusa, S. Archeologia e storia di un'isola nel Mediterraneo. In *Pantellerian Ware. Archeologia Subacquea e Ceramiche da Fuoco a Pantelleria, Santoro Bianchi*; Santoro Bianchi, G., Tusa, S., Eds.; Flaccovio Editore: Palermo, Italy, 2003; pp. 15–24.
55. Mantellini, S. The implications of water storage for human settlement in Mediterranean waterless islands: The example of Pantelleria. *Environ. Archaeol.* **2015**, *20*, 406–424. [CrossRef]
56. Civile, D.; Lodolo, E.; Zecchin, M.; Ben-Avraham, Z.; Baradello, L.; Accettella, D.; Cova, A.; Caffau, M. The lost Adventure Archipelago (Sicilian Channel, Mediterranean Sea): Morpho-bathymetry and Late Quaternary palaeogeographic evolution. *Glob. Planet. Chang.* **2015**, *125*, 36–47. [CrossRef]
57. Ferranti, L.; Antonioli, F.; Mauz, B.; Amorosi, A.; Dai Pra, G.; Mastronuzzi, G.; Monaco, C.; Orrù, P.; Pappalardo, M.; Radtke, U.; et al. Markers of the last interglacial sea level highstand along the coast of Italy: tectonic implications. *Quat. Int.* **2006**, *145*, 30–54. [CrossRef]
58. Serpelloni, E.; Anzidei, M.; Baldi, P.; Casula, G.; Galvani, A. Crustal velocity and strain-rate fields in Italy and surrounding regions: new results from the analysis of permanent and non-permanent GPS networks. *Geophys. J. Int.* **2005**, *161*, 861–880. [CrossRef]
59. Lodolo, E.; Nannini, P.; Baradello, L.; Ben-Avraham, Z. Two enigmatic ridges in the Pantelleria Vecchia Bank (NW Sicilian Channel). *Heliyon* **2023**, *9*, e14575. [CrossRef]
60. Lodolo, E.; Ben-Avraham, Z. A submerged monolith in the Sicilian Channel (central Mediterranean Sea): Evidence for Mesolithic human activity. *J. Archaeol. Sci. Rep.* **2015**, *3*, 398–407. [CrossRef]
61. Lodolo, E.; Baradello, L.; Ben-Avraham, Z. Exploring the nature of the concentric half-rings in the Pantelleria Vecchia Bank (Sicilian Channel). *Soc. Sci. Humanit. Open* **2024**, *9*, 100892. [CrossRef]
62. Tusa, S. Il popolamento di Pantelleria e Lampedusa dalle prime frequentazioni neolitiche al villaggio di Mursia. *Sci. Dell'antichità* **2016**, *22*, 363–385.
63. Ratti, D. *La Preistoria di Lampedusa*; Archivio Storico Lampedusa: Rome, Italy, 2015.
64. Surico, G. *Lampedusa: Dall'Agricoltura, alla Pesca, al Turismo*; Firenze University Press: Florence, Italy, 2020.
65. Ratti, D. Prehistoric village of Tabaccara coast. "Lampedusa: possible underwater prehistoric cult area". *Quad. Dell'associazione Cult. Arch. Stor. Lampedusa* **2014**, *5*, 1–23.
66. Ratti, D. Associazione Culturale Archivio Storico Lampedusa—August 2016. Lampedusa: Possible Underwater Prehistoric Place of Worship. Available online: <https://atlantipedia.ie/samples/tag/lampedusa/> (accessed on 4 October 2024).
67. Grasso, M.; Pedley, H.M. The Pelagian Islands: A new geological interpretation from sedimentological and tectonic studies and its bearing on the evolution of the Central Mediterranean Sea (Pelagian Block). *Geol. Romana* **1985**, *24*, 13–34.
68. Galili, E.; Ogloblin-Ramirez, I. Lampedusa Surveys. 2019; *Unpublished work*.
69. Ratti, D. Lampedusa Preistorica. Available online: https://www.academia.edu/92709656/Lampedusa_preistorica?auto=download (accessed on 4 October 2024).
70. Tusa, S.; Antonioli, F.; Anzidei, M. Il Monolite Sommerso a Pantelleria? E' Una Bufala. Ecco Perché. 2015. Available online: <https://www.tp24.it/2015/09/05/cultura/il-monolite-sommerso-a-pantelleria-e--una-bufala-ecco-perche/94020> (accessed on 4 October 2024).
71. Hassan, A.; Barber, S.J. The effects of repetition frequency on the illusory truth effect. *Cogn. Res. Princ. Implic.* **2021**, *6*, 1–12. [CrossRef] [PubMed]
72. Siddall, M.; Rohling, E.J.; Thompson, W.G.; Waelbroeck, C. Marine isotope stage 3 sea level fluctuations: Data synthesis and new outlook. *Rev. Geophys.* **2008**, *46*, 2007RG000226. [CrossRef]
73. Waelbroeck, C.; Labeyrie, L.; Michel, E.; Duplessy, J.C.; McManus, J.F.; Lambeck, K.; Balbon, E.; Labracherie, M. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. *Quat. Sci. Rev.* **2002**, *21*, 295–305. [CrossRef]
74. Lodolo, E.; Renzulli, A.; Cerrano, C.; Calcinai, B.; Civile, D.; Quarta, G.; Calcagnile, L. Unraveling past submarine eruptions by Dating Lapilli Tuff-Encrusting Coralligenous (Actea Volcano, NW Sicilian Channel). *Front. Earth Sci.* **2021**, *9*, 664591. [CrossRef]
75. Siddall, M.; Chappell, J.; Potter, E.K. Eustatic sea level during past interglacials. *Dev. Quat. Sci.* **2007**, *7*, 75–92.
76. Brooke, B.P.; Nichol, S.L.; Huang, Z.; Beaman, R.J. Palaeoshorelines on the Australian continental shelf: Morphology, sea-level relationship and applications to environmental management and archaeology. *Cont. Shelf Res.* **2017**, *134*, 26–38. [CrossRef]
77. Karkani, A.; Evelpidou, N.; Vacchi, M.; Morhange, C.; Tsukamoto, S.; Frechen, M.; Maroukian, H. Tracking shoreline evolution in central Cyclades (Greece) using beachrocks. *Mar. Geol.* **2017**, *388*, 25–37. [CrossRef]

78. Deiana, G.; Lecca, L.; Melis, R.T.; Soldati, M.; Demurtas, V.; Orrù, P.E. Submarine Geomorphology of the Southwestern Sardinian Continental Shelf (Mediterranean Sea): Insights into the Last Glacial Maximum Sea-Level Changes and Related Environments. *Water* **2021**, *13*, 155. [CrossRef]
79. Bar, A.; Bookman, R.; Galili, E.; Zviely, D. Beachrock omrphology along the Mediterranean coast of Israel: Typological Classification of Erosion Features. *J. Mar. Sci. Eng.* **2022**, *10*, 1571. [CrossRef]
80. Miller, W.R.; Mason, T.R. Erosional features of coastal beachrock and aeolianite outcrops in Natal and Zululand, South Africa. *J. Coast. Res.* **1994**, *10*, 374–394.
81. Shinn, E.A. The mystique of beachrock. *Int. Assoc. Sedimentol. Spec. Publ.* **2009**, *41*, 19–28.
82. Shah-Hosseini, M.; Morhange, C.; Beni, A.N.; Marriner, N.; Lahijani, H.; Hamzeh, M.; Sabatier, F. Coastal boulders as evidence for high-energy waves on the Iranian coast of Makran. *Mar. Geol.* **2011**, *290*, 17–28. [CrossRef]
83. Morhange, C.; Salamon, A.; Bony, G.; Flaux, C.; Galili, E.; Goiran, J.-P.; Zviely, D. Geoarchaeology of tsunamis and the revival of neo-catastrophism in the Eastern Mediterranean. In *Overcoming Catastrophes-Essays on Disastrous Agents Characterization and Resilience Strategies in Pre-Classical Southern Levant*; Nigro, L., Ed.; La Sapienza: Rome, Italy, 2014; pp. 61–81.
84. Marriner, N.; Kaniewski, D.; Morhange, C.; Flaux, C.; Giaime, M.; Vacchi, M.; Goff, J. Tsunamis in the geological record: Making waves with a cautionary tale from the Mediterranean. *Sci. Adv.* **2017**, *3*, e1700485. [CrossRef] [PubMed]
85. Corradino, M.; Faraci, C.; Monaco, C.; Pepe, F. Coastal boulder production controlled by columnar joints of ignimbrite and extreme waves: insights from the high-energy coast of Pantelleria Island (Sicily Channel, Mediterranean Sea). *Nat. Hazards* **2024**, 1–35. [CrossRef]
86. Abbott, A.T.; Pottratz, S.W. Marine pothole erosion, Oahu, Hawaii. *Pac Sci* **1969**, *23*, 276–290.
87. Erginal, A.E.; Kiyak, N.G.; Ekinici, Y.L.; Demirci, A.; Ertek, A.; Canel, T. Age, composition and paleoenvironmental significance of a Late Pleistocene eolianite from the western Black Sea coast of Turkey. *Quat. Int.* **2013**, *296*, 168–175. [CrossRef]
88. Lambeck, K.; Antonioli, F.; Purcell, A.; Silenzi, S. Sea-level change along the Italian coast for the past 10,000yr. *Quat. Sci. Rev.* **2004**, *23*, 1567–1598. [CrossRef]
89. Lodolo, E.; Galassi, G.; Spada, G.; Zecchin, M.; Civile, D.; Bressoux, M. Post-LGM coastline evolution of the NW Sicilian Channel: Comparing high-resolution geophysical data with Glacial Isostatic Adjustment modeling. *PLoS ONE* **2020**, *15*, e0228087. [CrossRef]
90. Bailey, G.N.; Harff, J.; Sakellariou, D. *Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf*; Springer: Cham, Switzerland, 2017; Volume 20.
91. Abelli, L.; Agosto, M.V.; Casalbone, D.; Romagnoli, C.; Bosman, A.; Antonioli, F.; Chiocci, F.L. Marine geological and archaeological evidence of a possible pre-Neolithic site in Pantelleria Island, Central Mediterranean Sea. *Geol. Soc. Lond. Spec. Publ.* **2016**, *411*, 97–110. [CrossRef]
92. Vella, C. Emerging aspects of interaction between prehistoric Sicily and Malta from the perspective of lithic tools. In *Malta in the Hybleans, the Hybleans in Malta/Malta negli Iblei, gli Iblei a Malta*; Bonanno, A., Militello, P., Eds.; Officina di Studi Medievali: Palermo, Italy, 2008; pp. 81–93, 321–326.
93. Evans, J.D. *The Prehistoric Antiquities of the Maltese Islands: A Survey*; The Athlone Press: University of London: London, UK, 1971.
94. Trump, D. *Skorba: Excavations Carried out on Behalf of the National Museum of Malta*; Society of Antiquaries of London: London, UK, 1966; pp. 1961–1963.
95. Trump, D.H.; Cilia, D. *Malta, Prehistory and Temples*; Midsea Books Ltd.: Santa Venera, Malta, 2002.
96. Bonanno, A. Insularity and isolation: Malta and Sicily in prehistory. In *Malta in the Hybleans, the Hybleans in Malta/Malta negli Iblei, gli Iblei a Malta*; Bonanno, A., Militello, P., Eds.; Officina di Studi Medievali: Palermo, Italy, 2008; pp. 27–37.
97. Procelli, E. Aspetti religiosi e apporti trasmarini nella cultura di Castelluccio. *J. Mediterr. Stud.* **1991**, *1*, 252–266.
98. Veca, C. Le tombe a camera dolmenica e la trasmissione di modelli funerari tra Malta e Sicilia durante il Bronzo. *Riv. Sci. Preist.* **2020**, *LXX* (Suppl. S1), 531–537.
99. Piccolo, S. *Ancient Stones: The Dolmen Culture in Prehistoric South-Eastern Sicily*; Brazen Head Publishing: Thornham, UK, 2013; pp. 9–28.
100. Antonioli, F.; Ferranti, L.; Fontana, A.; Amorosi, A.; Bondesan, A.; Braitenberg, C.; Dutton, A.; Fontolan, G.; Furlani, S.; Lambeck, K.; et al. Holocene relative sea-level changes and vertical movements along the Italian and Istrian coastlines. *Quat. Int.* **2009**, *206*, 102–133. [CrossRef]
101. Galili, E.; Zviely, D.; Ronen, A.; Mienis, H.K. Beach deposits of MIS 5e high sea stand as indicators for tectonic stability of the Carmel coastal plain, Israel. *Quat. Sci. Rev.* **2007**, *26*, 2544–2557. [CrossRef]
102. Galili, E.; Sevketoğlu, M.; Salamon, A.; Zviely, D.; Mienis, H.K.; Rosen, B.; Moshkovitz, S. Late Quaternary morphology, beach deposits, sea-level changes and uplift along the coast of Cyprus and its possible implications on the early colonists. In *Geology and Archaeology: Submerged Landscapes of the Continental Shelf*; Harff, J., Bailey, G., Lüth, F., Eds.; Special Publications: London, UK, 2016; Volume 411.
103. Galili, E.; Ronen, A.; Mienis, H.K.; Horwitz, L.K. Beach deposits containing Middle Paleolithic archaeological remains from northern Israel. *Quat. Int.* **2018**, *464*, 43–57. [CrossRef]
104. Dabrio, C.; Zazo, C.; Cabero, A.; Goy, J.; Bardají, T.; Hillaire-Marcel, C.; González-Delgado, J.; Lario, J.; Silva, P.; Borja, F.; et al. Millennial/submillennial-scale sea-level fluctuations in western Mediterranean during the second highstand of MIS 5e. *Quat. Sci. Rev.* **2011**, *30*, 335–346. [CrossRef]

105. Mauz, B.; Vacchi, M.; Green, A.; Hoffmann, G.; Cooper, A. Beachrock: A tool for reconstructing relative sea level in the far-field. *Mar. Geol.* **2015**, *362*, 1–16. [CrossRef]
106. Segre, A.G. Biogeografia delle Isole Pelagie. *Geologia. Rend. Accad. Naz. Dei XL* **1960**, *XI*, 115–162.
107. Lambeck, K.; Antonioli, F.; Anzidei, M.; Ferranti, L.; Leoni, G.; Scicchitano, G.; Silenzi, S. Sea level change along the Italian coast during the Holocene and projections for the future. *Quat. Int.* **2011**, *232*, 250–257. [CrossRef]
108. Galili, E.; Sharvit, J. Ancient coastal installations and the tectonic stability of the Israeli coast in historical times. *Geol. Soc. Lond. Spec. Publ.* **1999**, *146*, 147–163. [CrossRef]
109. Galili, E.; Sharvit, J. Haifa, Tel Shiqmona—Underwater and Coastal Survey. *Hadashot Arkheologiyot: Excav. Surv. Isr.* **2000**, *112*, 117.
110. Galili, E.; Sivan, D. Introduction, Shikmona site—Physical conditions and ancient maritime activity. *Tel Shikmona*, Gilboa, A., Ed.; 2024, *in press*.
111. Galili, E.; Zviely, D. Geo-archaeological markers reveal magnitude and rates of Israeli coastal cliff erosion and retreat. *J. Coast. Conserv.* **2018**, *23*, 747–758. [CrossRef]
112. Luo, E.C.-R. Formation of Beach Profile with the Design Criteria of Seawalls. *Civ. Eng. Arch.* **2014**, *2*, 24–32. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

Article

Edge Computing Architecture for the Management of Underwater Cultural Heritage

Jorge Herrera-Santos ^{1,*}, Marta Plaza-Hernández ¹, Sebastián López-Florez ¹, Vladimir Djapic ^{2,3},
Javier Prieto Tejedor ¹ and Emilio Santiago Corchado-Rodríguez ¹

¹ BISITE Research Group, Edificio Multiusos I+D+i, University of Salamanca, 37007 Salamanca, Spain; martaplaza@usal.es (M.P.-H.); sebastianlopezflorez@usal.es (S.L.-F.); javierp@usal.es (J.P.T.); escorchado@usal.es (E.S.C.-R.)

² H2O Robotics Ltd., Unska 3, 10000 Zagreb, Croatia; vladimir@h2o-robotics.com

³ Institute for Artificial Intelligence Research and Development, 21000 Novi Sad, Serbia

* Correspondence: jorgehsm@usal.es

Abstract: Underwater cultural heritage (UCH) is a valuable resource that preserves humanity's historical legacy, offering insights into traditions and civilisations. Despite its significance, UCH faces threats from inadequate regulatory frameworks, insufficient conservation technologies, and climate-induced environmental changes. This paper proposes an innovative platform combining the internet of underwater things and edge computing technologies to enhance UCH's real-time monitoring, localisation, and management. The platform processes data through a central unit installed on a buoy near heritage sites, enabling efficient data analysis and decision making without relying on cloud connectivity. Integrating acoustic communication systems, LoRa technology, and nonterrestrial networks supports a robust multilayered communication infrastructure for continuous operation, even in remote maritime areas. The platform's edge node deploys artificial intelligence models for real-time risk assessment, focusing on key environmental parameters to predict and mitigate corrosion rates and climate-related threats. A case study illustrates the system's capabilities in underwater localisation, demonstrating how edge computing and acoustic triangulation techniques enable precise tracking.

Keywords: underwater cultural heritage; edge computing; internet of underwater things; underwater location; generative AI

1. Introduction

Underwater cultural heritage (UCH) is an invaluable resource that encapsulates humanity's past, providing a tangible link to traditions and customs. Although it is underappreciated, UCH holds immense potential for socioeconomic and tourism development, serving as a knowledge source that can positively impact tourism chains and flows. With the ocean floor teeming with artifacts, ruins, wrecks, and remains of historical or archaeological significance, UCH acts as a storehouse of human civilisation.

Uncoordinated regulatory policies, the lack of adequate protection measures, the lack of suitable underwater techniques and materials, and insufficient adaptation to climate-related stressors and environmental degradation still pose significant threats to UCH. Therefore, strengthening its conservation is crucial. The 2001 UNESCO Convention on the Protection of Underwater Cultural Heritage [1] was a significant milestone in preserving UCH. Providing a detailed framework for states to cooperate, the Convention sets guidelines highlighting the need for in situ preservation, training, data sharing, and international cooperation.

The conservation challenge lies in its intrinsic demand for customisation. Each site or artifact presents unique characteristics, vulnerabilities, ecological or historical contexts, and risk factors. Consequently, a successful conservation strategy never involves just a

single approach but is rather a finely tuned ensemble of diverse methodologies. This complexity spawns distinct interdisciplinary research avenues, requiring collaboration among experts from diverse but intrinsically linked fields such as archaeology, geology, biology, oceanography, and the technology-oriented domains of engineering, marine sciences, as well as advanced technologies such as artificial intelligence (AI), robotics, and the internet of underwater things (IoUT). Projects like TECTONIC [2] (Technological Consortium to Develop Sustainability of Underwater Cultural Heritage) leverage this holistic approach, capitalising on cross-disciplinary synergies to engineer sophisticated tools, methodologies, and AI-based models for the sustainable management of UCH.

This work proposes an innovative platform combining IoUT and edge computing to enhance the monitoring, localisation, and management of UCH. The platform's architecture is designed to centralise data processing through a central unit deployed on ocean buoys located near the sensor networks and heritage sites. This allows for real-time event detection, classification, and responses without relying on cloud connectivity. Keeping most processing and decision making at the network edge dramatically improves system responsiveness. It ensures the continuous monitoring and protection of sites even during intermittent cloud connectivity. The edge nodes can still cache, analyse, and act on critical data until the cloud is reachable. This makes the overall system more reliable and robust to network failures or delays. Edge computing also reduces infrastructure costs and other costs associated with high-bandwidth undersea networks and cloud storage. By transmitting only processed metadata rather than raw sensor data to the cloud, it minimises network throughput requirements and data storage needs.

These nodes are equipped with acoustic communication technologies to receive data from sensors strategically located across the underwater site and from other elements such as divers or remotely operated vehicles (ROVs) as well as to measure the distance between them. These technologies, combined with edge computing, enable the triangulation and precise determination of the position of underwater assets. This integration allows for effective real-time monitoring and intervention, addressing the limitations of traditional GPS systems, which are ineffective underwater due to signal attenuation.

Long-range (LoRa) technology facilitates long-range communication between the edge nodes, enabling efficient and low-power data transmission from submerged environments. This is further complemented by nonterrestrial networks (NTNs), including satellite constellations, extending connectivity to remote and hard-to-access maritime areas. By integrating these technologies, the platform supports a resilient, multilayered communication and localisation system that ensures continuous operation, even during intermittent cloud connectivity. This approach not only improves the accuracy and reliability of underwater localisation but also enhances overall system responsiveness, making it ideal for real-time conservation efforts.

The proposed platform leverages AI models at the edge to provide real-time risk assessments based on data from public databases and in situ sensor measurements. This allows for the dynamic prioritisation of conservation efforts, making it possible to anticipate and mitigate the risks associated with environmental factors, such as sediment displacement and rising sea temperatures.

UCH-related platforms have been identified in the literature [3–7]. However, to the best of our knowledge, none integrate the edge computing paradigm. This type of architecture leverages distributed processing and storage capabilities to capture, analyse, and monitor large amounts of multimodal sensor data in real time. This helps address the current limitations in centralised cloud-based solutions by performing initial data filtering, processing, and analysis close to the data source using edge nodes [8]. While edge computing introduces security and management challenges due to increased network nodes, it also enhances privacy and security [9].

Overall, the platform not only addresses the current limitations in underwater heritage conservation but also provides a scalable and adaptable foundation for integrating

future technological advancements, ensuring the long-term protection and management of UCH sites.

This paper is organised as follows: Section 2 reviews the existing IoUT solutions applied to UCH conservation, identifying current gaps and challenges. Section 3 details the edge computing platform's architecture, layers, and components, explaining their interaction within the proposed system. Section 4 presents a case study focused on the underwater localisation system, demonstrating how the platform's acoustic communication could facilitate precise real-time tracking and monitoring of submerged heritage assets. Section 5 concludes this paper and outlines future work.

2. Related Work

The effects of climate change on UCH are increasingly concerning for researchers and policymakers alike [10,11]. Rising sea temperatures, ocean acidification, and changes in sea currents directly affect the structural integrity of submerged cultural assets [12]. Studies have shown that warmer water accelerates the corrosion of the metals found in shipwrecks, and acidification increases the degradation rate of organic materials such as wood and textiles [13]. The rising sea level could directly impact not only coastal but also underwater heritage. Some land-based sites will flood. Additionally, the disruption of sediment layers due to the changing ocean currents and extreme weather events exposes previously buried artifacts to more aggressive environmental conditions, further accelerating their decay [14].

Usually, fieldwork in UCH conservation has long relied on direct human intervention, with experimented divers conducting surveys and site maintenance. However, these methods pose significant risks to both the divers and to the delicate nature of the heritage sites [15]. This shift has led to the adoption of technological systems in conservation efforts, allowing for detailed exploration and monitoring of UCH without physically disturbing the site.

Three-dimensional surveying and mapping techniques have proven to be essential tools for the surveillance and documentation of UCH. They primarily rely on optical and acoustic sensors to acquire detailed representations of the sites to be digitalised by using 3D reconstruction techniques [16,17]. Single-beam echo sounders are instrumental in constructing maps via profiling, while multibeam echo sounders expedite mapping extensive areas using fan-shaped beams. Side-scan sonar generates 2D images of the surface using two fan beams. Sub-bottom profilers can penetrate sediment to create images of subsurface structures [18].

ROVs are manually controlled in real time and tethered to a surface vessel with an umbilical cable. They are equipped with various sensors and are commonly used for UCH monitoring and documentation [19]. Autonomous surface vehicles (ASVs) are unmanned robotic platforms typically equipped with sensors and cameras for mapping and monitoring tasks [20]. In addition to these functions, ASVs can play a crucial role in enhancing diver safety by tracking their position in real time, monitoring environmental conditions, and providing immediate alerts or support during underwater operations [21,22]. Autonomous underwater vehicles (AUVs) are fully autonomous robots that perform missions without human intervention or surface vessels. They carry advanced sensors such as side-scan sonar and multibeam echo sounders, allowing for the high-resolution 3D mapping of UCH sites [23,24].

The conservation of submerged archaeological complexes requires innovative and sustainable solutions that not only preserve these sites in situ but also leverage the available data for informed decision making. As the availability of environmental and archaeological data increases, the challenge for conservationists is how to intelligently combine this information to generate actionable insights [25]. In this context, sensors have emerged as highly efficient and cost-effective instruments for detecting changes in the environment [26]. Deployed at critical underwater locations, these sensors provide continuous measurements of environmental variables such as temperature, pressure, salinity, and pH levels, all of which play a significant role in the stability and preservation of submerged artifacts. By

integrating these sensors into underwater communication networks, real-time measurements can be conducted, allowing for the precise assessments of risks and enhancing the response capabilities for addressing potential threats to the integrity of heritage sites. The information gathered through sensor networks not only aids in assessing the immediate conditions surrounding a site but also serves as a foundation for predictive models that forecast future threats due to climate change, sediment displacement, or human activity. By leveraging these technological advancements, the conservation of UCH becomes more proactive, ensuring that interventions are timely and precisely targeted, thus prolonging the lifespan of these invaluable underwater resources.

In this context, underwater localisation plays a crucial role in conservation operations, where accurately identifying and marking points of interest is not only vital for research and documentation but also essential for ensuring the safety and coordination of conservation teams [27]. Accurate underwater localisation has long been recognised as a challenging task. The limited propagation of radio waves underwater, which form the basis of most surface localisation systems, has driven the search for alternative solutions. Acoustic communication has emerged as the most promising option, taking advantage of sound waves' ability to travel effectively through water [28]. However, the development of precise and reliable acoustic technologies continues to be a complex task, particularly when balancing technical complexity and cost-effectiveness. In response to these challenges, devices like the low-cost, compact NMv3 modem have been introduced. This modem facilitates communication and distance measurement between transmitter and receiver using acoustic technology in underwater environments [29].

The advancement of acoustic communication has been crucial for developing underwater wireless communication networks (UWCNs). Despite its limitations, acoustic communication remains the most versatile and widely used physical layer technology for underwater communication. This technological foundation has enabled the rise of the IoUT, an extension of the internet of things (IoT) to the underwater environment [30]. The IoUT establishes a network of interconnected smart devices capable of exchanging data and performing real-time measurements, representing a significant leap forward in the monitoring and conservation of aquatic ecosystems and submerged heritage. By applying the IoUT in underwater heritage conservation projects, the possibilities for precise identification, detailed documentation, and adequate protection of historically and culturally significant sites are greatly expanded. The application of IoUT in UCH conservation opens new possibilities for site monitoring and management. However, one of the critical challenges in deploying such networks is optimising both energy consumption and security, particularly in harsh underwater environments which are prone to jamming. Ref. [31] demonstrates that through content caching and selective encryption, UWCNs can enhance both security and energy efficiency, making IoUT applications in UCH conservation even more viable. By creating a network of smart and secure interconnected devices, the IoUT allows for the continuous, real-time monitoring of underwater interest points [32]. These smart devices not only monitor environmental conditions but also interpret and respond to changes, enhancing the strategies for preserving and managing underwater cultural heritage.

Marine IoT systems face significant challenges in establishing reliable communication networks due to their deployment in remote areas, often far from terrestrial communication infrastructure. These locations lack the connectivity provided by traditional networks, making it difficult to transmit data in real time, which is crucial for monitoring and managing maritime points of interest. LoRa technology has been widely adopted in IoT applications due to its low power consumption and long-range capabilities, making it suitable for monitoring in remote maritime environments [33]. Although LoRa is recognised for its long-range communication capabilities, reaching distances of approximately 10 km in direct line of sight, many maritime points of interest are located far beyond this range [34]. The lack of repeaters and gateway stations to extend the coverage over such vast distances significantly limits its ability to connect remote IoT systems to the global internet. As a result, LoRa is not a viable option for establishing real-time, large-scale data transmission

from remote areas to cloud-based services or centralised networks. However, LoRa can still be effectively employed for localised communication between surface nodes within its operational range. In rural environments, where there are fewer obstacles, the range can be extended up to 35 km using the narrowband internet of things (NB-IoT) technology. The signal strength in open areas allows the NB-IoT to achieve greater coverage, making it well suited for remote or sparsely populated regions, such as ocean environments [35].

Significant advancements in satellite communication technologies have addressed this limitation in the past decade, particularly with low Earth orbit (LEO) satellites. Companies such as Telesat, OneWeb, SpaceX, and Amazon have developed LEO satellite constellations that offer near-global broadband coverage, significantly enhancing connectivity for remote IoT systems [36]. NTN, including satellites, drones, and high-altitude platforms, are emerging as robust solutions for integrating IoT networks with space–air–sea systems, enabling seamless data transfer and the real-time monitoring of maritime environments [37]. Integrating the IoT with NTN has proven to be particularly transformative in fields such as maritime surveillance, environmental monitoring, and disaster response, where real-time data from remote sensors are essential [38]. This convergence of the IoT and NTN is paving the way for more resilient and efficient marine IoT applications.

Web-based platforms provide a comprehensive solution for conserving UCH. These platforms enable centralised storage and remote access to large UCH datasets from any location. Field data, including images, videos, and environmental parameters, can be uploaded in real time to the cloud, allowing for seamless access and processing. Cloud technology also facilitates photogrammetry and 3D modelling, which can be performed remotely, eliminating the need for specialised hardware and software during field surveys. Notable examples in the literature showcase the effectiveness of these platforms. For instance, the Lab4Dive system [6] is an innovative product designed for surveying, documenting, and preserving UCH in the Mediterranean Sea. This system comprises an underwater tablet to assist divers, a docking station that acquires and exchanges data from various environmental sensors and a high-resolution camera, and a remote server hosting the cloud database and performing 3D reconstruction using photos captured during the survey. Another notable platform is VIRTUALDiver [7], which leverages virtual reality (VR) and augmented reality (AR) technologies to design and manage interactive tourism experiences. In the Republic of Mauritius, UCH data are uploaded to an online platform called the E-platform, which stores a wide range of information, including archaeological articles, legislation, reports, field data, and remote services [39]. The MACHU project utilises the MACHU GIS system [40] as its central online platform, which is a web-based application integrating essential information for managing UCH, such as heritage details, environmental data, legislation, and historical maps.

Innovative architectures, such as satellite edge computing, enhance data processing efficiency, enabling faster response times and reducing bandwidth usage through localised computing [41]. Edge computing significantly reduces latency by offloading resource-intensive tasks to nearby nodes, optimising resource use, and improving user experience. This approach is particularly relevant for latency-sensitive services, where real-time resource allocation and offloading algorithms are critical. The authors of [42] proposed a resource allocation model for edge computing networks to minimise total latency by combining content caching and task offloading to edge servers, effectively reducing execution time and improving the efficiency of limited resources. In another approach, a deep reinforcement learning method was implemented to address both the latency and fairness in computation offloading to edge servers, demonstrating superior performance in reducing service latency through an optimised reinforcement learning framework [43].

3. Conceptual Framework

This work proposes an innovative IoUT platform that leverages edge computing technologies for the real-time monitoring and management of UCH. By distributing computing resources and data storage closer to where data are generated through edge nodes,

this architecture addresses the issues of network congestion and delays that plague traditional cloud-centric approaches. The platform seamlessly integrates real-time sensor measures with historical data stored in databases, painting a comprehensive picture. Its modular design allows the various components, such as sensors, edge nodes, and cloud services, to operate independently and collaboratively with other systems. This interoperability is crucial as UCH sites often span large areas requiring coordination across different types of infrastructure.

The orchestration of the elements is conducted via the platform modules, utilising a layered architectural model. This design facilitates a phased approach to developing application and service control, encompassing three layers. The first of these, the sensor layer, integrates sensor and actuator hardware for data gathering and command execution. The second, known as the edge layer, consists of edge nodes that are accountable for data processing, storage, network, and additional infrastructure resources. The third, the application layer, incorporates a range of cloud services for data analysis and visualisation. Figure 1 illustrates the proposed edge computing platform.

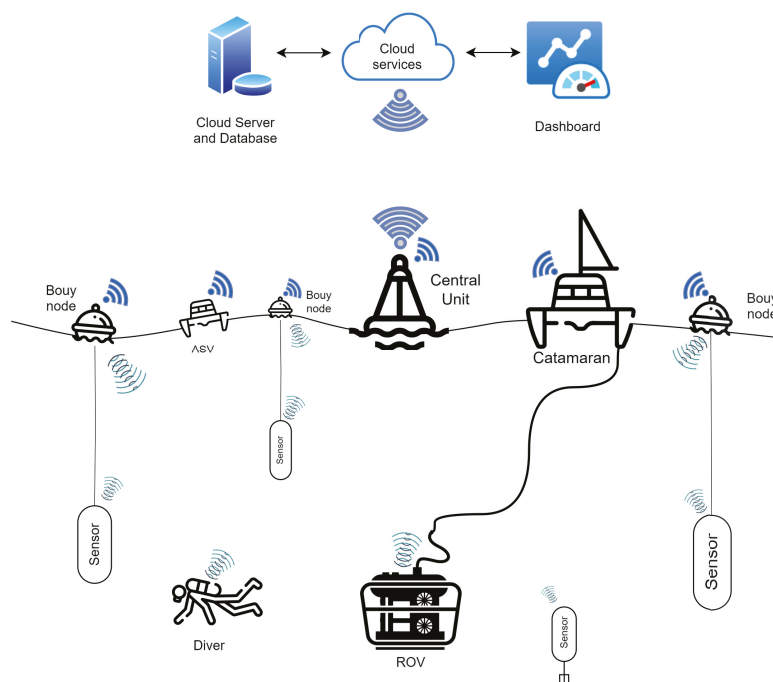


Figure 1. The suggested edge computing platform architecture demonstrates how real-time data that are processed in the edge rather than via the cloud can help improve management and safeguard underwater cultural heritage sites by minimising reliance on cloud connectivity.

Data collected from the sensor layer are instantly processed by the edge layer nodes, which execute the initial filtering and diagnostics of critical information. This allows the system to detect and identify relevant events or anomalies so that critical data are the only data sent to the application layer. These data include unprocessed data points, which are filtered for further processing, analysis, storage, and visualisation in the cloud-based application layer. This interaction between the different layers makes it possible for the platform to provide a high level of system performance without delay and to automatically send critical information to the cloud, ensuring the platform provides real-time alerts on crucial data information. Figure 2 illustrates the proposed system's communication architecture.

Below, the measuring systems and support elements are described. Some existing solutions have already been identified in the market. For example, we selected innovative and cutting-edge marine systems and technologies developed by H2O Robotics (H2O Robotics Ltd., Zagreb, Croatia) [44] and BlueRobotics (Blue Robotics Inc., Torrance, CA, USA) [45].

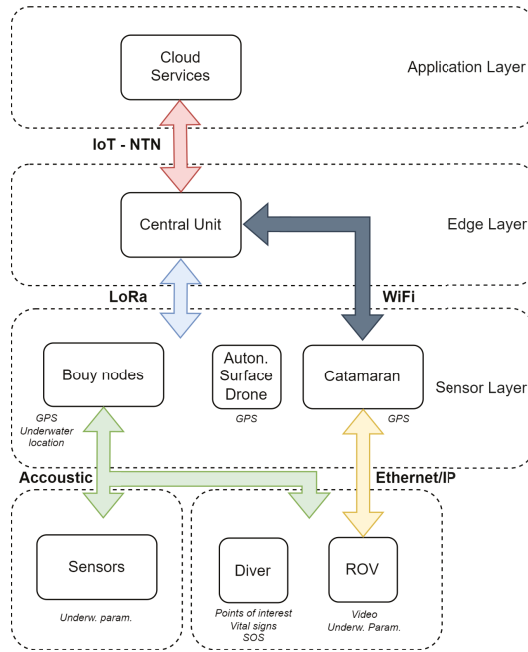


Figure 2. The system’s communication architecture enables a multilayered approach that improves data flow and real-time responses, crucial for the effective monitoring of remote underwater heritage sites.

3.1. Sensor Layer

The sensor layer is responsible for collecting data from the subsea environment through a network of sensors and actuators, strategically deployed throughout the UCH site. The sensors and elements can be categorised into continuous measurement systems and point support elements.

3.1.1. Continuous Measurement Systems

An underwater sensor network is deployed in the area of interest at different heights on the seabed. It records environmental parameters using acoustic communication technology to transmit the information to the surface, where a network of buoys receives the data. They are equipped with a battery system to provide the device with sufficient autonomy.

The node buoy network consists of a series of buoys deployed over the area of interest to act as a data gateway. They are responsible for receiving the data from both the sensor network and the support elements, such as the ROV or divers performing field inspections. By using acoustic transceivers, such as the H2Observe solution [46], that measure the time it takes for a pulse to travel from the transmitter to the receiver, each buoy can calculate the distance that separates it from the element with which it is communicating. In turn, the absolute position of the buoy is calculated by a GPS receiver built into the buoy. This device is responsible for redirecting the information received acoustically and transmitting it to a buoy that acts as a central unit using LoRa communication technology. It periodically sends data on its status (battery level, status of internal systems, etc.) and absolute position. It has a power supply system composed of batteries and solar panels to give the device total autonomy.

3.1.2. Point Support Elements

The point support elements include additional support systems that enhance data collection and site management:

ROVs with high-quality video imaging allow researchers to perform visual analysis. These devices transmit the information in cabled form to the control systems located on a catamaran. An acoustic transceiver allows for communication with the surface buoy

network, and, subsequently, the central unit calculates its absolute position. BlueROV2 [47] from BlueRobotics was selected as a high-performance ROV for underwater inspections.

A catamaran is used by researchers to travel to the point of study and control the ROV. Via LoRa communication, it also receives the processed data of the vehicle or diver's absolute position from the central buoy, allowing for the precise location of points of interest.

Divers play a crucial role in the conservation of archaeological sites. However, underwater inspections always involve risks, so it is crucial to always monitor the diver's condition. Using equipment that integrates acoustic transmitters, the diver can transmit relevant information, such as marking points of interest, SOS signals, sharing the position in real time, or monitoring vital signs. H2Orologio [48] is a solution that covers these requirements.

An ASV, such as the H2Orbit [49], warns, using acoustic or light signals, that divers are performing inspection work in the area. It receives the absolute position of the diver, which is processed and sent by the central unit. With the data of the diver's location and its own (obtained with GPS receivers), it calculates the route to position itself on the surface area where the work is being carried out. H2Observe can be attached to the AUV, underwater sensors, diver, or any other underwater asset, while H2Orbit provides connectivity.

3.2. Edge Layer

The edge layer consists of edge nodes, which have the functions of processing and storage of the data that have been collected from the sensor layer. These nodes are installed on ocean buoys and conveniently situated locations near UCH sites. Such nodes have processing power for filtering, preprocessing, and analysing data, which reduce transmission delay and network bandwidth utilisation.

The central unit (or de edge node) is a buoy that communicates via LoRa with the surface elements deployed in the area, such as node buoys, the catamaran, and the ASV. It incorporates equipment for data processing at the "edge" before being retransmitted to a cloud service. By processing information close to the source, the edge layer significantly reduces the need for high-bandwidth data transmission and improves the overall responsiveness of the system. Additionally, these nodes can cache critical data until cloud connectivity is restored, ensuring continuous monitoring even in remote areas. The processing of the received data allows the obtaining of the absolute position of the deployed underwater elements through triangulation algorithms, data preprocessing and filtering, anomaly identification, surface drone guidance, and so many more. Combined with autonomous power solutions such as solar panels and batteries, these units ensure continuous operation in remote areas.

The processing units of the edge nodes are based on mini-computers such as Raspberry Pi 4 (Raspberry Pi Ltd., Cambridge, England) or NVIDIA Jetson Nano (Nvidia Corporation, Santa Clara, CA, USA), which were chosen for their balance between computational power and low energy consumption [50], meeting the demands of the proposed architecture. Their modular design supports scalability, allowing for the integration of additional nodes as the system expands to larger or more complex UCH sites.

Risk Assessment Tool for Climate-Related Stressors

The edge layer features a risk assessment tool that is aimed at determining the consequences of climate stressors on UCH sites. This is achieved through AI models deployed at the edge to analyse the real-time data obtained from the sensor layer. By examining key environmental parameters such as water temperature, salinity, pressure, and pH levels, the system can assess the risks posed by factors like rising sea temperatures, sediment disruption, and ocean acidification.

The risk assessment tool employs a generative AI model that runs on the edge nodes to provide on-site evaluation without relying on cloud connectivity. The initial focus is on elements with materials particularly vulnerable to corrosion, such as steel, which is significantly affected by climate change factors. The model processes key environmental

parameters, including water temperature, pressure, salinity, and pH levels, as these directly influence the corrosion rate, an essential metric for assessing the condition of submerged heritage assets [51,52]. Additionally, databases with information on the thermohaline circulation and the sea level are combined (Table 1).

Table 1. Stressors related to climate change and how they are measured, whether via in situ measuring using sensors or by combining databases.

Climate Change Stressor	Input Parameter
Increase in the surface water temperature	T, pH, salinity (sensors)
Changes in the ocean currents	Thermohaline circulation (database)
Rising sea levels	Sea level (database)

The National Oceanic and Atmospheric Administration (NOAA) buoys are valuable for sourcing reliable and high-granularity hydroclimatic data. These buoys provide a stream of critical variables, such as water temperature, pressure, dissolved oxygen, CO₂, salinity, and pH. To build the degradation scale, images capturing the state of UCH are gathered. These images are subsequently annotated by a panel of experts in underwater archaeology or heritage conservation, who classify the state of degradation on a scale from 1 to 10. The combination of these climate variables and expert-annotated images aims to produce a robust, multidimensional model capable of assessing the current state of submerged heritage and offering predictive insights that could guide future conservation efforts.

Convolutional variational autoencoders (CNN VAEs) stand out as effective analytical tools for this problem. These deep learning models are proficient in automatically extracting latent feature vectors from high-dimensional data, such as images of the UCH site. The encoder part of the VAE $q_{\phi}(z|x)$ generates a probability distribution of latent variables z , which encapsulates the site's characteristic values affected by the input parameters. The decoder part $p_{\theta}(z|x)$, also known as the generative model, reconstructs the input data from these latent variables.

In the context of training the VAE model, the loss function L_{VAE} is employed, which is a weighted combination of the Kullback–Leibler (KL) divergence L_{KL} and the reconstruction loss L_{rec} , as shown in Equation (3):

- L_{KL} : The KL divergence quantifies the dissimilarity between the learned distribution of latent variables $q(z|x)$ and a prior distribution $p(z)$. This ensures that the latent space remains well structured and follows the desired prior distribution.
- L_{rec} : The reconstruction loss measures how accurately the decoder reconstructs the original input data from the latent variables, capturing the fidelity of the reconstructed data compared to the input.

$$L_{KL} = D_{KL}(q(x|z)||p(z)) \quad (1)$$

$$L_{rec} = -E_{q(Z|X)}[\log p(x|z)] \quad (2)$$

$$L_{VAE} = \gamma_1 L_{KL} + \gamma_2 L_{rec} \quad (3)$$

Here, γ_1 and γ_2 are hyperparameters that weigh the significance of each term in the overall loss function. The model uses this loss function to learn a latent scale ranging from 1 to 10, quantifying the risk of degradation or, in this case, the rate of corrosion at the UCH site. Thus, employing a CNN VAE can provide a nuanced and precise assessment of the corrosion rate, enabling more targeted and efficient conservation strategies. In this study, a variational autoencoder (VAE) with specialised 1D convolutional layers was used to process the one-dimensional signals originating from marine sensors. These one-dimensional signals serve as the input to the VAE model. The encoder part of the VAE architecture returns distribution variables μ and σ , which are subsequently used to

generate latent variables z . These latent variables z are then input into a fully connected classification layer. The classifier was designed to output a categorical score ranging from 1 to 10, reflecting the risk of degradation of the selected UCH elements. The VAE is trained unsupervised using TensorFlow's (www.tensorflow.org) capabilities for 1D convolutional networks. The latent variables z obtained are then employed to train a supervised classification layer. The layer uses a SoftMax activation function and is trained using a categorical cross-entropy loss function, thus enabling the model to assign degradation levels in a supervised context [53]. The proposed model is illustrated in Figure 3.

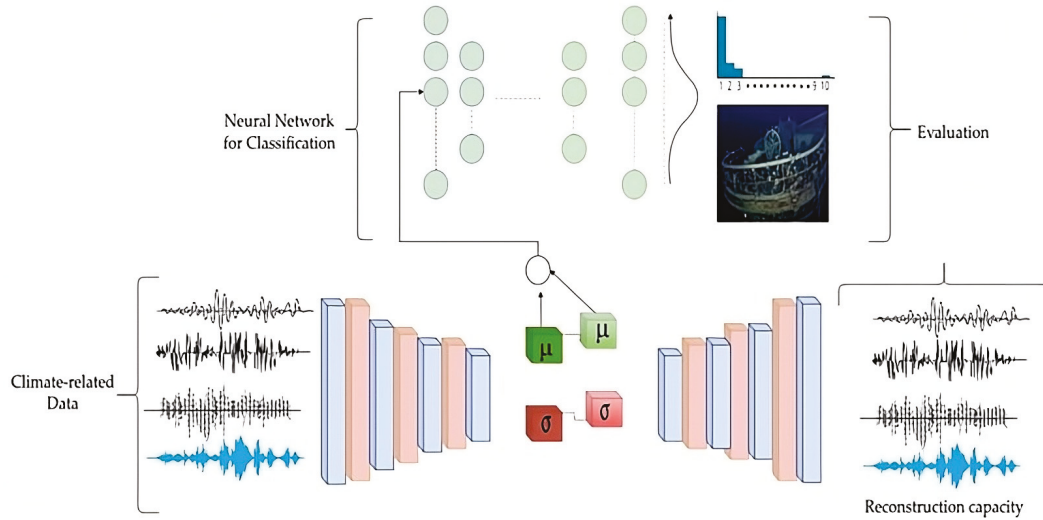


Figure 3. Outline of the multistage methodology employed for UCH risk assessment. The climate-related data illustrate the collection of hydroclimatic data from NOAA buoys, which serve as 1D input signals. The following image shows the architecture of a CNN-VAE, trained to learn latent representations of climate data. Finally, the top panel shows a fully connected neural network layer that maps these latent variables to an expert-defined degradation scale ranging from 1 to 10. Source: adapted from [53].

Certainly, if the fully connected layer is focused on classifying the degradation risk scale of underwater elements and the VAE is targeted towards capturing sensor signals related to climate change, then the latent space plays a crucial role in information sharing between these two aspects. L_{degrad} represents the loss from the fully connected layer, designed specifically for classifying the degradation scale, and it employs a categorical cross-entropy loss. L_{climate} reflects the VAE's performance in capturing sensor-based signals indicative of climate changes, combining the KL divergence and reconstruction loss. It is expressed as

$$L_{\text{climate}} = \gamma_1 L_{\text{KL}} + \gamma_2 L_{\text{rec}} \quad (4)$$

L_{degrad} is a new term that quantifies the efficacy of the latent space in capturing and sharing useful information between the degradation classification and climate signal representation. One can employ a correlation-based metric or a mutual information term to quantify this. The revised overall loss function L_{total} can then be defined as

$$L_{\text{total}} = \gamma_3 L_{\text{degrad}} + \gamma_4 L_{\text{climate}} + \gamma_5 L_{\text{latent}} \quad (5)$$

In this framework, the latent space becomes an information bridge that not only helps in the reconstruction of sensor signals but also aids in the effective classification of the degradation risk scale. The hyperparameters γ control the trade-off between these objectives. From a computational standpoint, this architecture would require a multiobjective optimisation strategy, and the backpropagation algorithm would need to be adapted to accommodate these multiple loss components. This approach would necessitate an in-

tricate balance in architecture design and hyperparameter tuning. However, it offers a more comprehensive understanding of the relationships between degradation and climate variables, which can be especially useful in contexts that require high interpretability and decision-making granularity.

3.3. Application Layer

Advanced data analytics, archiving, and visualisation are included in the cloud services integrated in the application layer. Transmitted data that were processed and filtered by the edges of the layer nodes to the cloud are stored in conjunction with historical datasets for analysis and modelling. This layer enables the creation and application of AI models for risk assessment and prediction in order to enhance the efficiency of conservation efforts in relation to current and historical information and trends.

There is also a cloud application containing a browser interface for heritage managers, which enables them to see data, alerts, and reports based on AI-generated analysis. This section also enables modular construction, so that this layer can be made compatible with a variety of IoUT platforms and allow for easier integration and ease in expanding the reach of the platform to wider deployment.

4. Buoy System for Underwater Location: A Case Study

This case study explored the practical implementation of the proposed edge-computing-based architecture for the conservation and management of UCH, specifically focusing on the buoy system designed for accurate underwater location tracking.

The ability to precisely track the position of assets such as ROVs, divers, and environmental sensors (among others) is essential for monitoring and protecting submerged sites. However, traditional methods of underwater localisation often face limitations due to poor GPS signal reception underwater and the complexity of marine environments. To address this challenge, a specialised buoy system was developed that integrates acoustic communication technology, GPS, and LoRa-based protocols. This system enables the real-time, accurate localisation of underwater acoustic elements (UAEs) by using edge computing to process data directly at the buoy level, reducing latency and ensuring continuous operation even in areas with intermittent cloud connectivity. By decentralising data processing and utilising advanced communication methods, this solution provides a robust and reliable tool for tracking and managing UCH assets, ensuring better protection and conservation outcomes.

The prototype system proposed for underwater localisation was designed in accordance with the specifications of the TECTONIC project [2]. This solution is structured around the main components of the architecture presented before (Figure 1). The elements that comprise the electronic architecture of the buoys are presented in Figure 4:

A Succorfish Delphis V3 modem (Succorfish Ltd., North Shields, England) [54], along with an acoustic transducer, were essential for facilitating underwater communication, taking charge of generating and analysing the necessary acoustic signals for this purpose. This modem acted as a gateway between serial communication and acoustic communication. For serial communication with an external device, it had an RS232 interface, ensuring the transmitted data's integrity, effectively protecting them from noise and possible interference.

The Nordic uC PCB, developed by the research group LABUST (Laboratory for Underwater Systems and Technologies - LABUST, Zagreb, Croatia) [55], integrated the Nordic nRF52840 microcontroller (Nordic Semiconductor ASA, Trondheim, Norway) and was responsible for the communication between the acoustic modem and the ESP32 + LoRa board (Soldered Electronics, Osijek, Croatia), as well as for the voltage regulation for the electronic components. The ESP32 + LoRa board, from e-radionica (now Soldered Electronics [56]), featured an ESP32-WROOM-32D microcontroller (Espressif Systems Co., Ltd., Shanghai, China) that supported WiFi and Bluetooth and had an embedded LoRa module for long-distance transmissions. Communication with the GPS module and with

the Nordic microcontroller board was carried out via UART serial buses and with the LoRa module through SPI.

An Adafruit Ultimate GPS module [57] was included, providing location, speed, and time data in real time through satellite tracking. It communicated with the ESP32 microcontroller via UART.

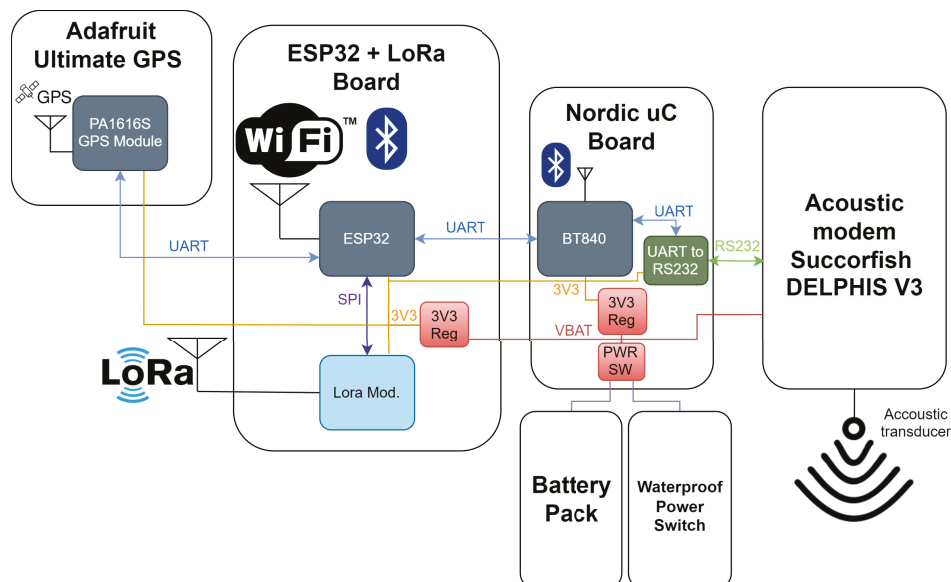


Figure 4. The electronic architecture of the buoys, integrating acoustic and LoRa communication, enables precise real-time communication and localisation of underwater elements.

For a robust and reliable power supply, Li-Ion 18650 battery systems were used in parallel, achieving a total capacity of 7500 mAh and 3.7 V. This ensures uninterrupted operation, even in challenging conditions. Additionally, a waterproof power switch from Blue Robotics added a layer of control without compromising the system's waterproofness. This set of electronic components, encapsulated in the buoys (Figure 5), was crucial in developing and validating the prototype.

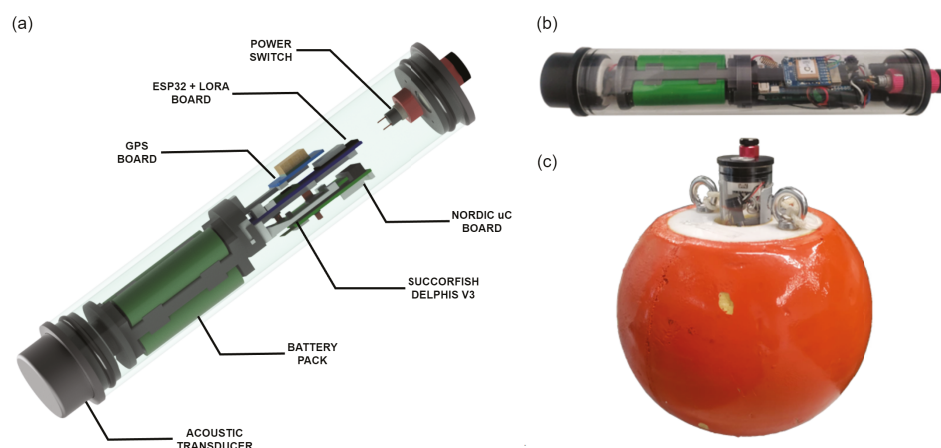


Figure 5. This assembly of buoy components illustrates the robust design and adaptability of the proposed solution for real-time underwater localisation, essential for effective UCH site management. The three-dimensional design of the buoy components (a), assembled buoy components (b), and functional prototype of the buoy (c).

Field tests were conducted in Lake Jarun in Zagreb, Croatia, on 24 August 2023. During these tests, a system comprising three buoys and an underwater acoustic element (UAE) was deployed to evaluate the system's performance. Of the three buoys, one acted as the

central unit, responsible for orchestrating the range measurements and processing the data collected. This central buoy communicated with the two other buoys, which functioned solely as measurement nodes. When prompted by the central unit, these measurement nodes conducted range calculations relative to the UAE and promptly transmitted their results back to the central buoy for processing.

The UAE, positioned on an object equipped with an acoustic transmitter, was guided through the water by a surface boat. This configuration allowed the system to assess the UAE's precise underwater location as it moved along its designated trajectory. The structured setup and communication between the central buoy, measurement nodes, and UAE enabled the collection of essential data regarding the system's accuracy, responsiveness, and effectiveness in tracking and monitoring underwater acoustic elements.

Below, one of the successful messages sent by the buoy system is analysed:

24/08/2023 12:23:19 B1, RNG, 4.22, 45.779338836669918, 15.936838150024414, 81

24/08/2023 12:23:19 B2, RNG, 10.1, 45.779228210449218, 15.936708450317382, 81

24/08/2023 12:23:19 B3, RNG, 1.88, 45.779338836669918, 15.936790466308594, 81

The message was composed as follows:

<time> B#, RNG, <range>, <lat>, <lon>, <e_GPS>

where

- Time: date and time formatted as dd/mm/yyyy hh:mm:ss.
- B#: buoy to which the message belongs (B1: central unit, B2: bouy node 1, B3: bouy node 2).
- RNG: range correctly calculated. Otherwise, it shows LOG.
- Range: distance between the buoy and the underwater acoustic element, in meters.
- Lat: latitude, in decimal degrees.
- Lon: longitude, in decimal degrees.
- e_GPS: error, in centimeters.

Each point, corresponding to the location of the buoys, was overlaid with a sphere that symbolised the distance to the UAE. The radius r_i of these spheres equaled the sum of the distance d_i between the buoy and the UAE plus the GPS error e_{GPS} margin and the error in the acoustic range measurement $e_{Acoustic}$ (0.1 m according to the manufacturer), thus offering a detailed three-dimensional representation of the position and the uncertainty associated with each measurement (Figure 6).



Figure 6. The trilateration algorithm used for underwater localisation provides accurate spatial mapping of buoys and UAEs, enhancing the platform's capacity to precisely track assets in submerged environments. Location of the buoys (a). Data processed using the trilateration algorithm (b).

$$r_i = d_i + e_{\text{GPS}} + e_{\text{Acoustic}} \quad (6)$$

To obtain a graphical representation of the results, the data were processed using a spherical trilateration algorithm (Equation (6)), in which each of the obtained points was accurately represented in space based on the known distances p_i between the buoys, taking one of them as the origin.

$$(x - p_{i,0})^2 + (y - p_{i,1})^2 - r_i^2 = 0 \quad (7)$$

Figure 6 provides a 3D spatial visualisation of the buoy network and how the relative buoy distances are used to pinpoint the object's position accurately. The approach effectively accounts for and visualises the uncertainty inherent in the measurements, offering a comprehensive view of the spatial configuration and accuracy of the localisation system.

In the future, buoys equipped with acoustic sensors can be utilised not only for localisation but also for the detection of diver bubbles. The ability to detect diver bubbles has significant practical implications for managing underwater cultural heritage, particularly in identifying unauthorised divers who may pose a threat to sensitive sites. By leveraging advanced techniques, such as the block-based threshold theory and IMCRA (BIED) method, the buoy system described in this section can detect diver bubbles at considerably greater distances than traditional methods, reaching up to 40 m under optimal conditions with signal enhancement and noise reduction [58].

5. Conclusions and Future Work

The conservation of UCH is a matter of preserving not only our past but also resources of immense value for understanding our history. With climate change posing one of the most significant threats to UCH, it becomes imperative to harness available data and direct our research towards intelligent solutions.

The proposed platform and its implementation provide a robust, real-time approach to monitoring and managing UCH. Integrating IoUT with edge computing technologies allows for the effective processing and monitoring of UCH sites, improving system reliability and responsiveness even in environments with intermittent cloud connectivity. The case study of the buoy system highlights the effectiveness of this approach in achieving precise underwater localisation, overcoming the limitations of traditional GPS-based systems and validating the platform's capability to track underwater assets in real-time.

However, while the initial results are promising, further work is needed to refine the platform's capabilities. Future research should focus on extending the scalability of the system, allowing it to manage larger UCH sites with more complex environments and a greater number of deployed assets, while ensuring energy efficiency through the optimisation of power consumption. Enhancing the robustness and accuracy of the localisation algorithms, especially in highly dynamic underwater conditions, is another key area for improvement. Testing the system in more diverse and challenging marine environments will also be critical to ensuring its effectiveness and adaptability across different heritage sites.

Additionally, integrating machine learning models to automate data processing and risk assessment at the edge will further advance the platform's ability to proactively manage and conserve UCH. The CNN-VAE model for risk assessment proposed in this work is currently theoretical and requires practical validation. Future efforts will focus on implementing and fine tuning the model using data collected from pilot sites. This will include optimising hyperparameters, evaluating the model's performance in real-world conditions, and exploring alternative generative AI approaches. This practical validation is essential to ensure the applicability and robustness of the proposed AI-driven risk assessment tool.

Future work is targeted towards the practical application of this platform at the pilot sites of the TECTONIC project: the Bengala shipwreck near Isola di Capo Rizzuto in

Italy, the ancient harbour of Aegina in Greece, and the shipwreck site of the HMS Swift in Argentina.

Author Contributions: Conceptualisation: J.H.-S., M.P.-H., S.L.-F., J.P.T., V.D. and E.S.C.-R.; methodology: J.H.-S., M.P.-H. and S.L.-F.; software: J.H.-S.; validation: J.H.-S., M.P.-H., S.L.-F., J.P.T., V.D. and E.S.C.-R.; formal analysis: J.H.-S., M.P.-H. and S.L.-F.; investigation: J.H.-S., M.P.-H. and S.L.-F.; data curation: J.H.-S.; writing—original draft: J.H.-S., M.P.-H. and S.L.-F.; writing—review and editing: J.P.T., V.D. and E.S.C.-R.; visualisation: J.H.-S.; project administration: J.P.T. All authors have read and agreed to the published version of this manuscript.

Funding: This research has been supported by the project “Technological Consortium TO develop sustainability of underwater Cultural heritage (TECTONIC)”, financed by the European Union (Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement 873132).

Data Availability Statement: The original data presented in the study are openly available in GitHub at <https://github.com/jorgehsmp/TECTONIC-Underwater-Location-System/>.

Conflicts of Interest: Author Vladimir Djapic was employed by the company H2O Robotics Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Underwater Heritage (Convention 2001). Available online: <https://www.unesco.org/en/underwater-heritage/2001-convention> (accessed on 3 December 2024).
2. TECTONIC Project. Available online: <https://www.tectonicproject.eu/> (accessed on 3 December 2024).
3. Wang, X.; Tu, Y.; Liu, J.; Han, G.; Yu, C.; Cui, J.-H. Edge-Enabled Modulation Classification in Internet of Underwater Things Based on Network Pruning and Ensemble Learning. *IEEE Internet Things J.* **2024**, *11*, 13608–13621. [CrossRef]
4. Cardia, C.; Corsalini, S.; Davidde, B.; Petrioli, C.; Piccialli, V.; Spaccini, D. Submerged Archaeological Heritage Preservation Through IoUT Environmental Monitoring. In Proceedings of the OCEANS 2023—MTS/IEEE U.S. Gulf Coast, Biloxi, MS, USA, 25–28 September 2023; pp. 1–10. [CrossRef]
5. Lupia, M.; Gagliardi, G.; Cario, G.; Cicchello Gaccio, F.; D’Angelo, V.; Folino, P. A Smart System for Environmental Parameter Monitoring in Underwater Archaeological Sites. *Electronics* **2023**, *12*, 2918. [CrossRef]
6. Scaradozzi, D.; Zingaretti, S.; Panebianco, L.; Ciuccoli, N.; Screpanti, L.; Cesaretti, L.; Costa, D.; Palmieri, G.; Bruno, F.; Muzzupappa, M.; et al. The Lab4Dive project: A mobile smart lab for augmented archaeological dives—Overview and first results. In Proceedings of the IMEKO TC4 International Conference on Metrology for Archaeology and Cultural Heritage, Lecce, Italy, 23–25 October 2017.
7. Pehlivanides, G.; Monastiridis, K.; Tourtas, A.; Karyati, E.; Ioannidis, G.; Bejelou, K.; Antoniou, V.; Nomikou, P. The VIR-TUALDiver Project. Making Greece’s Underwater Cultural Heritage Accessible to the Public. *Appl. Sci.* **2020**, *10*, 8172. [CrossRef]
8. Porambage, J.; Okwuibe, M.; Liyanage, M.; Ylianttila, M.; Taleb, T. Survey on Multi-Access Edge Computing for Internet of Things Realization. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 2961–2991. [CrossRef]
9. Porambage, P.; Gür, G.; Osorio, D.P.; Liyanage, M.; Gurtov, A.V.; Ylianttila, M. The Roadmap to 6G Security and Privacy. *IEEE Open J. Commun. Soc.* **2021**, *2*, 1094–1122. [CrossRef]
10. Henderson, J. Oceans without History? Marine Cultural Heritage and the Sustainable Development Agenda. *Sustainability* **2019**, *11*, 5080. [CrossRef]
11. Gregory, D.; Dawson, T.; Elkin, D.; Van Tilburg, H.; Underwood, C.; Richards, V.; Viduka, A.; Westley, K.; Wright, J.; Hollesen, J. Of time and tide: The complex impacts of climate change on coastal and underwater cultural heritage. *Antiquity* **2022**, *96*, 1396–1411. [CrossRef]
12. Perez-Alvaro, E. Climate change and underwater cultural heritage: Impacts and challenges. *J. Cult. Herit.* **2016**, *21*, 842–848. [CrossRef]
13. Wright, J. Maritime Archaeology and Climate Change: An Invitation. *J. Mar. Arch.* **2016**, *11*, 255–270. [CrossRef]
14. Dunkley, M. Climate is what we expect, weather is what we get: Managing the potential effects of climate change on underwater cultural heritage. In *Water and Heritage: Material, Conceptual, and Spiritual Connections*; Willems, W., van Shaik, H., Eds.; Sidestone Press: Leiden, The Netherlands, 2015; pp. 217–230.
15. Sanz, P.J.; Peñalver, A.; Sales, J.; Fernández, J.J.; Pérez, J.; Fomas, D.; García, J.C. Multipurpose underwater manipulation for archaeological intervention. *Instrum. Viewp.* **2015**, *56*, 50–51. Available online: <http://hdl.handle.net/2117/77627> (accessed on 17 October 2024).
16. Menna, F.; Agrafiotis, P.; Georgopoulos, A. State of the art and applications in archaeological underwater 3D recording and mapping. *J. Cult. Herit.* **2018**, *33*, 231–248. [CrossRef]

17. Skarlatos, D.; Agraftiotis, P. Image-Based Underwater 3D Reconstruction for Cultural Heritage: From Image Collection to 3D. Critical Steps and Considerations. In *Visual Computing for Cultural Heritage*; Springer Series on Cultural Computing; Springer: Cham, Switzerland, 2020. [CrossRef]
18. Geraga, M.; Christodoulou, D.; Eleftherakis, D.; Papatheodorou, G.; Fakiris, E.; Dimas, X.; Georgiou, N.; Kordella, S.; Prevenios, M.; Iatrou, M.; et al. Atlas of Shipwrecks in Inner Ionian Sea (Greece): A Remote Sensing Approach. *Heritage* **2020**, *3*, 1210–1236. [CrossRef]
19. Kapetanović, N.; Vasiljević, A.; Nađ, Đ.; Zubčić, K.; Mišković, N. Marine Robots Mapping the Present and the Past: Unraveling the Secrets of the Deep. *Remote Sens.* **2020**, *12*, 3902. [CrossRef]
20. Giannakopoulos, V.; Papatheodorou, G.; Christodoulou, D.; Fakiris, E.; Geraga, M.; Gkionis, P.; Mavrommatis, N.; Levy, T. A low cost Unmanned Surface Vehicle for mapping shallow-water UCH sites: Ancient and historical shipwrecks in Methoni bay, Greece. In Proceedings of the 2022 IMEKO TC4 International Conference on Metrology for Archaeology and Cultural Heritage, Calabria, Italy, 19–21 October 2022. [CrossRef]
21. Miskovic, N.; Nad, D.; Rendulic, I. Tracking Divers: An Autonomous Marine Surface Vehicle to Increase Diver Safety. *IEEE Robot. Autom. Mag.* **2015**, *22*, 72–84. [CrossRef]
22. Dudek, G.; Jenkin, M.; Prahacs, C.; Hogue, A.; Sattar, J.; Giguere, P.; German, A.; Liu, H.; Saunderson, S.; Ripsman, A.; et al. A visually guided swimming robot. In Proceedings of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, Edmonton, AB, Canada, 2–6 August 2005; pp. 3604–3609. [CrossRef]
23. Mogstad, A.A.; Ødegård, Ø.; Nornes, S.M.; Ludvigsen, M.; Johnsen, G.; Sørensen, A.J.; Berge, J. Mapping the Historical Shipwreck Figaro in the High Arctic Using Underwater Sensor-Carrying Robots. *Remote Sens.* **2020**, *12*, 997. [CrossRef]
24. Georgiou, N.; Dimas, X.; Fakiris, E.; Christodoulou, D.; Geraga, M.; Koutsoumpa, D.; Baika, K.; Kalamara, P.; Ferentinos, G.; Papatheodorou, G. A Multidisciplinary Approach for the Mapping, Automatic Detection and Morphometric Analysis of Ancient Submerged Coastal Installations: The Case Study of the Ancient Aegina Harbour Complex. *Remote Sens.* **2021**, *13*, 4462. [CrossRef]
25. Silva, B.N.; Khan, M.; Han, K. Towards Sustainable Smart Cities: A review of trends, architectures, components, and open challenges in smart cities. *Sustain. Cities Soc.* **2018**, *38*, 697–713. [CrossRef]
26. Javaid, M.; Haleem, A.; Rab, S.; Singh, R.P.; Suman, R. Sensors for daily life: A review. *Sens. Int.* **2021**, *2*, 100121. [CrossRef]
27. Severino, U.; Fortuna, S.; Lagudi, A.; Bruno, F.; Mišković, N.; Djapic, V. Architecture of a Low-Cost Solution for ROVs to Improve Navigation and Data Collection. In *Distributed Computing and Artificial Intelligence, Special Sessions I, 20th International Conference. DCAI 2023*; Mehmood, R., Alves, V., Praça, I., Wikarek, J., Parra-Domínguez, J., Loukanova, R., de Miguel, I., Pinto, T., Nunes, R., Ricca, M., Eds.; Lecture Notes in Networks and Systems; Springer: Cham, Switzerland, 2023; Volume 741. [CrossRef]
28. Su, X.; Ullah, I.; Liu, X.; Choi, D. A review of underwater localization techniques, algorithms, and challenges. *J. Sens.* **2020**, *2020*, 1–24. [CrossRef]
29. Sherlock, B.; Morozs, N.; Neasham, J.; Mitchell, P. Ultra-Low-Cost and Ultra-Low-Power, miniature acoustic modems using multipath tolerant Spread-Spectrum techniques. *Electronics* **2022**, *11*, 1446. [CrossRef]
30. Domingo, M.C. An overview of the internet of underwater things. *J. Netw. Comput. Appl.* **2012**, *35*, 1879–1890. [CrossRef]
31. Islam, K.Y.; Ahmad, I.; Rong, Y.; Habibi, D. Joint Energy and Security Optimization in Underwater Wireless Communication Networks. *IEEE Internet Things J.* **2024**, *11*, 14282–14295. [CrossRef]
32. Felemban, E.; Shaikh, F.K.; Qureshi, U.M.; Sheikh, A.A.; Qaisar, S.B. Underwater Sensor Network Applications: A Comprehensive survey. *Int. J. Distrib. Sens. Netw.* **2015**, *11*, 896832. [CrossRef]
33. Raychowdhury, A.; Pramanik, A. Survey on LoRa Technology: Solution for Internet of Things. In *Intelligent Systems, Technologies and Applications. Advances in Intelligent Systems and Computing*; Springer: Singapore, 2020; Volume 1148. [CrossRef]
34. Parri, L.; Parrino, S.; Peruzzi, G.; Pozzebon, A. Low Power Wide Area Networks (LPWAN) at sea: Performance analysis of offshore data transmission by means of LORAWAN connectivity for marine monitoring applications. *Sensors* **2019**, *19*, 3239. [CrossRef] [PubMed]
35. Li, Y.; Cheng, X.; Cao, Y.; Wang, D.; Yang, L. Smart Choice for the Smart Grid: Narrowband Internet of Things (NB-IoT). *IEEE Internet Things J.* **2017**, *5*, 1505–1515. [CrossRef]
36. Pachler, N.; del Portillo, I.; Crawley, E.F.; Cameron, B.G. An Updated Comparison of Four Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband. In Proceedings of the 2021 IEEE International Conference on Communications Workshops (ICC Workshops), Montreal, QC, Canada, 14–23 June 2021; pp. 1–7. [CrossRef]
37. Hassan, S.S.; Kim, D.H.; Tun, Y.K.; Tran, N.H.; Saad, W.; Hong, C.S. Seamless and Energy-Efficient Maritime Coverage in Coordinated 6G Space–Air–Sea Non-Terrestrial Networks. *IEEE Internet Things J.* **2023**, *10*, 4749–4769. [CrossRef]
38. Jung, S.; Jeong, S.; Kang, J.; Kang, J. Marine IoT Systems With Space–Air–Sea Integrated Networks: Hybrid LEO and UAV Edge Computing. *IEEE Internet Things J.* **2023**, *10*, 20498–20510. [CrossRef]
39. Mamode, S.A.H.; Runghen, H.; Munnaroo, S.; Dass Bissessur, D.; Coopen, P.; von Arnim, Y.; Manfio, S.; Seetah, K.; Motah, B.A.; Badal, R. Mapping of Underwater Cultural Heritage: The Geophysical Survey and Data Management of HMS Sirius Shipwreck. In Proceedings of the OCEANS 2022, Chennai, India, 23 February 2022. [CrossRef]
40. Manders, M. Dutch Involvement in Asian Underwater Cultural Heritage Management: Building Upon Old Connections. *J. Mar. Arch.* **2010**, *5*, 117–127. [CrossRef]
41. Kim, T.; Kwak, J.; Choi, J.P. Satellite Edge Computing Architecture and Network Slice Scheduling for IoT Support. *IEEE Internet Things J.* **2022**, *9*, 14938–14951. [CrossRef]

42. Zhang, J.; Hu, X.; Ning, Z.; Ngai, E.C.H.; Zhou, L.; Wei, J.; Cheng, J.; Hu, B.; Leung, V.C. Joint Resource Allocation for Latency-Sensitive Services Over Mobile Edge Computing Networks with Caching. *IEEE Internet Things J.* **2019**, *6*, 4283–4294. [CrossRef]
43. Hao, H.; Xu, C.; Zhang, W.; Yang, S.; Muntean, G.-M. Computing Offloading With Fairness Guarantee: A Deep Reinforcement Learning Method. *IEEE Trans. Circuits Syst. Video Technol.* **2023**, *33*, 6117–6130. [CrossRef]
44. H2O Robotics. Innovative and Cutting-Edge Marine Systems and Technologies. Available online: <https://h2o-robotics.com/> (accessed on 3 December 2024).
45. BlueRobotics. We're on a Mission to Enable the Future of Marine Robotics. Available online: <https://bluerobotics.com/> (accessed on 3 December 2024).
46. H2Observe. Available online: <https://h2o-robotics.com/h2observe/> (accessed on 3 December 2024).
47. BlueROV2. Available online: <https://bluerobotics.com/store/rov/bluerov2/> (accessed on 3 December 2024).
48. H2Orologio. Available online: <https://h2o-robotics.com/h2orologio/> (accessed on 3 December 2024).
49. H2Orbit. Available online: <https://h2o-robotics.com/h2orbit/> (accessed on 3 December 2024).
50. Garcia-Perez, A.; Miñón, R.; Torre-Bastida, A.I.; Zulueta-Guerrero, E. Analysing Edge Computing Devices for the Deployment of Embedded AI. *Sensors* **2023**, *23*, 9495. [CrossRef] [PubMed]
51. Jiang, Y.; Dong, J.; Qi, X.; Wang, F. Improvement of Monitoring Technology for Corrosive Pollution of Marine Environment under Cloud Computing Platform. *Coatings* **2022**, *12*, 938. [CrossRef]
52. Abbas, M.; Shafiee, M. An overview of maintenance management strategies for corroded steel structures in extreme marine environments. *Mar. Struct.* **2020**, *71*, 102718. [CrossRef]
53. Ahmed, T.; Longo, L. Examining the Size of the Latent Space of Convolutional Variational Autoencoders Trained with Spectral Topographic Maps of EEG Frequency Bands. *IEEE Access* **2022**, *10*, 107575–107586. [CrossRef]
54. Succorfish Delphis V3. Available online: <https://succorfish.com/products/delphis/> (accessed on 3 December 2024).
55. LABUST. Available online: <https://labust.fer.hr/> (accessed on 3 December 2024).
56. Soldered Electronics. Available online: <https://soldered.com/> (accessed on 3 December 2024).
57. Adafruit. Available online: <https://www.adafruit.com/product/746> (accessed on 3 December 2024).
58. Tu, Q.; Yuan, F.; Yang, W.; Cheng, E. An Approach for Diver Passive Detection Based on the Established Model of Breathing Sound Emission. *J. Mar. Sci. Eng.* **2020**, *8*, 44. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

Article

A Risk Assessment of Underwater Cultural Heritage for Wave-Induced Hazards: The Impact of Climate Change on Cadiz Bay

C. Ferrero-Martín ^{1,*}, A. Izquierdo ¹, M. Bethencourt ² and T. Fernández-Montblanc ^{3,*}

¹ Department of Applied Physics, University of Cadiz, INMAR, 11510 Cadiz, Spain; alfredo.izquierdo@uca.es

² Department of Materials Science, Metallurgical Engineering and Inorganic Chemistry, University of Cadiz, INMAR, 11510 Cadiz, Spain; manuel.bethencourt@uca.es

³ Earth Sciences Department, University of Cadiz, INMAR, 11510 Cadiz, Spain

* Correspondence: carmen.ferrero@uca.es (C.F.-M.); tomas.fernandez@uca.es (T.F.-M.)

Abstract: The combination of future changes in sea levels and wave climate in coastal areas represents one of the greatest threats to the preservation of underwater cultural heritage (UCH). This study presents a new methodology to assess climate change's impacts on UCH preservation in shallow waters, focusing on wave-induced hazards like decontextualization, scouring, and wear erosion. The approach uses hybrid downscaling of bias-corrected wave fields from the RCP4.5 and RCP8.5 CMIP5 scenarios. The methodology was applied in the Bay of Cadiz, where an overall reduction in wave energy flux was observed. However, local increases were detected in rocky outcrops and coastal areas with high UCH density. As a result, the shallow zones exhibited significant changes in decontextualization and scouring hazards. However, the most relevant risk changes were linked to wear erosion, particularly at sites on rocky outcrops near Cadiz. The methodology proposed in this study is essential for identifying areas with higher risk and for evaluating UCH preservation under future climate conditions. It offers an effective tool for discriminating sites at risk and for conducting a long-term assessment of these risks in coastal environments affected by climate change.

Keywords: underwater cultural heritage; climate change; hybrid downscaling; decontextualization risk; scouring risk; wear erosion risk, numerical modelling, ocean waves

1. Introduction

The alterations in wave climate attributable to global warming are of vital importance in coastal areas given the fundamental role of waves in shaping coastal dynamics and coastal hazards. These modifications have the potential to change coastal morphology [1] and significantly impact human activities. Assessing the impacts resulting from climate change (CC) in littoral areas is of great interest as these regions not only represent the most densely populated areas but also holds high value in terms of underwater cultural heritage (UCH).

The preservation of UCH is crucial for local communities, and it is necessary to recognize and properly appreciate its value [2] as its degradation not only implies a loss of cultural capital but also reductions in tourism and recreational, educational, and scientific activities, as well as a decline in local ecological knowledge [3]. In this regard, within the framework of the European Green Deal, it is anticipated that the preservation of cultural heritage will serve as a powerful driver of economic recovery [4]. Littoral UCH is continuously subjected to the impact of marine agents that accelerate its degradation. Among these, waves stand out as one of the main factors affecting the preservation and

evolution of UCH in shallow water areas exposed to wave action [5,6]. Wave energy is released on the coast, generating three fundamental hazards for submerged cultural heritage: decontextualization, scouring, and wear erosion [7].

The complex interaction among archeological sites, suspended sediment transport, and hydrodynamic processes has been recognized and extensively investigated in the context of the in situ preservation of underwater archeological sites [5,6,8–13]. Changes in sediment budgets can compromise the stability of shipwrecks, leading to the exposure and/or burial of valuable artifacts. Additionally, scouring influences chemical and biological processes affecting the composition of the benthic community. This has effects on metallic materials [14], the corrosion rates of metal [15], and the degradation of stone materials [16] and wood [17].

CC will affect atmospheric and marine conditions, thereby impacting the conservation of coastal and underwater archeological sites. However, despite the relevance and high density of UCH in coastal areas, studies analyzing wave-induced hazards [7,18] have not considered long-term changes in environmental conditions.

Long-term changes in large-scale atmospheric circulation and in local wind patterns, coupled with changes in the occurrence and characteristics of tropical and extra-tropical cyclones, indicate long-term changes in wind wave statistics [19]. Reguero et al. [20] indicated that upper-ocean warming is altering the global wave climate, suggesting that global wave energy has increased by 0.4% per year since 1948. Global-scale studies have assessed projected changes in wave climate under different CC scenarios [21–23], finding a robust increase in the annual mean significant wave height in the Southern Hemisphere, while a reduction has been observed in the Northern Hemisphere. In the case of the North Atlantic, a reduction in significant wave height is expected by the end of the century, with greater decreases under the RCP8.5 scenario (~10%) compared to RCP4.5 (~5%) [24]. Furthermore, the extreme wave height is also projected to decrease in the northeast Atlantic [25–27], with the largest decrease being more than 1 m (12%) occurring south of 45° N [28].

These potential changes in global wave climate, along with sea level rise, underscore the need for further studies to downscale global trends regionally, analyze changes in wave climate in coastal shallow waters, and to evaluate how these changes will affect UCH preservation. Therefore, this study aims to develop a methodology to assess UCH-related risk associated with wave-induced hazards in current and future climates under climate change conditions. This methodology is tested in the Bay of Cadiz, a region characterized by a large number of UCH sites with great diversity. To achieve this, an assessment of wave climate and changes in the main hazards affecting UCH is carried out for the RCP 4.5 and RCP 8.5 scenarios. To attain the spatial resolution demanded by coastal applications and to reduce the uncertainties inherent in using global models for local-scale studies, a hybrid downscaling approach is employed to propagate waves from deep to shallow waters.

The remainder of this paper is structured as follows: The next section introduces the study area; the Methods Section describes the methodology developed and the datasets used for validation; the Results Section presents the downscaled wave climate and the assessment of CC's impact on UCH risks and hazards; the Discussion Section analyzes the applicability, limitations, and potential of the methodology based on the results; and, finally, the main findings of this study are summarized.

Study Area

The Bay of Cadiz is located in the southwest of Spain, extending from Punta Candor to the Sancti Petri estuary (Figure 1A). The seabed mainly consists of unconsolidated sediments, with a mean grain size ranging from very fine quartz sand to very fine gravel. Exceptions to this general pattern are localized rocky outcrops in the study area. The

bay is a mesotidal shallow estuary with a maximum depth of 20 m at its seaward edge, and it is characterized by dominantly semidiurnal co-oscillating tides with amplitudes of ~ 1 m for the M2 component and ~ 0.4 m for the S2 component [29]. The typical waves in the Bay of Cadiz are wind waves with periods below 7 s and significant heights around 0.5 m in summer and 1.0 m in winter, increasing during storm events. The longer swell components of the wave spectrum have periods of 12–15 s and a height of about 1.5 m [30]. The predominant wave direction is from the west, while the most energetic waves (wave heights exceeding the 95th percentile) originate from the west-southwest (Figure 1B). Winds in the Bay of Cadiz show significant seasonality with dominant Atlantic winds from the W and WNW, and less frequent but more intense Mediterranean winds from the ESE. S-SSW winds reaching speeds of $10\text{--}20\text{ m}\cdot\text{s}^{-1}$ are associated with typical storm event conditions, occurring when low-pressure systems move along a SW-NE trajectory [6].

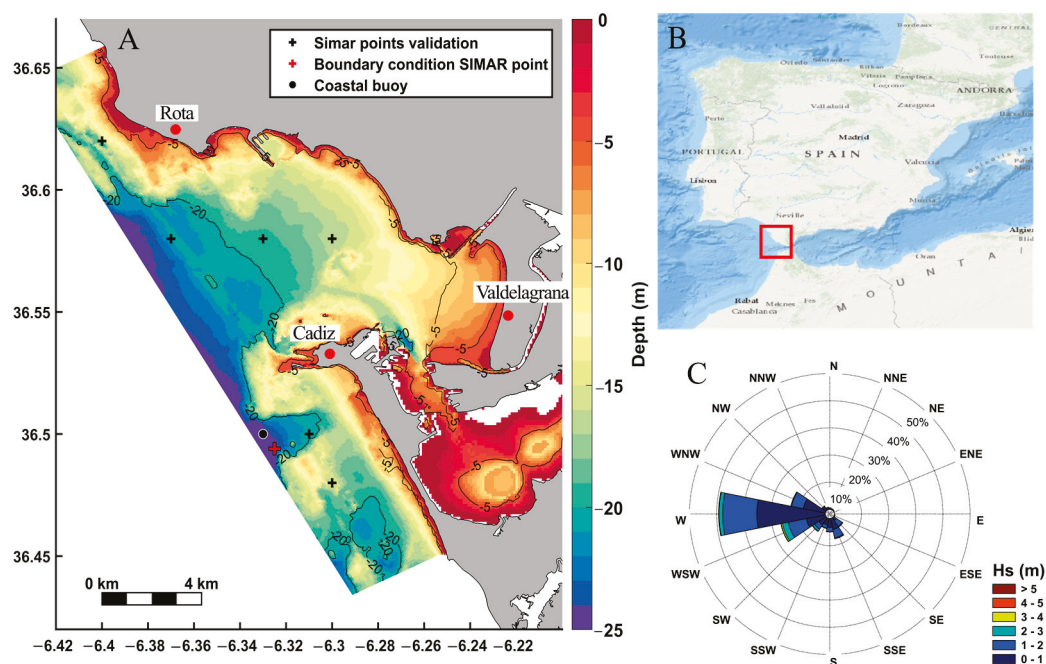


Figure 1. (A) Study area with overlaid bathymetry. (B) Location of the study area, Bay of Cadiz, Andalusia, Spain (C) A wave rose diagram of the significant wave height for a directional wave buoy.

The coastline stretching from the mouth of the Guadalquivir River to the Bay of Cadiz is one of the areas with the highest density of shipwrecks in the world owing to the presence of maritime trade routes since ancient times and the navigational hazards characteristic of this zone. The great archeological significance of Cadiz Bay drove their inclusion under the figure of maximum archeological protection of Andalusia in 2008 (BOJA n°48 of 03/10/2008, Resolution of 17 January 2008).

2. Methods

The proposed methodology for assessing the impact of climate change on the risk of UCH due to wave-induced hazards is structured into four phases (Figure 2). To better assess the temporal evolution of the risk, three time slices are considered: the baseline (1981–2005), the mid-century period (2036–2060), and the end-of-century (2075–2099) period. For each of these time slices, we create two climate change scenarios corresponding to the Representative Concentration Pathways (RCPs) defined in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC): RCP4.5 and RCP8.5. RCP4.5 represents a moderate emission mitigation scenario, while RCP8.5 reflects a high-end, business-as-usual scenario.

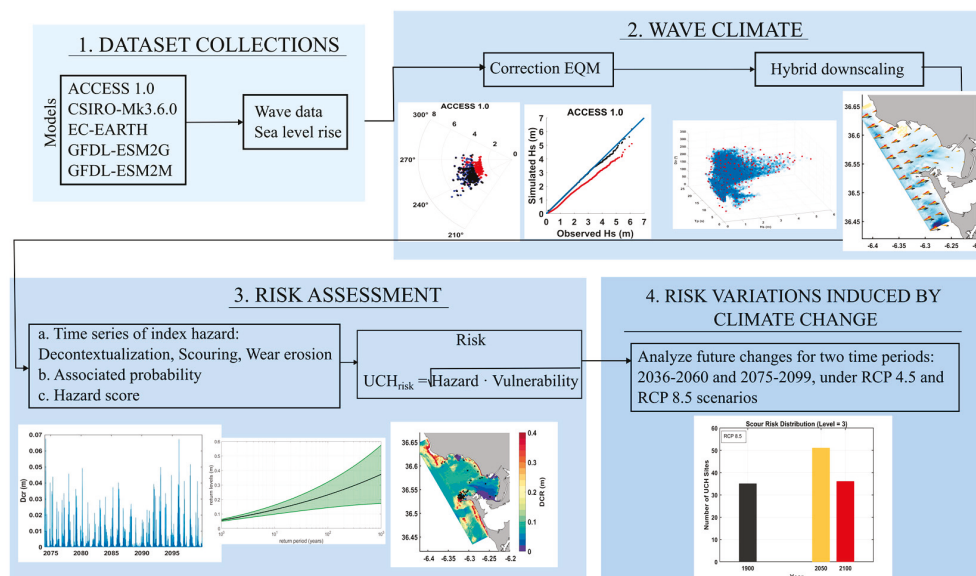


Figure 2. The workflow of the methodology developed to assess the impact of climate change on UCH risk due to wave-induced hazards.

In the first phase, time series of wave parameters and mean global sea level rise are extracted from the output of different global climate models corresponding to the historical runs and RCP4.5 and RCP8.5 climate change scenarios [31]. The second phase involves the treatment of RCP4.5 and RCP8.5 wave projections. This includes applying bias correction procedure, followed by propagating the bias-corrected wave field into shallow coastal waters using the hybrid downscaling method while considering sea level perturbation (tide + SLR). In the third phase, a risk assessment is performed for each of the considered hazards: decontextualization, scouring, and wear erosion. Finally, an ensemble mean is calculated using the variables and indices obtained for each of the global climate models, and the impacts of climate change on the risk are analyzed.

2.1. Datasets Collection

Wave Data and Sea Level Rise Projections

The historical wave data used in this study are detailed in Table 1. Given the temporal limitation of available data at the coastal buoy of Cadiz (6.33° W, 36.50° N, 21 m water depth), the buoy data are used to correct the longer timeseries from Med-Wav reanalysis [32] (maintained and distributed by the Copernicus Marine Service). The corrected Med-Wav reanalysis is then utilized for bias adjustment of the global climate model wave projection data (Table 2).

Table 1. Summary of wave data.

Name of Product	Spatial Resolution	Temporal Resolution	Available Period	Obser-Model	Bias Adjust	Institution
Coastal buoy of Cadiz	-	3 h (1996–1997)/ 1 h (1998–2014)	Scalar data: 1996–2019; directional data: 2001–2014	Obser.	none	Puertos del Estado
SIMAR	2.8 km	1 h	From 13-12-2005 to the present	Model	none	Puertos del Estado
MEDSEA-Wav	~4.6 km ($1/24^\circ$)	1 h	1993–2016	Model	EQM by buoy	Copernicus Marine

Table 2. Wave and sea level rise projections. The table includes spatial and temporal atmospheric resolution, bias adjust applied, and affiliated institution.

Model	Atm. Spatial Resolution	Atm. Temporal Resolution	Bias Adjust	Institution
ACCESS 1.0	1.25° × 1.9°, L38	3 h	EQM by MEDSEA-WAVE	CSIRO and Bureau of Meteorology
CSIRO-Mk3.6.0	1.9° × 1.9°, L18	6 h	EQM by MEDSEA-WAVE	CSIRO, Industrial Research Organization & QCCCE
EC-EARTH	1.1° × 1.1°, L62	3 h	EQM by MEDSEA-WAVE	EC-EARTH consortium
GFDL-ESM2G	2° × 2.5°, L48	3 h	EQM by MEDSEA-WAVE	NOAA Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	2° × 2.5°, L48	3 h	EQM by MEDSEA-WAVE	NOAA Geophysical Fluid Dynamics Laboratory

The SIMAR reanalysis dataset (provided by Puertos del Estado) is used to validate the wave propagation methodology to shallow waters (downscaling) in the study area. The SIMAR dataset was generated by concatenating two simulated datasets, SIMAR-44 and WANA. To model wave fields over time, two third-generation models, WAM and WaveWatch III, are used with a nested grid scheme. These models are fed with wind data obtained from the HARMONIE-AROME mesoscale model provided by the State Meteorological Agency (AEMET, Spain). First, SIMAR point data (315047108) are used to propagate the wave time series into the Bay of Cadiz. The propagated wave field is then validated using data from SIMAR points located in intermediate waters at eight different locations within the study area (see Figure 1A). The validation period from 13 December 2005 to 1 May 2003 was selected based on the availability of SIMAR data.

The global wave projection data used in this study (Table 2) were generated using the spectral wave model WaveWatch III (version 4.18, [33]) forced by 10 m wind extracted from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models ACCESS 1.0 (CSIRO-BOM, Australia), CSIRO-Mk3.6.0 (CSIRO-QCCCE, Australia), EC-EARTH (EC-EARTH consortium), GFDL-ESM2G, and GFDL-ESM2M (NOAA Geophysical Fluid Dynamics Laboratory USA). These models attain a horizontal resolution of 0.5° and a temporal resolution of 6 h [23]. The selection of these models is based on their high performance in reproducing synoptic situations and inter-annual variability across Europe [34]. CMIP5 models have a typical resolution of around 1°, which means they do not resolve tropical cyclones and poorly represent midlatitude storms [35].

In our analysis, sea level perturbation considers both tides and mean sea level. In CMIP models, ocean dynamic sea level (DSL) is diagnosed as ZOS [36]. However, DSL simulations from global climate models (GCMs) do not include the effect of sea level pressure on sea level (inverted barometer effect). ZOS varies locally due to ocean circulation and horizontal gradients, with its global mean being zero at every time step. As a result, ZOS excludes global mean sea level rise (GMSLR). The mean sea level, due to thermal expansion, changes in salinity affecting density, and water flows from the atmosphere, land, and glaciers, while always maintaining a constant total volume, is represented by ZOSGA. For this reason, as an approximation to sea level, we use the “adjusted ZOS,” which is the sum of ZOS and ZOSGA. These variables were retrieved from the Earth System Grid (ESG) for the five global models previously mentioned. For the CSIRO-Mk360 model, ZOSTOGA (global mean thermosteric sea level rise; GMTSLR) is used instead of ZOSGA. Meanwhile, for the EC-EARTH model, only ZOS data are available. These are monthly data, so we interpolate them every 6 h and incorporate the tidal effect in order to later integrate them into the reconstruction of wave patterns within the bay. Furthermore, by using 3 h and 6 h wind fields to force wave models, much of the high-frequency nature of the wind climate

is not captured, which could lead to substantial errors when estimating the wave energy resource in a region [37].

2.2. Wave Climate Reconstruction

Global wave models are the most comprehensive tools available for simulating past and future wave climate on a global scale. However, they are unable to accurately simulate wave transformation processes in intermediate and shallow waters due to their limited spatial resolution. This limitation prevents the proper representation of bathymetric and coastal features, leading to systematic biases in the coastal zone.

2.2.1. Bias Adjustment of Global Wave Model

To mitigate these uncertainties, outputs from global wave models are corrected in two stages using wave buoy measurement and high-resolution wave reanalysis data (Med-WAV), involving both scalar and directional corrections. Since directional data from the buoy are limited and only available from 2001 onwards, we are unable to use directly observational data to correct the data from the global wave model, so the correction process is performed in two phases. First, the observational data (1983–2014) are used for the correction of the Med-WAV reanalysis at the location closest to the coastal buoy of Cadiz. Subsequently, in a second phase, the corrected Med-WAV model output (1993–2005) is used to adjust the bias in the global wave projections. The correction in both phases involves a scalar correction using the Empirical Quantile Mapping (EQM) method to address biases across different quantiles [38]. Subsequently, directional adjustment is carried out by dividing wave directions into 22.5° sectors. Within each sector, the difference between the mean directions of Med-WAV and global wave projections is calculated and applied as a correction [39]. The bias adjustment process is applied to the entire analysis period (baseline: 1981–2005; projections: 2006–2099), assuming that model biases and correction functions remain stationary over time.

2.2.2. Hybrid Downscaling

The adjusted global wave model time series are downscaled from deep water to shallow water using the hybrid downscaling methodology proposed by Camus et al. [40]. This approach combines a numerical wave model with statistical techniques and involves selecting a limited number of cases, within the range of 189 to 254 cases, based on the slide period and model. These cases ensure a proper representation of the possible sea states through bulk wave parameters (H_s , T_p , and Dir) and sea level (SL) in deep waters using a maximum dissimilarity selection algorithm. SL accounts for the tide and sea level rise associated with each period and model.

The selected sea states are propagated in the Bay of Cadiz using the third-generation wave model SWAN (“Simulating Waves Nearshore”; [41]). The spatial domain is discretized in a regular mesh with 37.5 m resolution. The mesh resolution is selected to balance the computational cost and the accurate representation of the bathymetric features (i.e., rocky outcrops, rocky shoals, and navigation channels) in the study area. We employ 36 directional bins ($\Delta\theta = 10^\circ$) and 24 frequencies, with logarithmic spacing from 0.05 to 1.00 Hz. The range of the frequency is representative of the wave condition measured in the study area provided by the wave buoy used for the correction of MEDSEA-WAV reanalysis (2001–2014), where most of the data exhibit peak periods shorter than 20 s (see Figure 1 and [7]). The Battjes and Janssen [42] formula represents the depth-limited wave breaking. Then, the time series of the parameters of the propagated sea states are reconstructed at each node of the grid using an interpolation technique based on radial basis functions [40].

The effectiveness and accuracy of the EQM correction procedure and the wave propagation method are evaluated according to the following statistical indicators for scalar quantities:

- The correlation coefficient $ro = \sum_{i=1}^N (S_i - \bar{S})(R_i - \bar{R}) / \sigma_S \sigma_R$, where N denotes the number of data, S_i and R_i are simulations and reference data, σ_S and σ_R are their corresponding standard deviations, and the over bar denotes time averaging.
- The symmetrically normalized root mean square error, HH, introduced by Hanna and Heinold [43], $HH = \sqrt{\sum_{i=1}^N (S_i - R_i)^2 / \sum (S_i R_i)}$. This indicator combines information on the components of average error and dispersion and is characterized by not being biased towards simulations that underestimate the average [44].
- The root mean square error (RMSE), $RMSE = \sqrt{\frac{1}{N} \left[\sum_{i=1}^N (S_i - R_i) \right]^2}$.
- The normalized root mean square error (NRMSE):

$$NRMSE = \sqrt{\frac{\sum_{i=1}^N (S_i - R_i)^2}{\sum_{i=1}^N (R_i)^2}}$$

- The bias (BIAS), $BIAS = \bar{S} - \bar{R}$.
- The normalized bias (NBI), $NBI = \sum_{i=1}^N (S_i - R_i) / \sum_{i=1}^N (R_i)$.
- The scatter index (SI), $SI = \sqrt{\frac{1}{N} \left[\sum_{i=1}^N (S_i - \bar{S})(R_i - \bar{R}) \right]^2 / \bar{R}_i^2}$.

For the circular direction (θ), the normalized bias (NBI_θ) and the normalized root mean square error ($NRMSE_\theta$) are normalized by employing a 2π radians angle [45]:

- $NRMSE_\theta = \sqrt{\frac{\sum_{i=1}^N \text{mod}_{-\pi, \pi}(\theta_{Si} - \theta_{Ri})^2 / N}{2\pi}}$
- $NBIAS_\theta = \sum_{i=1}^N \text{mod}_{-\pi, \pi}(\theta_{Si} - \theta_{Ri}) / 2\pi N$ where the modulo operator $\text{mod}_{-\pi, \pi}$ indicates that if $(\theta_{Si} - \theta_{Ri}) > \pi$, a 2π angle is subtracted from the difference, and if $(\theta_{Si} - \theta_{Ri}) < -\pi$, a 2π angle is added to the difference.

The skill scores are computed for the whole time series but also for the upper tail (>99th) in order to specifically evaluate the capability of the global wave model and downscaling methods to reproduce extreme wave conditions because of their large potential to damage UCH.

2.2.3. Bathymetry and Sediment Characterization

The bathymetry and seabed slope required for wave modeling were derived from multibeam echosounder data obtained during a comprehensive eco-cartographic study conducted in 2011 [46]. Additionally, seafloor mapping using multibeam backscatter data allowed for the classification of seafloor types, distinguishing between rocky and unconsolidated sediments. Sediment grain size was determined using 460 samples collected using a Van Veen grab.

2.2.4. Archeological Datasets

The archeological database, compiled by Fernández-Montblanc et al. [7], provides information about the main characteristics of UCH sites. This dataset includes attributes such as provenance and chronology; material composition (organized into five categories: metallic, stone, glass, ceramic, and wood/organic materials) and dominant material; meta-data, including data source; and basic environmental characteristics of the sites, such depth and seabed type (when available). The archeological database comprises 56 sites of different chronologies spanning from 500 BC to AD 1820.

2.3. Risk Assessment

The risk assessment methodology evaluates UCH vulnerability to wave-induced hazards by calculating a risk index specific to each archeological site [7]. Each UCH site is treated as an asset susceptible to wave-induced damage.

The risk index is calculated as a function of vulnerability (determined by archeological materials, seabed slope, and type) and hazard. The analysis focuses on three primary wave-induced hazards that influence the long-term preservation of UCH: archeological decontextualization (DCR), scouring (SC), and erosive wear (EW). Each of these hazards is assessed independently without considering interactions between them. A response-based approach [47] is used, where hazard probability is directly calculated without presupposing underlying drivers or governing variables.

An indicator is defined for each hazard, and its assessment follows three sequential steps [48,49]. First, the time series of the hazard indicator are calculated based on the depth, seabed, grain size, wave characteristics, and sea level perturbation (tide + sea level rise). Second, extreme hazard probabilities are modeled using a transformed-stationary methodology. In this case, storm events are decluttered using a 72 h time window, and a constant threshold (97th percentile) is applied to select extreme events. The selected extreme events are fitted to a generalized Pareto distribution (see [50] for further details). For the case of archeological decontextualization and scour hazard, values corresponding to a 10-year return period are used as intermediate values in the extreme distribution. However, for the case of erosive wear hazard, a 1-year return period is selected to account for the continuous impact of wear on UCH materials. This reflects the high-frequency, cumulative damage of wear rather than isolated extreme events. Hazard indicators for each return period are ranked, and hazard scores (0 to 5) are assigned (see Table 3).

Table 3. Hazard indicator scores for decontextualization, scouring, and wear erosion.

Critical Size of Decontextualized Object, DCR (m) RT10	Scouring Volume, SV (m ³) RT10	Erosive Wear Potential, EWP (J/m ³) RT1	Scores	Level of Hazard
Dcr < 0.02	SV < 0.05	−20 ≥ EWP < −18	0	None
0.02 ≥ Dcr < 0.04	0.05 ≥ SV < 0.1	−18 ≥ EWP < −16	1	Low
0.04 ≥ Dcr < 0.08	0.1 ≥ SV < 0.15	−16 ≥ EWP < −13.5	2	Low/medium
0.08 ≥ Dcr < 0.12	0.15 ≥ SV < 0.3	−13.5 ≥ EWP < −12.5	3	High/medium
0.12 ≥ Dcr < 0.16	0.3 ≥ SV < 0.4	−12.5 ≥ EWP < −11.5	4	High
Dcr ≥ 0.16	SV ≥ 0.4	EWP ≥ −11.5	5	Very high

RT10 corresponds to the value of a 10-year return period and RT1 to a 1-year return period.

Given the limited amount of information about UCH sites, we assume that all of them have the same exposure value. The risk index is calculated as the geometric square root of the product of the hazard and the vulnerability scores [48,51]. The vulnerability index ranges from 1 to 5 and is determined by the material composition of the UCH site and the specific hazard considered (refer to Table 4).

$$\text{UCHrisk} = \sqrt{\text{Hazard} \cdot \text{Vulnerability}} \quad (1)$$

Table 4. Vulnerability scores in common material in underwater cultural heritage sites for decontextualization, scouring, and wear erosion hazard.

	Material Category	Material Type	Vulnerability Score
Decontextualization	Metallic	Gray iron	1
	Stone	Marble	2
	Glass	Glass	3

Table 4. Cont.

	Material Category	Material Type	Vulnerability Score
Scouring	Ceramics	Coarse ware	4
	Wood/organic material	Oak	5
	Glass	Glass	1
	Metallic	Gray iron	2
	Ceramics	Coarse ware	3
	Stone	Marble	4
	Wood/organic material	Oak	5
	Stone	Marble	1
Wear erosion	Metallic	Gray iron	2
	Ceramics	Coarse ware	3
	Glass	Glass	4
	Wood/organic material	Oak	5

Sites are classified as “at risk” when $UCH_{Risk} > 3.2$, a threshold derived as the rounded geometric mean of “low” (2) and “very high” (5) classes. Higher UCH_{Risk} values indicate a combination of medium to very high vulnerability and hazard classes.

2.4. Wave Energy Flux

Wave energy flux (WEF) serves as comprehensive indicator of wave climate within the study area.

To account for water depth effects, the WEF calculation follows the methodology outlined by Liang et al. [52]:

$$WEF = \frac{\pi \rho g h H_s^2}{16 T_e} \left[1 + \frac{2kh}{\sinh(2kh)} \right] \quad (2)$$

where ρ is the water density, g is the gravitational acceleration, h is the water depth taking into account the sea level perturbation (tide and sea level rise), and H_s and T_e are the significant wave height and energy period, respectively, where T_e can be approximated as $T_e = T_p$. T_p denotes the peak period, while $k = 2\pi/L$ represents the wave number, and L is the wavelength. An extreme value analysis of the WEF time series is conducted for each grid node using the methodology in Section 2.3, focusing on a 10-year return period.

2.5. Variations in WEF and UCH Risk Induced by Climate Change

From the 5-member model ensemble, and for each considered period and scenario, we calculate the ensemble mean and standard deviation of WEF, hazard indices, and risk.

Model agreement is evaluated based on the coefficient of variation (CV) [53–55]. The CV is defined as the ratio of the standard deviation of the model ensemble, σ , to the ensemble mean value:

$$CV = \frac{\sigma_\alpha}{\bar{\alpha}} \quad (3)$$

where σ_α is the standard deviation of the model ensemble and $\bar{\alpha}$ is the ensemble mean. CV decreases as intra-model variability becomes a smaller fraction of the ensemble mean value, implying greater agreement among models and statistical significance of the ensemble mean value. To reduce uncertainty, values with $|CV| > 0.8$ are not considered, corresponding approximately to an average agreement of four out of five models (i.e., 80% probability).

Finally, WEF or UCHrisk variation induced by climate change is assessed by means of absolute changes ($\Delta\alpha$) for each period (mid-century and end-of-century periods) corresponding to the RCP 4.5 and RCP 8.5 scenarios (α_{RCP}) with respect to baseline values ($\alpha_{baseline}$):

$$\Delta\alpha = \alpha_{RCP} - \alpha_{baseline} \quad (4)$$

3. Results

3.1. Wave Climate

3.1.1. EQM Correction

Global wave model outputs, with and without correction, were compared with corrected Med-WAV (Figure 3). The uncorrected global models underestimate significant wave height (Hs) values and extreme Hs values. This is particularly noticeable for ACCESS 1.0, GFDL-ESM2G, and GFDL-ESM2M (Figure 3A,D,E; also, see Table S1 in SM) where the EQM largely improves the Hs NBI index. CSIRO-Mk3.6.0 and EC-EARTH show better performance (HH ~ 0.8 ; Table S1 in SM) with an EQM improvement of $\sim 5\%$ in HH.

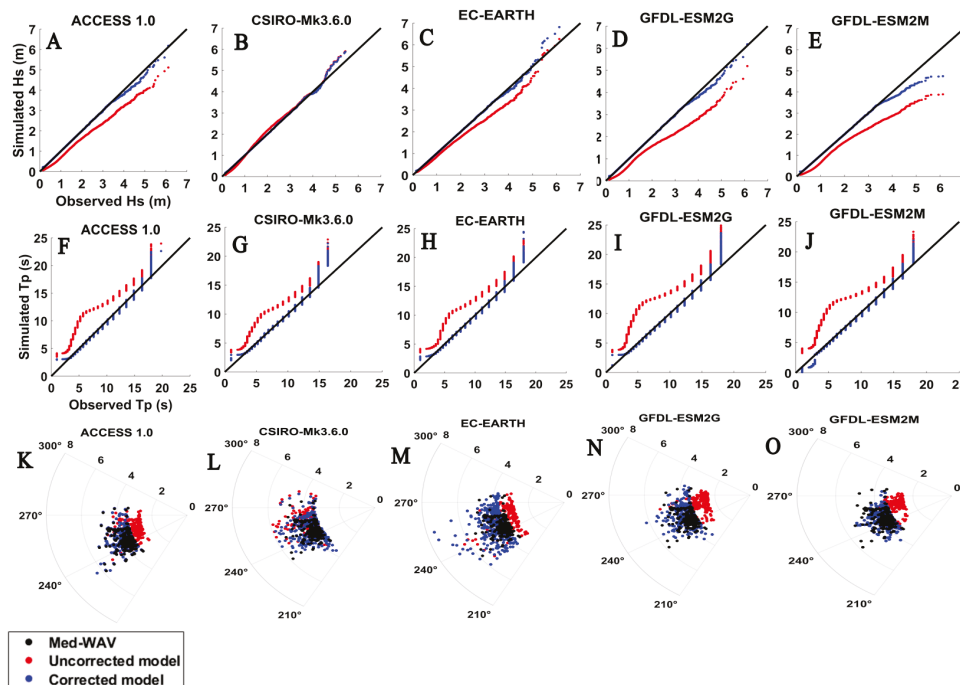


Figure 3. Q-Q plot of significant wave height (Hs) (A–E) peak period (Tp) (F–J). Polar plot for wave heights exceeding 99th percentile (K–O). Uncorrected global wave model (red), corrected global wave model (blue), and Med-WAV reanalysis (black) are represented.

The uncorrected global wave model outputs overestimate, in general, the peak period (Tp) (NRMSE ~ 0.6), with EQM correction improving $\sim 10\%$ for CSIRO-Mk3.6.0 and EC-EARTH models (Figure 3G,H) and $\sim 18\%$ for the rest of the models (Figure 3F,I,J).

For the case of wave directions with an Hs greater than or equal to the 99th percentile (P99), the uncorrected models show a deviation of approximately 25° (NRMSE₀ $\sim 39^\circ$; Figure 3K,L,N,O). After applying the EQM correction, this improves by 63% (NRMSE₀ $\sim 20^\circ$), except for the case of EC-EARTH, where the bias increases by 66% (Figure 3M). Overall, in the study area, EC-EARTH and CSIRO-Mk3.6.0 show the best agreement with the Med-WAV reanalysis, both with and without correction. Specifically, CSIRO shows better alignment for Hs, especially for extreme values. On the other hand, EC-EARTH performs better in capturing extreme Tp values compared to the other models. Regarding wave direction, EC-EARTH

shows the best agreement among the uncorrected models. However, after applying the EQM correction, CSIRO achieves the most accurate alignment with the observed data.

3.1.2. The Validation of the Wave Propagation Method

This section summarizes the performance of the wave propagation method to reproduce average and extreme wave conditions (>99th). This step is crucial for reducing the uncertainties associated with global models, which do not accurately represent wave transformation processes in intermediate and shallow waters due to their limited spatial resolution. Due to the lack of observational data within the bay, SIMAR points were selected to assess the model's performance within the bay. SIMAR reanalysis was selected as the best alternative due to its wide spatial distribution in the region, good temporal coverage, and frequent use in wave studies conducted across the Iberian Peninsula (e.g., [56,57]). Table 5 shows the average values of skill scores for Hs, Tp, and Dir calculated in the eight SIMAR locations in the Bay of Cadiz. The validation indicates a good performance, especially for extreme wave conditions, for Hs ($ro = 0.95$; $HH = 0.07$) and Tp ($ro = 0.82$; $HH = 0.18$). The biases related to Hs are practically zero, while Tp is generally affected by a negative bias. However, the results are quite adequate. The wave direction shows also good agreement, although performance worsens in extreme events.

Table 5. Statistical scores for mean and extreme significant wave height, peak period, and mean direction between propagated series and SIMAR points.

	ro	HH	NRMSE	NBI
Hs (m)	0.96	0.18	0.18	0.05
P99 Hs	0.95	0.07	0.07	−0.02
Tp (s)	0.82	0.28	0.26	−0.14
P99 Tp (s)	0.83	0.18	0.17	−0.11
Dir (°)	-	-	2.60	−1.72
P99 Dir (°)	-	-	13.42	38.39

3.2. Changes in WEF

Scalar and Direction Climate

The WEF associated with a 10-year return period (RT10) shows maxima (around $15 \times 10^4 \text{ Wm}^{-1}$) in the outer domain and by the rocky outcrops outside the bay. Minima appear by the coast, where shallow depths and the wave breaking limit reduce the WEF, and inside the bay due to the protective effect of the Cadiz tombolo against wave front propagation (Figure 4A). Under RCP4.5, the WEF associated with RT10 shows a general decrease, slightly increasing only by some coastal stretches, over rocky outcrops and inside the bay (Figure 4B,C). The general WEF decrease is weaker in the end-of-century period than in the mid-century period as a result of the larger SLR. The mid-century RCP8.5 WEF change pattern replicates that of the RCP4.5 WEF, but with a weaker general decrease and slightly larger increments located in the shallower areas (Figure 4E). By the end-of-century period in RCP8.5, there is a general WEF increase, with maxima located at shallow waters and rocky outcrops (Figure 4F). Additionally, a southward shift in the WEF direction is evident in all cases except for RCP4.5 in the mid-future period.

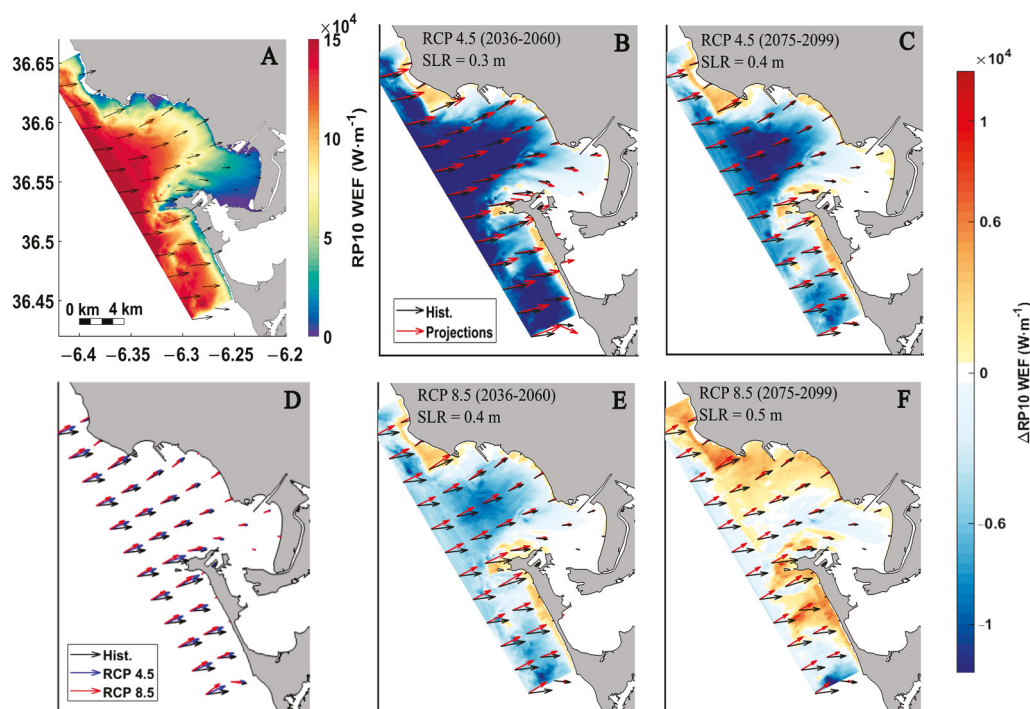


Figure 4. (A) The wave energy flux corresponding to the 10-year return period and the mean direction associated with the 99th percentile or greater of the WEF (black arrow). The absolute change and mean direction associated with the 99th percentile of the WEF for each simulation (red arrow): (B) the 2036–2060 period of the RCP 4.5 scenario, (C) the 2075–2099 period of the RCP 4.5 scenario, (E) the 2036–2060 period of the RCP 8.5 scenario, and (F) the 2075–2099 period of the RCP 8.5 scenario. The sea level rise (SLR) for each period is shown in the bottom left corner and represents the average increase calculated from the five global models used. (D) The mean direction associated with the 99th percentile or greater of the WEF for the historical period (black arrow), the end-of-century period of the RCP 4.5 scenario (blue arrow), and the end-of-century period of the RCP 8.5 scenario (red arrow).

Such a direction shift also takes place for the most energetic waves. Figure 4D shows the average of the directions of the extreme waves (>99th) for the historical period and for the end-of-century period in the RCP 4.5 and RCP 8.5 scenarios. While the most energetic waves impact the bay from the west (ca. 263°) during the historical period, they come from 250° in the RCP 4.5 scenario and from 240° in RCP 8.5. This change in the direction of incident waves in the bay leads to an alteration in their propagation within the Bay of Cadiz, resulting in a greater impact on the areas of Rota, Cadiz, and the surrounding areas.

To determine how the increase in sea level affects wave propagation, the methodology is repeated without considering the SLR (Figure 5). These results show a larger WEF decrease than when considering SLR, which is particularly notable over the shallow coastal areas and rocky outcrops, where the depth increase due to SLR makes a substantial contribution to the WEF.

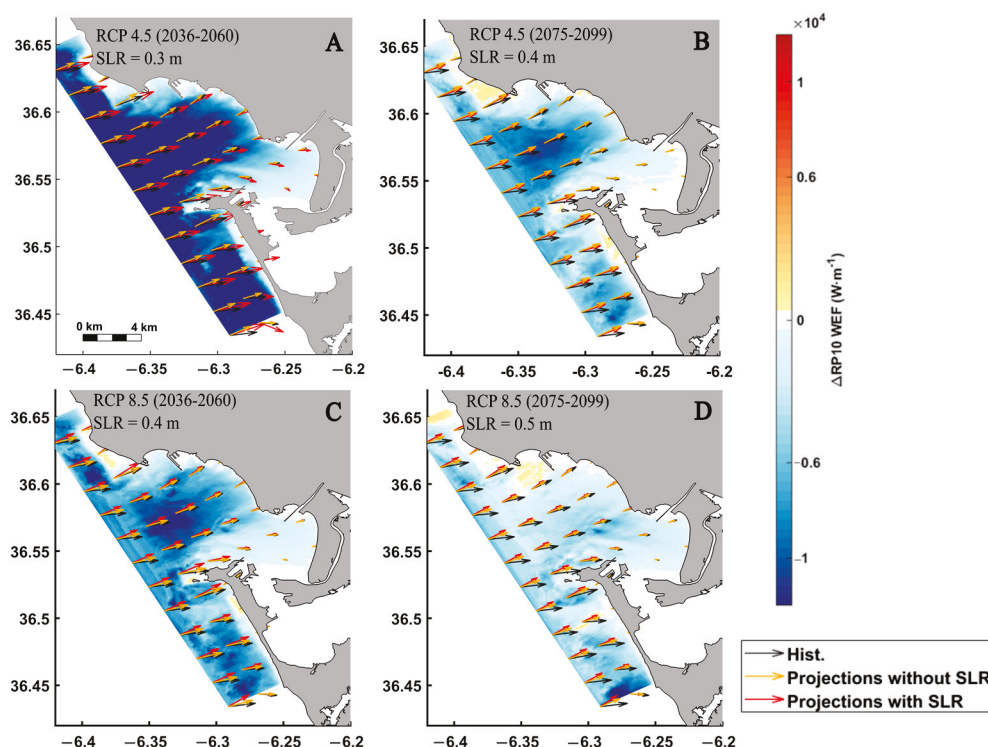


Figure 5. The absolute changes in wave energy flux (WEF) with and without sea level rise are shown for the following: (A) the 2036–2060 period of the RCP 4.5 scenario, (B) the 2075–2099 period of the RCP 4.5 scenario, (C) the 2036–2060 period of the RCP8.5 scenario, and (D) the 2075–2099 period of the RCP 8.5 scenario. The mean direction associated with the 99th percentile or greater of the WEF for the historical period (black arrow) is shown with sea level rise (red arrow) and without SLR (orange arrow) projections.

3.3. Hazard Assessment

3.3.1. Decontextualization Hazard

We relate decontextualization hazard (DCR) to the maximum critical diameter of an object (we assume sphericity) susceptible to be displaced due to wave action over a 10-year return period (Figure 6). All projections present a slight general reduction in the value of DCR, except for the bay's interior and shallower areas, where local significant increases (up to 25%) are observed compared to the historical period. This result aligns with the projected general reduction in the WEF and its local increase in shallower areas. In shallow areas, the wave-induced bottom stress is larger, but as wave orbital velocity strongly attenuates with an increasing depth (Figure S1), DCR is reduced throughout the rest of the bay. The mid-century RCP4.5 and the end-of-century RCP8.5 scenarios exhibit the most substantial hazard changes. However, the result of these changes reflects only as a decrease in the bay area under a hazard score of 3 and an increase in the bay area as a hazard score of 2. The percentages of the bay area classified as high and very high hazards (scores of 4 and 5; Figure 6D) remain nearly unchanged.

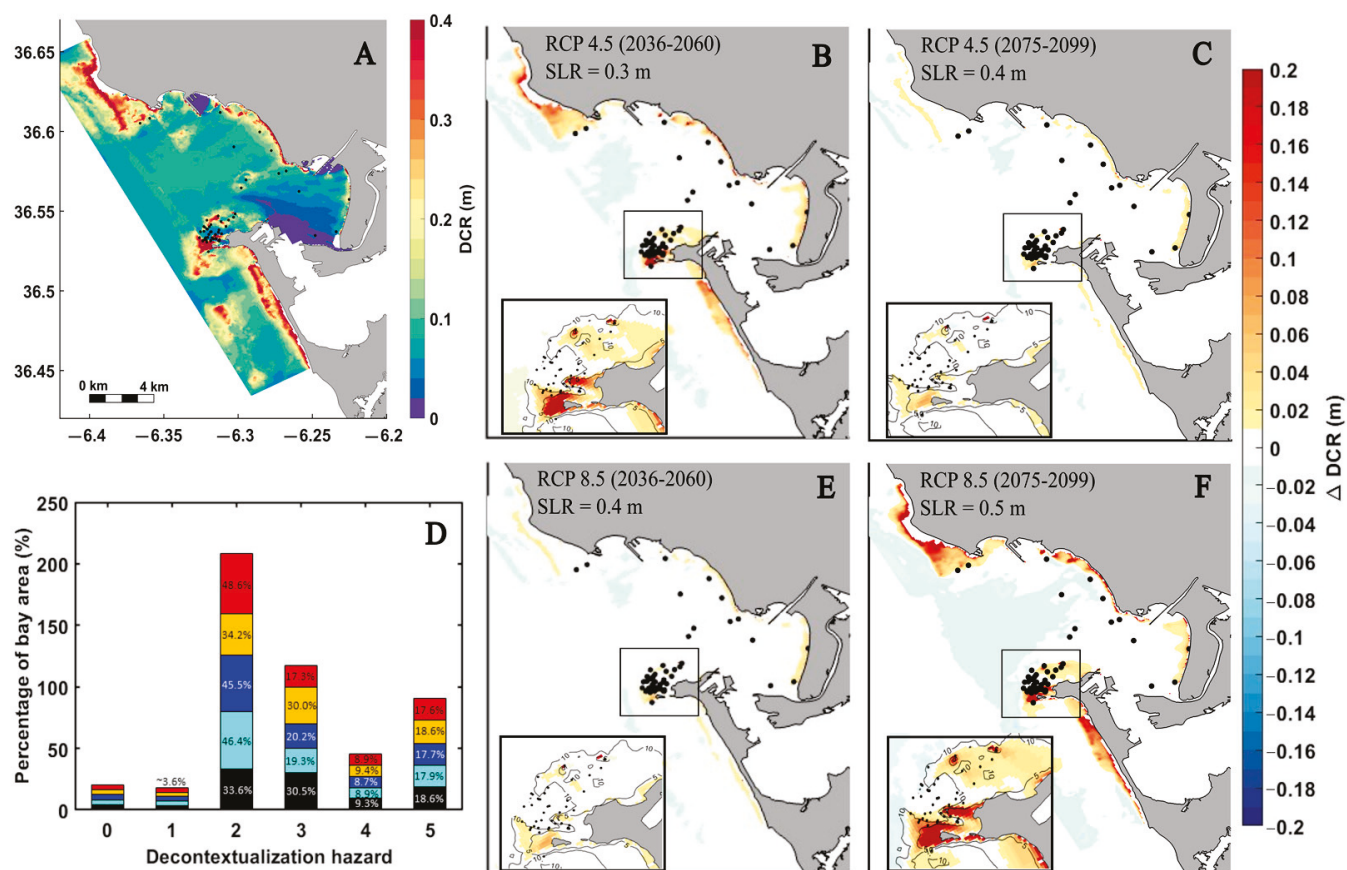


Figure 6. (A) A map of decontextualization hazard (the critical diameter of an object moved under wave action) for the historical period. The absolute change in this hazard for (B) the 2036–2060 period of the RCP 4.5 scenario, (C) the 2075–2099 period of the RCP 4.5 scenario, (E) the 2036–2060 period of the RCP 8.5 scenario, and (F) the 2075–2099 period of the RCP 8.5 scenario compared with the historical period. The black points indicate the locations of UCH sites. (D) A histogram of the hazard at UCH sites and hazard classes. The sea level rise (SLR) for each period is shown in the bottom left corner and represents the average increase calculated from the five global models used.

3.3.2. Scour Hazard

The scour hazard indicator is represented by the potential volume of scouring corresponding to a 10-year return period (Figure 7). In general, no significant changes in the scouring hazard are observed in the Bay of Cadiz for all the scenarios and periods considered. However, locally significant variations are identified in the shallower areas of the bay (less than 5 m) and in some rocky outcrops, such as those located off Rota and Cadiz. In these areas, the RCP 4.5 scenario for the mid-century period and the RCP 8.5 scenario for the end-of-century period show mostly positive anomalies, while the RCP 4.5 scenario for the end-of-century period and the RCP 8.5 scenario for the mid-century period exhibit mostly negative anomalies. These changes result in an increase in the percentage of the bay area classified as a high hazard level (4), accompanied by a decrease in the very high hazard level (5; Figure 7D). The percentage change is very similar across all periods; however, it is at the end of the century for the RCP 4.5 scenario where the greatest reduction in the percentage of the bay area classified as having a very high hazard level is observed.

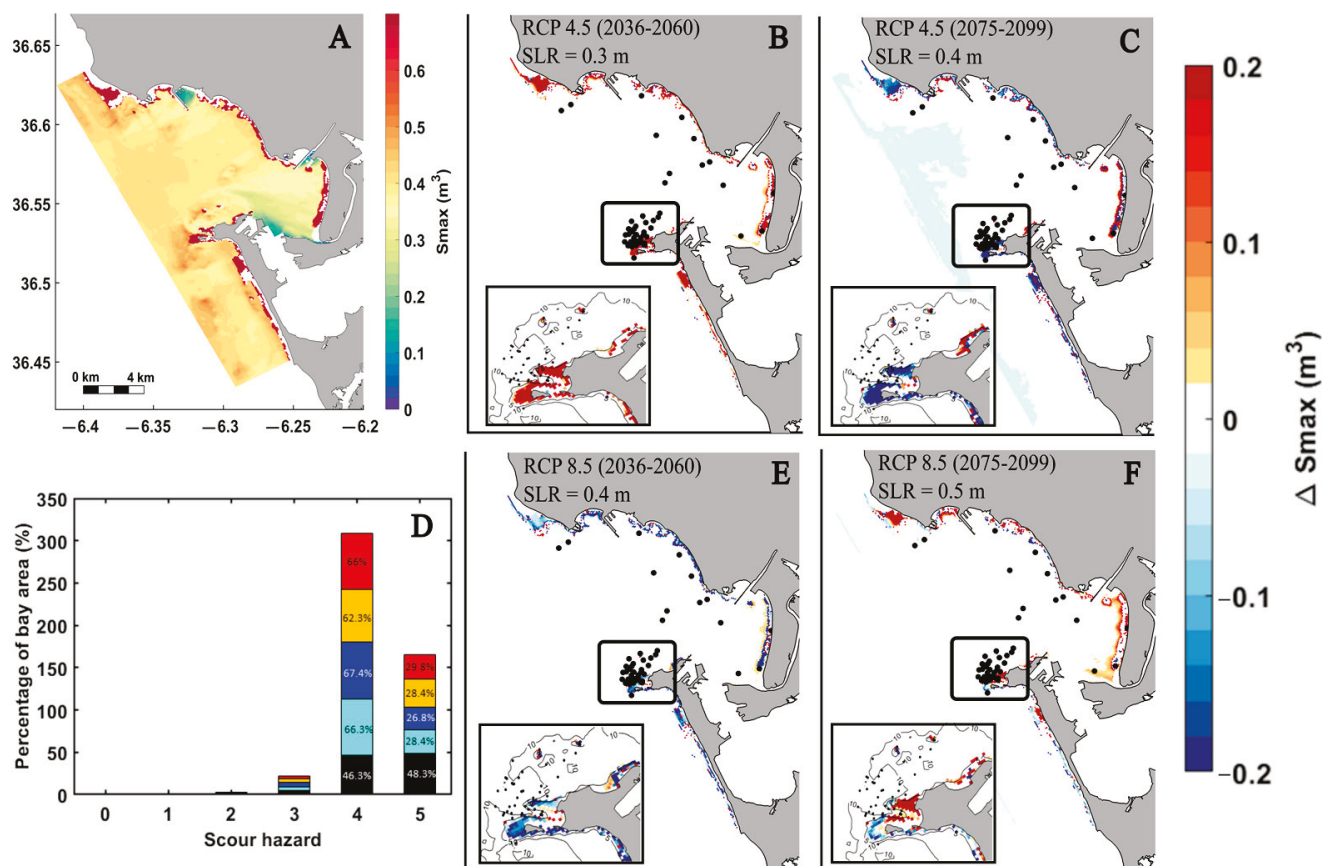


Figure 7. (A) A map of the scour hazard (scour volume) for the historical period. The absolute change in this hazard for (B) the 2036–2060 period of the RCP 4.5 scenario, (C) the 2075–2099 period of the RCP 4.5 scenario, (E) the 2036–2060 period of the RCP 8.5 scenario, and (F) the 2075–2099 period of the RCP 8.5 scenario compared with the historical period. The black points indicate the locations of UCH sites. (D) A histogram of the hazard at UCH sites and hazard classes. The sea level rise (SLR) for each period is shown in the bottom left corner and represents the average increase calculated from the five global models used.

3.3.3. Wear Erosion Hazard

The indicator erosive wear hazard is analyzed by means of the erosion potential (Figure 8). This hazard exhibits the most significant future changes compared to the historical period. The changes for both scenarios are predominantly positive, indicating an increase in the magnitude of the hazard. These changes are more intense near the southern entrance of the bay, where most UCH sites are located. However, significant negative anomalies are also recorded at the rocky outcrops off the city of Cadiz, being more pronounced in the RCP 8.5 scenario, particularly towards the end of the century. As a result, there is an increase in the percentage of the bay area that will be affected by a very high hazard level (5) for erosive wear hazard (Figure 8D).

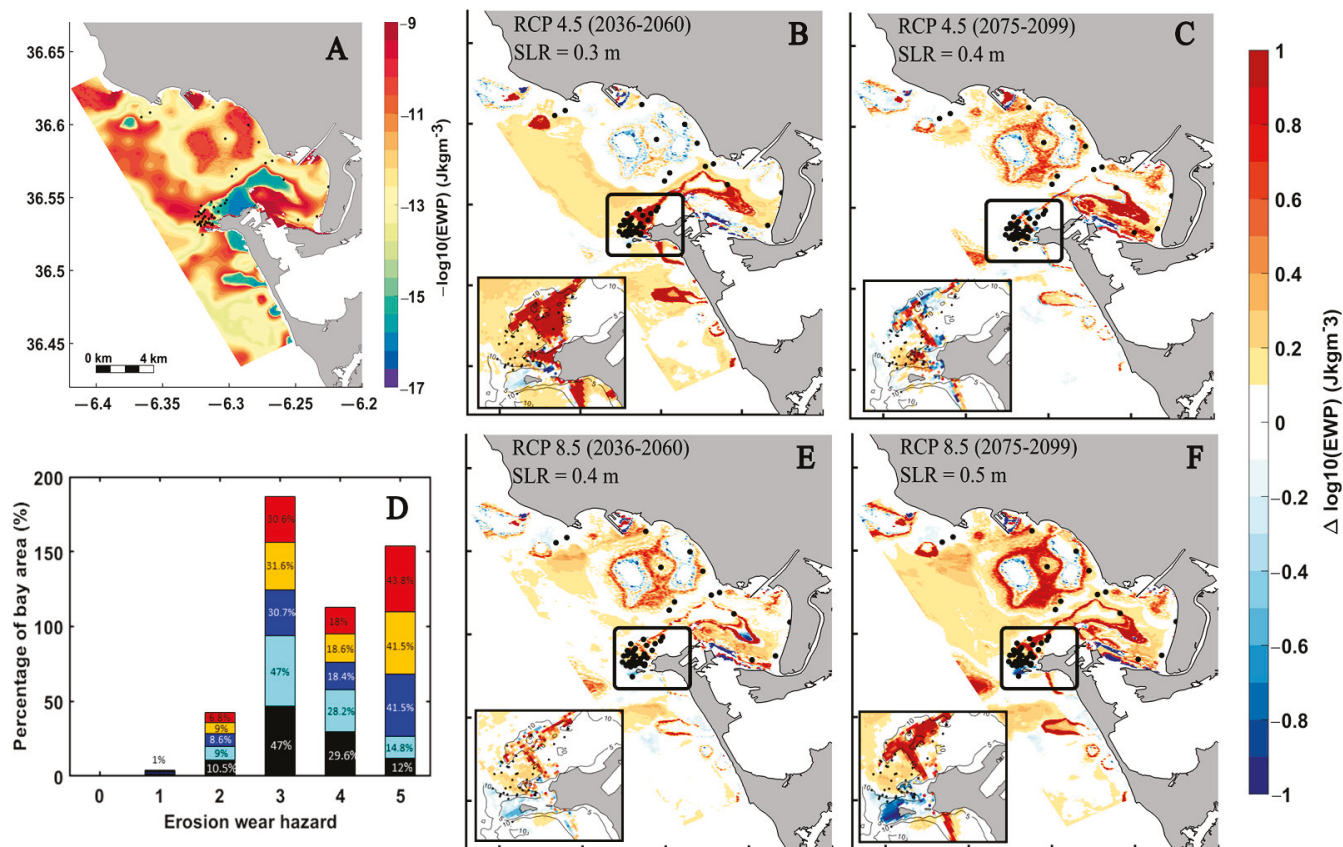


Figure 8. (A) A map of the erosive wear hazard (log of erosive wear potential) for the historical period. The absolute change in this hazard for (B) the 2036–2060 period of the RCP 4.5 scenario, (C) the 2075–2099 period of the RCP 4.5 scenario, (E) the 2036–2060 period of the RCP 8.5 scenario, and (F) the 2075–2099 period of the RCP 8.5 scenario compared with the historical period. The black points indicate the locations of UCH sites. (D) A histogram of the hazard at UCH sites and hazard classes. The sea level rise (SLR) for each period is shown in the bottom left corner and represents the average increase calculated from the five global models used.

3.4. UCH Risk Assessment

Figure 9 shows the underwater cultural heritage risks (UCHRs) at the studied sites in the Bay of Cadiz. During the historical period, there are 7 UCH sites under decontextualization risk, 19 under scour risk, and 21 under wear erosion risk (UCHR_{DE} , UCHR_{SC} , and $\text{UCHR}_{\text{EW}} > 3.2$). The sites under risk are mainly located around the city of Cadiz, with the exception of two located by the eastern coast of the Bay of Cadiz (Valdelagrana). In general, the sites present lower risk values associated with decontextualization and larger risk values associated with erosion wear. In the historical period, the distribution of risks is skewed towards low values for UCHR_{DE} , centered near 3.2 for UCH_{SC} , and it presents a bimodal distribution with a narrow peak at 3.8 for UCH_{WE} . In the future scenarios, the number of UCH sites at risk (>3.2) remains unchanged for the risks of decontextualization and scouring. However, for wear erosion under the RCP 4.5 scenario, the number of sites at risk increases from 21 to 23 at the mid-century period and to 22 at the end of the century (Figure 10). The sites turning under risk are located at the rocky outcrops off the city of Cadiz and are related to strong and very local changes in erosion wear hazard (see Figure 8).

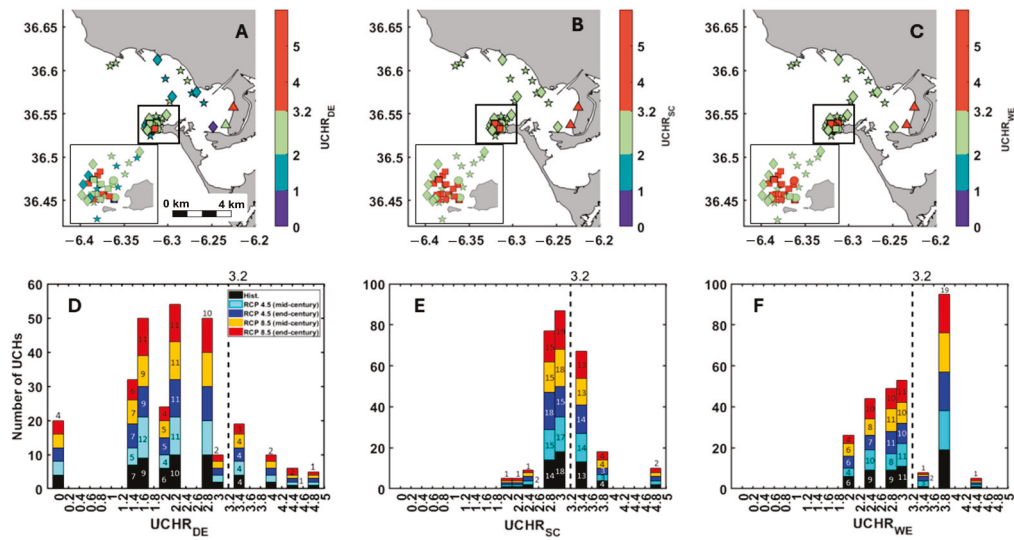


Figure 9. (A) The decontextualization risk (UCHR_{DE}) for UCH sites located in the Bay of Cadiz, (B) the scour risk (UCHR_{SC}) for UCH sites, and (C) the wear erosion risk (UCHR_{WE}) for UCH sites. Warm colors indicate a higher risk index, and different shapes refer to the prevalent material (diamonds, metallic material; squares, ceramic material; filled circles, stone; triangles, wood/organic material; pentagons, unknown material). Accumulated graphs of the classification of UCHs in terms of the risks of (D) decontextualization, (E) scour, and (F) wear erosion.

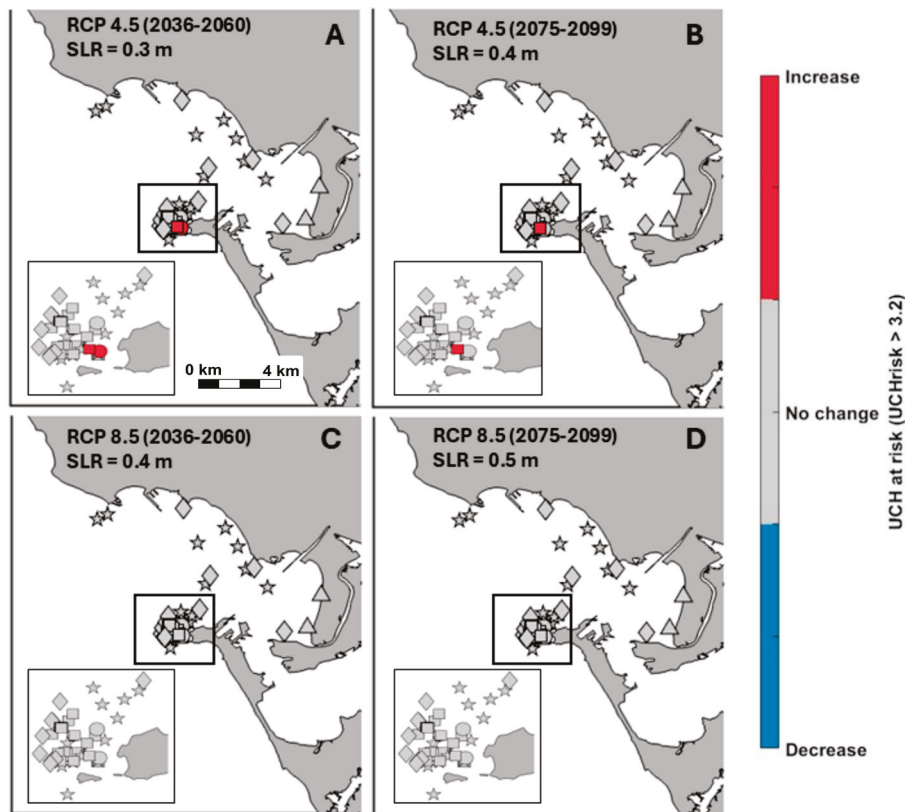


Figure 10. The erosive wear risk (UCHR_{WE}) for UCH sites located in the Bay of Cadiz. The absolute change for (A) the 2036–2060 period of the RCP 4.5 scenario, (B) the 2075–2099 period of the RCP 4.5 scenario, (C) the 2036–2060 period of the RCP 8.5 scenario, and (D) the 2075–2099 period of the RCP 8.5 scenario compared with the historical period. The sea level rise (SLR) for each period is shown in the bottom left corner and represents the average increase calculated from the five global models used.

4. Discussion

This study outlines a methodology to evaluate the impacts of climate change on UCH through wave-induced hazards. It is based on a hybrid downscaling [33] of the bias-corrected wave fields [31,32] corresponding to the CMIP5 RCP4.5 and RCP8.5 scenarios. Both scenarios show a robust reduction in significant wave height in the North Atlantic (see also Wang et al. [58] and Lemos et al. [59]). However, most UCH is placed in shallow coastal areas, where the wave fields will be affected by shallow water processes, coastline orientation and bathymetric relief, and by the concurrent SLR; therefore, downscaling the global wave fields is necessary. Our results show that the use of the EQM method and the directional adjustment improved the global wave model outputs (see Table S1). This correction is key for obtaining accurate high-resolution wave propagated fields. This is corroborated by the validation of the wave downscaled fields against SIMAR reanalysis points (Table 3). The validation presented very good results for both mean wave climate and for extreme P99 waves.

Changes in the future WEF are the result of the combination of changes in projected significant wave height, energy (~peak) period, and depth changes (Equation (2)). As changes in peak period are small, the resulting WEF changes result from the opposite contribution of significant wave height diminution and sea level rise. The result is a general reduction in the WEF in the Bay of Cadiz, with local increases in shallow rocky outcrops and coastal areas, where the depth increase by SLR allows for the higher waves to appear without breaking. These results are consistent with the findings of Aarns et al. [25] and Chaigneau et al. [28], who demonstrated that changes in depth induced by sea level rise can lead to higher wave amplitudes near the coast. The impact of sea level variations is substantially more important on extreme significant wave heights over the wide continental shelf where shallow water dynamics prevail, particularly in large tidal range areas [28]. However, our results show the important contribution of SLR to changes in the WEF in a mesotidal bay (see Figure 5). This demonstrates that accurate high-resolution wave propagation fields enable better capture of the nonlinear interactions between sea level and waves. Additionally, there is a shift in the direction of incident waves, increasing the wave exposure in certain areas of Cadiz and Rota. Along with these changes in the WEF, there is a reduction in wave orbital velocity (Figure S1; increased depth and decreased H_s), which is a fundamental parameter for UCH risk assessment, either by direct impact of orbital velocity on object decontextualization or scour and wear erosion impact.

Our assessment of the impact of wave climate changes on UCH hazards shows limited consequences. For decontextualization and scour hazard, the changes in the critical diameter of the moved object and in scour volume are, in general, small. There are considerable changes only in those locations (shallows and coastal areas), where the hazard indicators already had maximum values and had very high hazard levels (>0.16 m and >0.4 m³ for decontextualization and scour indicators, respectively (Table 3; Fernández-Montblanc et al. [7])). Therefore, it is not surprising that remarkable increases, such as the 0.2 m increase in the decontextualization hazard indicator, have no clear impact on the distribution of hazard levels within the bay. Indeed, there is a strong sensitivity of the hazard change assessment to the definition of the hazard level classes.

Hazard and vulnerability thresholds are mainly determined through the likelihood of exceeding certain predefined thresholds [60] and active participation from local users and stakeholders responsible for the management and conservation of cultural heritage [61,62]. The reliance on hazard categories based on historical data assumes that future conditions will follow probability distributions similar to those of the past. However, climate change is significantly altering these distributions, increasing the frequency and intensity of extreme events, which shifts hazard thresholds toward higher categories. This could explain

why there are not important changes in UCH risk under the considered climate change scenarios; however, this does not imply that such changes are not occurring. The lack of quantitative data on observed and projected impacts under different climate scenarios limits the ability to establish acceptable risk thresholds and develop effective adaptation and mitigation strategies [63].

The proposed methodology represents the first attempt, to our knowledge, for addressing UCH risk assessment for wave-induced hazards under climate change projections, and it is not free of shortcomings and limitations. Some of the methodological limitations related to the simplifications applied to hazard quantification are exposed in [7]. Here, it is necessary to add the assumption used in the EQ bias correction that the wave parameter distributions (period, height, and direction) will remain unchanged in the future. Clearly, this may not be the case in real life, but it is the simplest and best choice we have. It is important to note that our study did not include the contribution of storm surge to the water level, as it was initially omitted due to the predominant influence of tides on the total water level in the study area. Additionally, the lack of consideration for possible changes in morphodynamic processes, such as those related to depth and the interaction between waves and currents, represents a significant limitation in our analysis. It is crucial to recognize that the relative rise in sea level could be mitigated by sediment accommodation depending on the sediment budget, which would have a substantial impact on coastal dynamics. Furthermore, the impact of waves on sea level was not included; if this factor was incorporated into the ocean model, it would result in a higher sea level, which, in turn, would have a greater effect on wave propagation and the hazards affecting underwater cultural heritage. For future research, it would be valuable to conduct a multiple-hazard analysis to assess whether risky events occur simultaneously in a cascading or cumulative manner over time. In risk assessment studies, multidisciplinary approaches and the use of precise data are of utmost importance for managing the impacts of climate change in coastal contexts [64]. Furthermore, the proposed methodology must be expanded to other environmental factors influencing UCH preservation (i.e., water temperature, salinity, and pH) to provide a holistic methodology to assess the evolution of the natural hazards affecting the in situ preservation of UCH in the context of CC.

5. Conclusions

Future changes in sea levels and wave climate in coastal areas represent one of the major threats to the preservation and conservation of underwater cultural heritage (UCH). However, understanding how these changes will unfold in the long term and the associated hazards remains a challenge due to the complexity and interaction between the processes involved. In this study, we propose an innovative methodology to assess the risk to UCH in shallow waters based on hybrid downscaling using an ensemble derived from CMIP5 wave projections. This methodology applies downscaling to bias-corrected wave fields corresponding to the RCP4.5 and RCP8.5 scenarios from CMIP5. The approach focuses on the primary wave-induced hazards, considering their impact on the long-term preservation of UCH: archeological decontextualization, scouring, and wear erosion. To evaluate the effects of climate change, we compare the historical period (1981–2005) with two future periods, the mid-century (2036–2060) and end-of-century (2075–2099) periods, for both scenarios.

First, we present and validate the methodology for wave correction and propagation. Our results show that the use of the EQM method and directional adjustment improved the global wave model outputs, which is essential for obtaining high-resolution and accurate propagated wave fields. Second, we assessed changes in wave climate, observing a general reduction in the wave energy flux in the Bay of Cadiz, with local increases in rocky outcrops

and coastal areas, where the increased depth due to SLR allows higher waves to appear without breaking. This finding highlights the importance of high-resolution wave fields in capturing the nonlinear interactions between sea level and waves. Additionally, a shift in the direction of incident waves was identified, increasing wave exposure in certain areas of Cadiz and Rota.

In the bay, a general reduction in wave orbital velocity is observed due to increased depth and decreased significant wave height. This parameter is crucial for assessing UCH risk, as most UCH sites lie on the seafloor. However, in shallow areas, where the highest density of UCH is concentrated, significant changes in decontextualization and scouring hazards are observed. The only relevant changes in risk ($UCH_{risk} > 3.2$) are associated with wear erosion, particularly in the sites located on rocky outcrops off the city of Cadiz, where local changes in this hazard are marked. However, the strict definitions of hazard level classes, which shift thresholds toward higher categories, do not adequately reflect the changes in hazard classes. This factor could explain why significant changes in UCH risk are not observed under the considered climate change scenarios, although this does not imply that such changes are not occurring.

In conclusion, this study emphasizes the importance of conducting local-scale studies that incorporate the nonlinear interactions between sea level and waves in extreme wave studies, as these interactions could lead to local trends in wave energy that are different to those indicated in the global projections. This could result in variations in the impact on UCH risk in specific areas. It is also crucial to consider the high sensitivity in defining hazard level classes, as inadequate definitions may mask significant changes in UCH risk. The obtained results offer the possibility to iteratively redefine the hazard level and/or hazard classes accounting for future changes. The proposed methodology offers a tool to perform a quantitative analysis on the impact of CC on UCH rather than the existing state-of-the-art qualitative approach and method. The methodology developed in this study therefore represents a crucial step toward a more accurate understanding and more effective management of UCH risk in the face of climate change, an area that has been relatively overlooked until now. This tool provides innovative approaches for decision making in the protection and conservation of this invaluable heritage.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/jmse13010136/s1>.

Author Contributions: Conceptualization, C.F.-M., A.I. and T.F.-M.; methodology, C.F.-M., A.I. and T.F.-M.; software, C.F.-M., A.I. and T.F.-M.; validation, C.F.-M., A.I. and T.F.-M.; formal analysis, C.F.-M., A.I. and T.F.-M.; investigation, C.F.-M., A.I. and T.F.-M.; resources, C.F.-M., A.I., M.B. and T.F.-M.; data curation, C.F.-M., A.I. and T.F.-M.; writing—original draft preparation, C.F.-M.; writing—review and editing, C.F.-M., A.I., M.B. and T.F.-M.; visualization, C.F.-M.; supervision, A.I. and T.F.-M.; project administration, M.B. and T.F.-M.; funding acquisition, M.B. and T.F.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This study was partially supported by the Ministry of Science and Innovation through the project “Vulnerability of littoral cultural heritage to environmental agents: impact of climate change (VOLICHE)” (PID2020-117812RB-I00/AEI/10.13039/501100011033).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Acknowledgments: The authors acknowledge Lorenzo Mentaschi for his useful suggestions and for providing the global wave projection dataset used in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Thiébot, J.; Idier, D.; Garnier, R.; Falqués, A.; Ruessink, B.G. The Influence of Wave Direction on the Morphological Response of a Double Sandbar System. *Cont. Shelf Res.* **2012**, *32*, 71–85. [CrossRef]
- Pérez-Reverte Mañas, C.; Cerezo Andreo, F.; López Osorio, P.; González Gallero, R.; Mariscal Rico, L.; Arévalo González, A. Underwater Cultural Heritage as an Engine for Social, Economic and Cultural Development. State of Research at the University of Cadiz (Andalusia, Spain). *Heritage* **2021**, *4*, 2676–2690. [CrossRef]
- Khakzad, S.; Pieters, M.; Van Balen, K. Coastal Cultural Heritage: A Resource to Be Included in Integrated Coastal Zone Management. *Ocean Coast. Manag.* **2015**, *118*, 110–128. [CrossRef]
- Potts, A.L.A. *European Cultural Heritage Green Paper*; Europa Nostra: The Hague, The Netherlands; Brussels, Belgium, 2021.
- Quinn, R. The Role of Scour in Shipwreck Site Formation Processes and the Preservation of Wreck-Associated Scour Signatures in the Sedimentary Record—Evidence from Seabed and Sub-Surface Data. *J. Archaeol. Sci.* **2006**, *33*, 1419–1432. [CrossRef]
- Fernández-Montblanc, T.; Quinn, R.; Izquierdo, A.; Bethencourt, M. Evolution of a Shallow Water Wave-Dominated Shipwreck Site: Fougueux (1805), Gulf of Cadiz. *Geoarchaeology* **2016**, *31*, 487–505. [CrossRef]
- Fernández-Montblanc, T.; Bethencourt, M.; Izquierdo, A. Underwater Cultural Heritage Risk Assessment Methodology for Wave-Induced Hazards: The Showcase of the Bay of Cadiz. *Front. Mar. Sci.* **2022**, *9*, 1005514. [CrossRef]
- Fernández-Montblanc, T.; Izquierdo, A.; Quinn, R.; Bethencourt, M. Waves and Wrecks: A Computational Fluid Dynamic Study in an Underwater Archaeological Site. *Ocean Eng.* **2018**, *163*, 232–250. [CrossRef]
- McNinch, J.E.; Wells, J.T.; Trembanis, A.C. Predicting the Fate of Artefacts in Energetic, Shallow Marine Environments: An Approach to Site Management. *Int. J. Naut. Archaeol.* **2006**, *35*, 290–309. [CrossRef]
- Astley, A.J. The Taphonomy of Historic Shipwreck Sites. Ph.D. Thesis, University of Southampton, Southampton, UK, 2016.
- Bates, C.R.; Lawrence, M.; Dean, M. Robertson Geophysical Methods for Wreck-Site Monitoring: The Rapid Archaeological Site Surveying and Evaluation (RASSE) Programme. *Int. J. Naut. Archaeol.* **2011**, *40*, 404–416. [CrossRef]
- Quinn, R.; Smyth, T.A.G. Processes and Patterns of Flow, Erosion, and Deposition at Shipwreck Sites: A Computational Fluid Dynamic Simulation. *Archaeol. Anthropol. Sci.* **2018**, *10*, 1429–1442. [CrossRef]
- Plets, R.; Quinn, R.; Forsythe, W.; Westley, K.; Bell, T.; Benetti, S.; McGrath, F.; Robinson, R. Robinson Using Multibeam Echo-Sounder Data to Identify Shipwreck Sites: Archaeological Assessment of the Joint Irish Bathymetric Survey Data. *Int. J. Naut. Archaeol.* **2011**, *40*, 87–98. [CrossRef]
- Bethencourt, M.; Fernández-Montblanc, T.; Izquierdo, A.; González-Duarte, M.M.; Muñoz-Mas, C. Study of the Influence of Physical, Chemical and Biological Conditions That Influence the Deterioration and Protection of Underwater Cultural Heritage. *Sci. Total Environ.* **2018**, *613–614*, 98–114. [CrossRef] [PubMed]
- Angelini, E.; Grassini, S.; Tusa, S. Underwater Corrosion of Metallic Heritage Artefacts. In *Corrosion and Conservation of Cultural Heritage Metallic Artefacts*; Woodhead Publishing: Cambridge, UK, 2013; pp. 236–259. [CrossRef]
- Cámara, B.; De Buergo, M.Á.; Bethencourt, M.; Fernández-Montblanc, T.; La Russa, M.F.; Ricca, M.; Fort, R. Biodeterioration of Marble in an Underwater Environment. *Sci. Total Environ.* **2017**, *609*, 109–122. [CrossRef]
- Björdal, C.G.; Nilsson, T. Reburial of Shipwrecks in Marine Sediments: A Long-Term Study on Wood Degradation. *J. Archaeol. Sci.* **2008**, *35*, 862–872. [CrossRef]
- Alexandrakis, G.; Petrakis, S.; Kampanis, N. Preliminary Assessment of Wave Energy Hazards in a Shallow Underwater Cultural Heritage Site. In Proceedings of the 2023 IMEKO TC-4 International Conference on Metrology for Archaeology and Cultural Heritage, Rome, Italy, 19–21 October 2023.
- Weisse, R.; von Storch, H. *Marine Climate and Climate Change, Storms, Wind Waves and Storm Surges*; Praxis Publishing: Chichester, UK, 2010.
- Reguero, B.G.; Losada, I.J.; Méndez, F.J. A Recent Increase in Global Wave Power as a Consequence of Oceanic Warming. *Nat. Commun.* **2019**, *10*, 205. [CrossRef]
- Casas-Prat, M.; Wang, X.L.; Swart, N. CMIP5-Based Global Wave Climate Projections Including the Entire Arctic Ocean. *Ocean Model.* **2018**, *123*, 66–85. [CrossRef]
- Hemer, M.A.; Fan, Y.; Mori, N.; Semedo, A.; Wang, X.L. Projected Changes in Wave Climate from a Multi-Model Ensemble. *Nat. Clim. Change* **2013**, *3*, 471–476. [CrossRef]
- Mentaschi, L.; Vousdoukas, M.I.; Voukouvalas, E.; Dosio, A.; Feyen, L. Global Changes of Extreme Coastal Wave Energy Fluxes Triggered by Intensified Teleconnection Patterns. *Geophys. Res. Lett.* **2017**, *44*, 2416–2426. [CrossRef]
- Morim, J.; Hemer, M.; Wang, X.L.; Cartwright, N.; Trenham, C.; Semedo, A.; Young, I.; Brichenno, L.; Camus, P.; Casas-Prat, M.; et al. Robustness and Uncertainties in Global Multivariate Wind-Wave Climate Projections. *Nat. Clim. Change* **2019**, *9*, 711–718. [CrossRef]

25. Aarnes, O.J.; Reistad, M.; Breivik, Ø.; Bitner-Gregersen, E.; Ingolf Eide, L.; Gramstad, O.; Magnusson, A.K.; Natvig, B.; Vanem, E. Projected Changes in Significant Wave Height toward the End of the 21st Century: Northeast Atlantic. *J. Geophys. Res. Ocean.* **2017**, *122*, 3394–3403. [CrossRef]
26. Morim, J.; Vitousek, S.; Hemer, M.; Reguero, B.; Erikson, L.; Casas-Prat, M.; Wang, X.L.; Semedo, A.; Mori, N.; Shimura, T.; et al. Global-Scale Changes to Extreme Ocean Wave Events Due to Anthropogenic Warming. *Environ. Res. Lett.* **2021**, *16*, 074056. [CrossRef]
27. Meucci, A.; Young, I.R.; Hemer, M.; Kirezci, E.; Ranasinghe, R. Projected 21st Century Changes in Extreme Wind-Wave Events. *Sci. Adv.* **2020**, *6*, eaaz7295. [CrossRef] [PubMed]
28. Chaigneau, A.A.; Law-Chune, S.; Melet, A.; Voldoire, A.; Refray, G.; Aouf, L. Impact of Sea Level Changes on Future Wave Conditions along the Coasts of Western Europe. *Ocean Sci.* **2023**, *19*, 1123–1143. [CrossRef]
29. Alvarez, O.; Izquierdo, A.; Tejedor, B.; Mañanes, R.; Tejedor, L.; Kagan, B.A. The Influence of Sediment Load on Tidal Dynamics, a Case Study: Cádiz Bay. *Estuar. Coast. Shelf Sci.* **1999**, *48*, 439–450. [CrossRef]
30. Kagan, B.A.; Tejedor, L.; Álvarez, O.; Izquierdo, A.; Tejedor, B.; Mañanes, R. Weak Wave–Tide Interaction Formulation and Its Application to Cádiz Bay. *Cont. Shelf Res.* **2001**, *21*, 697–725. [CrossRef]
31. Meinshausen, M.; Smith, S.J.; Calvin, K.; Daniel, J.S.; Kainuma, M.L.T.; Lamarque, J.-F.; Matsumoto, K.; Montzka, S.A.; Raper, S.C.B.; Riahi, K.; et al. The RCP Greenhouse Gas Concentrations and Their Extensions from 1765 to 2300. *Clim. Change* **2011**, *109*, 213–241. [CrossRef]
32. Korres, G.; Ravdas, M.; Zacharioudaki, A. Mediterranean Sea Waves Hindcast (CMEMS MED-Waves) 2019. [Data Set]. [CrossRef]
33. Tolman, H.L. User Manual and System Documentation of WAVEWATCH III R Version 4.18. Available online: <https://polar.ncep.noaa.gov/waves/wavewatch/manual.v4.18.pdf> (accessed on 29 December 2024).
34. Perez, J.; Menendez, M.; Mendez, F.J.; Losada, I.J. Evaluating the Performance of CMIP3 and CMIP5 Global Climate Models over the North-East Atlantic Region. *Clim. Dyn.* **2014**, *43*, 2663–2680. [CrossRef]
35. De Winter, R.C.; Sterl, A.; Ruessink, B.G. Wind Extremes in the North Sea Basin under Climate Change: An Ensemble Study of 12 CMIP5 GCMs. *JGR Atmos.* **2013**, *118*, 1601–1612. [CrossRef]
36. Griffies, S.M.; Danabasoglu, G.; Durack, P.J.; Adcroft, A.J.; Balaji, V.; Böning, C.W.; Chassignet, E.P.; Curchitser, E.; Deshayes, J.; Drange, H.; et al. OMIP Contribution to CMIP6: Experimental and Diagnostic Protocol for the Physical Component of the Ocean Model Intercomparison Project. *Geosci. Model Dev.* **2016**, *9*, 3231–3296. [CrossRef]
37. Goward Brown, A.J.; Neill, S.P.; Lewis, M.J. The Influence of Wind Gustiness on Estimating the Wave Power Resource. *Int. J. Mar. Energy* **2013**, *3–4*, e1–e10. [CrossRef]
38. Lobeto, H.; Menendez, M.; Losada, I.J. Future Behavior of Wind Wave Extremes Due to Climate Change. *Sci. Rep.* **2021**, *11*, 7869. [CrossRef] [PubMed]
39. Fanti, V.; Ferreira, Ó.; Kümmerer, V.; Loureiro, C. Improved Estimates of Extreme Wave Conditions in Coastal Areas from Calibrated Global Reanalyses. *Commun. Earth Environ.* **2023**, *4*, 151. [CrossRef]
40. Camus, P.; Mendez, F.J.; Medina, R. A Hybrid Efficient Method to Downscale Wave Climate to Coastal Areas. *Coast. Eng.* **2011**, *58*, 851–862. [CrossRef]
41. Booij, N.; Ris, R.C.; Holthuijsen, L.H. A Third-Generation Wave Model for Coastal Regions: 1. Model Description and Validation. *J. Geophys. Res.* **1999**, *104*, 7649–7666. [CrossRef]
42. Battjes, J.A.; Janssen, J.P. Energy Loss and Set-up Due to Breaking of Random Waves. In Proceedings of the Sixteenth Conference on Coastal Engineering, Hamburg, Germany, 27 August–3 September 1978; pp. 569–587. [CrossRef]
43. Hanna, S.R.; Heinold, D.W. *Development and Application of a Simple Method for Evaluating Air Quality*; Technical Report; American Petroleum Institute, Health and Environmental Affairs Dept: Washington, DC, USA, 1985.
44. Mentaschi, L.; Besio, G.; Cassola, F.; Mazzino, A. Problems in RMSE-Based Wave Model Validations. *Ocean Model.* **2013**, *72*, 53–58. [CrossRef]
45. Mentaschi, L.; Besio, G.; Cassola, F.; Mazzino, A. Performance Evaluation of Wavewatch III in the Mediterranean Sea. *Ocean Model.* **2015**, *90*, 82–94. [CrossRef]
46. Spanish Ministry of Agriculture, Food and Environment. Data from: Plan de Ecocartografías del litoral Español. 2012. Available online: <https://www.miteco.gob.es/es/costas/temas/proteccion-costa/ecocartografias/ecocartografia-cadiz.html> (accessed on 29 December 2024).
47. Garrity, N.J.; Battalio, R.; Hawkes, P.J.; Roupe, D. Evaluation of Event and Response Approaches to Estimate the 100-Year Coastal Flood for Pacific Coast Sheltered Waters. In *Coastal Engineering 2006*; World Scientific Publishing Company: San Diego, CA, USA, 2007; pp. 1651–1663. [CrossRef]
48. Viavattene, C.; Jiménez, J.A.; Ferreira, O.; Priest, S.; Owen, D.; McCall, R. Selecting Coastal Hotspots to Storm Impacts at the Regional Scale: A Coastal Risk Assessment Framework. *Coast. Eng.* **2018**, *134*, 33–47. [CrossRef]
49. Ferreira, O.; Viavattene, C.; Jiménez, J.A.; Bolle, A.; Das Neves, L.; Plomaritis, T.A.; McCall, R.; Van Dongeren, A.R. Storm-Induced Risk Assessment: Evaluation of Two Tools at the Regional and Hotspot Scale. *Coast. Eng.* **2018**, *134*, 241–253. [CrossRef]

50. Mentaschi, L.; Vousdoukas, M.; Voukouvalas, E.; Sartini, L.; Feyen, L.; Besio, G.; Alfieri, L. The Transformed-Stationary Approach: A Generic and Simplified Methodology for Non-Stationary Extreme Value Analysis. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 3527–3547. [CrossRef]
51. Gornitz, V. Vulnerability of the East Coast, U.S.A. to Future Sea Level Rise. *J. Coast. Res.* **1990**, *9*, 201–237.
52. Liang, B.; Shao, Z.; Wu, G.; Shao, M.; Sun, J. New Equations of Wave Energy Assessment Accounting for the Water Depth. *Appl. Energy* **2017**, *188*, 130–139. [CrossRef]
53. Alfieri, L.; Burek, P.; Feyen, L.; Forzieri, G. Global Warming Increases the Frequency of River Floods in Europe. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 2247–2260. [CrossRef]
54. Knutti, R.; Sedláček, J. Robustness and Uncertainties in the New CMIP5 Climate Model Projections. *Nat. Clim. Change* **2013**, *3*, 369–373. [CrossRef]
55. Vousdoukas, M.I.; Voukouvalas, E.; Annunziato, A.; Giardino, A.; Feyen, L. Projections of Extreme Storm Surge Levels along Europe. *Clim. Dyn.* **2016**, *47*, 3171–3190. [CrossRef]
56. Del Río, L.; Plomaritis, T.A.; Benavente, J.; Valladares, M.; Ribera, P. Establishing Storm Thresholds for the Spanish Gulf of Cádiz Coast. *Geomorphology* **2012**, *143–144*, 13–23. [CrossRef]
57. Ribeiro, A.S.; deCastro, M.; Costoya, X.; Rusu, L.; Dias, J.M.; Gomez-Gesteira, M. A Delphi Method to Classify Wave Energy Resource for the 21st Century: Application to the NW Iberian Peninsula. *Energy* **2021**, *235*, 121396. [CrossRef]
58. Wang, X.L.; Feng, Y.; Swail, V.R. Changes in Global Ocean Wave Heights as Projected Using Multimodel CMIP5 Simulations. *Geophys. Res. Lett.* **2014**, *41*, 1026–1034. [CrossRef]
59. Lemos, G.; Semedo, A.; Dobrynin, M.; Behrens, A.; Staneva, J.; Bidlot, J.-R.; Miranda, P.M.A. Mid-Twenty-First Century Global Wave Climate Projections: Results from a Dynamic CMIP5 Based Ensemble. *Glob. Planet. Change* **2019**, *172*, 69–87. [CrossRef]
60. Raposeiro, P.D.; Fortes, C.J.; Reis, M.T.; Ferreira, J.C. Development of A Methodology to Evaluate the Flood Risk at the Coastal Zone. Available online: <https://repositorio.inec.pt/handle/123456789/1002230> (accessed on 29 December 2024).
61. Sevieri, G.; Galasso, C.; D’Ayala, D.; De Jesus, R.; Oreta, A.; Grió, M.E.D.A.; Ibabao, R. A Multi-Hazard Risk Prioritisation Framework for Cultural Heritage Assets. *Nat. Hazards Earth Syst. Sci.* **2020**, *20*, 1391–1414. [CrossRef]
62. Canesi, L.; Sardella, A.; Vogler, R.; Kaiser, A.; Vaccaro, C.; Bonazza, A. Hazard Analysis and Vulnerability Assessment of Cultural Landscapes Exposed to Climate Change-Related Extreme Events: A Case Study of Wachau (Austria). *Heritage* **2024**, *7*, 1917–1934. [CrossRef]
63. Bonazza, A.; Sardella, A. Climate Change and Cultural Heritage: Methods and Approaches for Damage and Risk Assessment Addressed to a Practical Application. *Heritage* **2023**, *6*, 3578–3589. [CrossRef]
64. Pica, A.; Lämmle, L.; Burnelli, M.; Del Monte, M.; Donadio, C.; Faccini, F.; Lazzari, M.; Mandarino, A.; Melelli, L.; Perez Filho, A.; et al. Urban Geomorphology Methods and Applications as a Guideline for Understanding the City Environment. *Land* **2024**, *13*, 907. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

Article

Caesarea SubMaritima: Insights into the Entrance of the Roman Harbour of Sebastos as Obtained Through High-Resolution Multimodal Remote Sensing Surveys

Gil Gambash ^{1,*}, Ehud Arkin-Shalev ¹, John Wood ², Emmanuel Nantet ¹ and Timmy Gambin ²

¹ School of Archaeology and Maritime Cultures, University of Haifa, Haifa 3103301, Israel; ehud.arkin@gmail.com (E.A.-S.); enantet@univ.haifa.ac.il (E.N.)

² Department of Classics and Archaeology, University of Malta, MSD 2080 Msida, Malta; jinjamu@gmail.com (J.W.); timmy.gambin@um.edu.mt (T.G.)

* Correspondence: ggambash@univ.haifa.ac.il

Abstract: This article presents the results of high-resolution multimodal remote sensing surveys which were performed in the Roman city of Caesarea Maritima at the sunken Herodian harbour of Sebastos. A joint team of scholars from the Universities of Malta and Haifa conducted the surveys at the area of the harbour's entrance in order to answer questions related to its original architecture, long-term functioning, and gradual degradation processes. The core methodology employed comprised teams of divers performing a meticulous photogrammetric survey in order to generate a high-resolution 3D plan of the harbour's entrance. The results present two different architectural styles on either side of the harbour entrance, which suggests two different building stages, potentially deriving from a late renovation attempt. The current state of the entrance channel, still deep and wide enough for the passage of vessels despite collapse and sedimentation processes, suggests the long-term functionality of the entrance, even while other parts of the harbour have structurally deteriorated and gone out of use.

Keywords: Caesarea Maritima; Sebastos; Roman harbours; remote sensing archaeology; under-water surveys

1. Introduction

Ancient harbours are vital for our understanding of the Mediterranean economy in antiquity, and none more so than the large-scale artificial installations that emerged at the time when the oikumene experienced rapid processes of globalisation under Roman hegemony. Caesarea Maritima was built by Herod the Great as a coastal city, boasting the largest hydraulic concrete-based harbour in the Mediterranean Sebastos [1]. It was inaugurated in the year 10 BCE, many decades before the Roman emperors would engage in a similar endeavour for the purpose of serving the prodigious needs of the city of Rome.

The remains of Sebastos are located by the coast near modern-day Caesarea, just south of the Carmel coast (Figure 1 inset). Of the three original basins of the ancient harbour, the inner (shallow) basin silted up and is now completely landlocked (Figure 1a). The middle and outer basins are located in the open sea at depths of up to 9 m (Figure 1b,c). The harbour's massive breakwaters (Figure 1d,e) and associated structures, which protected these basins, are now submerged, and the debate concerning the circumstances behind the collapse of the harbour currently favours the impact of high-energy winter storms, rather than tectonic activity, tsunami events, or a rise in relative sea levels [2,3].

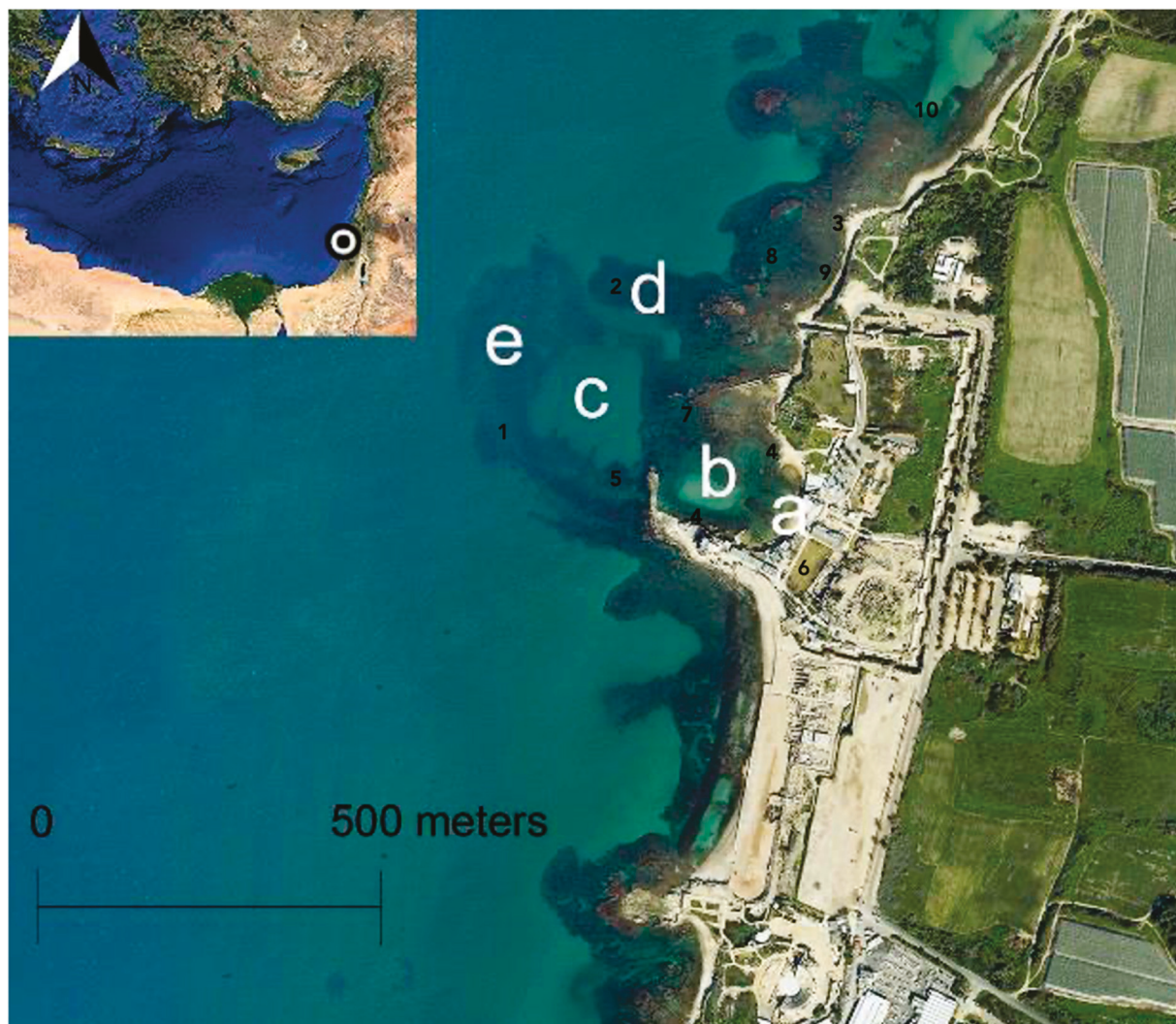


Figure 1. Sebastos and its inner (a), middle (b), and outer (c) basins, northern breakwater (d) and southern breakwater (e). Inset: Location of Sebastos on the coastline of Judea/Palestine. Google earth credit: Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat/Copernicus. The numbers correspond to the harbour features as listed on the following pages.

Early surveys of the site were conducted by the Palestine Exploration Fund in the early 1880s. The first underwater excavations of the harbour were headed by A.D. Link in 1960. Between the years 1963 and 1972, excavations were conducted on behalf of the Underwater Exploration Society of Israel, headed by E. Linder. From 1975 to 2005, the harbour and the city were excavated and studied by the Recanati Institute of Maritime Studies at the University of Haifa, headed by A. Raban and Y. Porat on behalf of the Israel Antiquities Authority. No significant changes in the local landscape have been registered between the beginning of archaeological work in Caesarea and now.

Raban [4] summarised the historical and archaeological studies concerning the operation of the harbour and its decline, conjecturing that the deterioration of the outer basin began in the 1st century CE and the siltation of the inner basin started in the 2nd century CE. During the early 6th century CE, Procopius of Gaza wrote the following: “The harbour of the city named after Caesar had disintegrated through age and lay open to every threat from the sea. Its structure no longer measured up to the category of harbour, but of its former condition it kept the name alone”. Procopius refers to the Byzantine emperor Anastasius I (491–518 CE), who provided resources to repair the harbour, though

the project was probably meant as an act of munificence and was, therefore, basic and far from long-lasting [5,6].

Relying on numismatic evidence, Ringel [7] and Hohlfelder [8] suggested that the harbour remained operational during the 3rd–5th centuries CE. Based on botanical remains of crops species collected in the eastern basin, Ramsay [9] suggested that maritime activity took place there in the 4th–6th century CE. A study of shipwreck remains discovered on the breakwaters of the western basin [4] revealed a wreck with amphoras of types that were in use from the end of the 2nd century CE until the end of the 3rd century CE. Thus, Raban inferred that during the 3rd–4th centuries CE, the breakwaters were already partly ruined and the main breakwater had deteriorated, proposing that the western basin of the harbour underwent tectonic subsidence.

Later studies reported on a cargo of lead ingots found in area K, at the northern end of the main breakwater, and dated it to the years 83–96 CE according to inscriptions [10]. The excavators assumed that the ingots originated from a shipwreck on the breakwater and suggested that this part of the port ceased to function about a hundred years after its construction.

Strikingly, these are, in sum, the hypotheses available for modern research regarding the harbour of Sebastos and research questions related to it. Crude generalisations regarding function and maintenance and the low resolution of chronological data are accompanied by the lack of a reliable plan for the site, which should be a mandatory initial step in evaluating every aspect related to the harbour.

Previous research, based on visual surveys and focused excavations, has invested significant efforts in studying the remains of Sebastos, to the effect of identifying the general function of many of its structures, now partly or fully submerged (for orientation, see Figure 1 above), as follows:

1. The south-western breakwater of the Herodian harbour, extending to a length of c. 650 m, built of Hydraulic concrete, following the instructions of Vitruvius [11].
2. The northern sea-wall breakwater of the Herodian harbour, extending to a length of c. 250 m, built of Hydraulic concrete, following the instructions of Vitruvius [11].
3. The quay of the Hellenistic northern harbour, built of headers, and described by Raban.
4. Harbour wharfs in the central basin, built on the kurkar ridge. Next to them, a Roman quay was built of headers on the south-western side of this basin. Another quay was excavated by Raban on the north-eastern side of this basin and was dated to the Herodian period.
5. A surface built of large ashlars—this surface was discovered in the western basin at a depth of more than 5 m. This structure was interpreted as a submerged pavement, supposedly indicating that the western basin of the harbour underwent tectonic subsidence and could no longer function as a port.
6. Roman harbour installations in the eastern basin—a Roman mooring stone and staircase leading to it were found on the eastern quay of the eastern basin.
7. A Crusader mole in the northern part of the central basin. The Crusader mole was built of pillars in secondary use, placed on a flat rocky surface.
8. Abrasion platforms—north and south of the harbour, the coastal aeolianite sandstone ridge was abraded by the sea.
9. Beach rock north of the northern Crusader wall. A 50 m long deposit of beach rock, with Roman marble chunks trapped in it, is attached to the kurkar rock at the present-day sea-level elevation.
10. Beach rock ridge in the north anchorage. A massive strip of beach rock deposit, about 2.8 m thick, is at 0.2–3.0 m below the present sea level. The deposit is located parallel

to the coast, some 60 m west of the present shore and the remains of the aqueduct foundations. This beach rock probably marks the location of the ancient coastline before the construction of the harbour and the aqueduct.

So far, however, technological limitations have not allowed researchers to generate a high-resolution plan of the entire array of structures, and multiple questions concerning the site's plan, function, chronology, and decline were bound to remain unanswered or at least hotly debated. The area of the entry channel to the harbour, while partially covered by the campaigns described above, thus remains, as of yet, far from fully explored and understood, thus serving as the focus of the present investigation (for the coverage of past and current projects, see Figure 2).

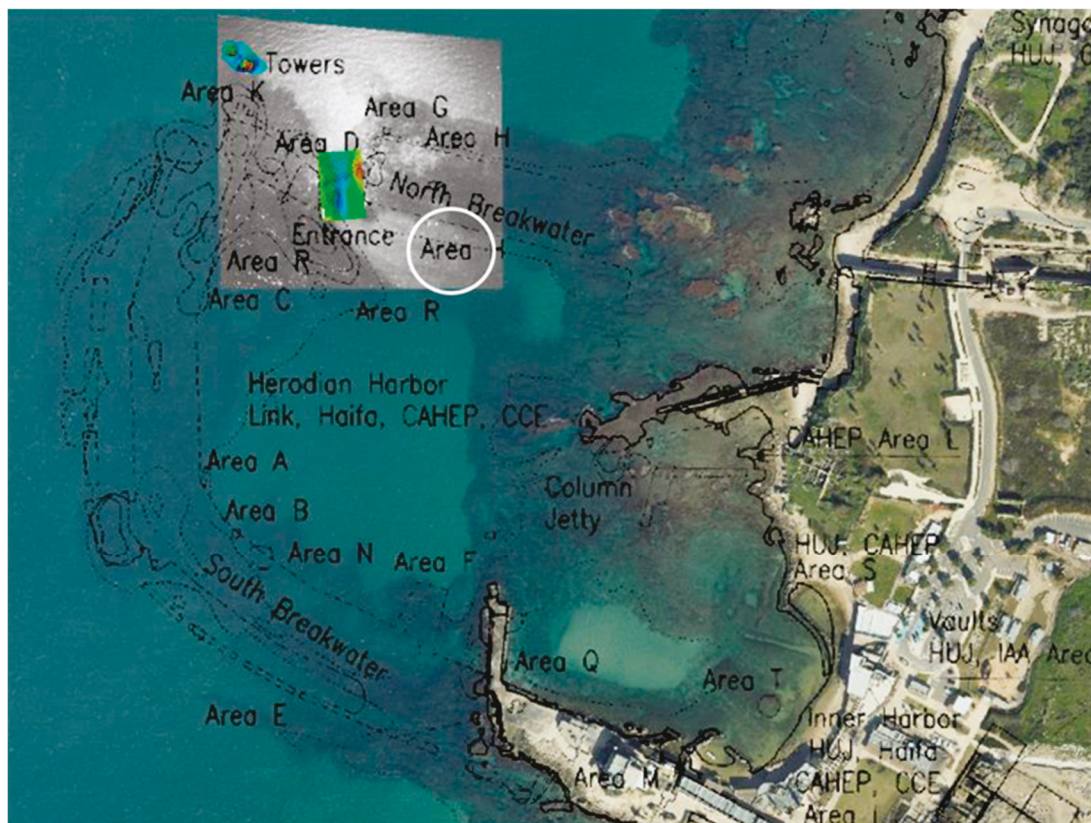


Figure 2. Location of the newly modelled areas superimposed on previous excavation areas as drawn by Raban [12].

Through the generation and analysis of new underwater 3D multimodal data, the *Caesarea SubMaritima* project seeks to retrace the site's history at a resolution far higher than ever available before and to produce solutions to these and other problems pertaining to local and regional economic systems. The project has been launched at the opportune moment, when the fusion of underwater multimodal remote sensing capabilities, including photogrammetric 3D modelling [13], sub-bottom profiling [14], shallow water frequency-domain electromagnetic (FDEM) methods [15], and multi-beam surveys [16], is becoming not only sufficiently accurate and available, but also practiced and tested by the leading edge of the research community in select projects of relevance [17].

For studying the functionality of the harbour, the type and size of ships it would have been able to host, and the key processes in its decline and collapse, we identified the harbour's entrance as a key feature and useful proxy, therefore designating its investigation as the first stage of our project. Accordingly, we aimed initially to record the main features of the harbour's entrance, the extremities of the two breakwaters which create its entry

channel, the debris scattered along this channel, and the structures placed just outside of the harbour's entrance. Thus, we will contribute to documenting the collapse process that more specifically affected key port areas. The results presented here emerge from the initial phase of the *Caesarea SubMaritima* project. They comprise 3D photogrammetric models focusing on the entrance to the harbour of Sebastos, designated by previous researchers as areas G and K, as well as on two blocks of stone on which colossal statues stood, according to historical sources (Figure 2). These results also serve as a successful proof of concept for the project as a whole.

2. Methods

Alternative approaches for modelling submerged structures exist and have been considered thoroughly by our team and others engaged in similar projects elsewhere, yet none of them have proven able to produce the combination of viability and high-quality results that diver-borne photogrammetry offers. Employing a large Remotely Operated Vehicle (ROV) from a survey vessel would be too costly and not very efficient, mostly on account of its limited manoeuvrability. A small ROV could be deployed from the coast or from a vessel, but the shallow depths at which the site is located, combined with the high energy of the sea, currents, waves, and winds, render this option impractical. The camera and lighting system of a small ROV would not produce the same resolution obtainable with diver-borne systems. Furthermore, the features of the site would challenge ROV tether management, as well as communications with the USBL transceiver and the accurate positioning of the ROV underwater.

A multibeam survey would deliver accurate bathymetric information that could be processed to produce a digital elevation model (DEM). However, smaller features might not be recognised by this technology, and multiple individual elements of the surveyed construction would not be identified through a DEM alone, whereas photogrammetry would deliver both a DEM *and* unambiguous visual information, facilitating a detailed assessment of specific features. For all of these reasons, the latter technology is the one adopted by *Caesarea SubMaritima*.

The research presented here leverages cutting-edge methodologies, benefitting from recent advancements in high-resolution three-dimensional underwater documentation and modelling technologies. Key to this project is the utilisation of high-performance Geographic Information System (GIS) software (QGIS 3.42.2), able to compile, analyse, and present large-scale, densely populated datasets. Additionally, Computer Assisted Design (CAD) software (AutoCAD 39) plays a pivotal role, enabling computational, non-destructive procedures for engineering failure analysis. Such methodologies have been employed successfully in recent relevant projects, which shed revealing light, for example, on the history of Methoni Bay and of the ancient harbour of Aegina, Greece [14,18].

In the initial phase of the project, a comprehensive underwater 2D data acquisition campaign was undertaken by a team of survey divers employing multiple cameras, synchronised with lighting systems and prefabricated custom calibration targets. This methodology ensured the continuous capture of images of submerged harbour components at a rate of three frames per second (FPS). The subsequent processing of these 2D images utilised Agisoft Metashape (2.2.0), a software implementing Structure-from-Motion (SfM) algorithms to author 3D models within the GIS framework.

The resulting 3D dense point clouds were geo-rectified using ESRI ArcMAP GIS software (10.8.2), facilitating the creation of Digital Elevation Models (DEMs) with precise x, y, and z coordinates per pixel. The initial 3D models also yielded quantitative insights in the form of architectural element evaluations at a level of precision and confidence previously unattainable. By circumscribing the modelled remnants through polygons and factoring in

the three-dimensional surfaces of these elements, we approximated the volumetric content within the modelled zones. For computational expediency, our current methodology adopted the mean seabed elevation for each area, omitted potential subsurface remnants, and excluded plausible water-filled interstices amid remains.

Through the integration of these complementary techniques and their application to the Sebastos harbour entrance area, a detailed digital model of the area's various components was meticulously crafted. This model was subjected to a comprehensive analysis, incorporating insights from Roman harbour archaeology, pertinent historical evidence, and data from previous archaeological campaigns. Furthermore, part of our team had previously participated in the Azure Window project, where a well-documented natural arch on the west coast of the island of Gozo (Malta) recently collapsed [13]. The project used similar 3D technologies to the ones now employed in Caesarea and managed to document complex underwater geomorphologies, produce an accurate high-resolution geomorphic plan of the site, and reconstruct the process of the collapse—all methodologies for which have now been employed in the Caesarea project.

3. Results

Analysis of the initial models of the harbour's entrance area identifies distinct construction and collapse patterns flanking the entry channel (Figure 3). Eastward of the channel lies the terminus of the northern breakwater, characterised by substantial hewn stone blocks, some reaching a length of 3 m (Figure 4). Evidently, these blocks have shifted and slid, undergoing westward displacement over time. In stark contrast, the southern breakwater, positioned west of the channel, manifests an extensive scatter of rubble, devoid of discernible architectural attributes (Figure 5). These observations underscore critical unresolved aspects concerning the different construction phases of Sebastos and their implications for the design and functionality of the harbour entrance.

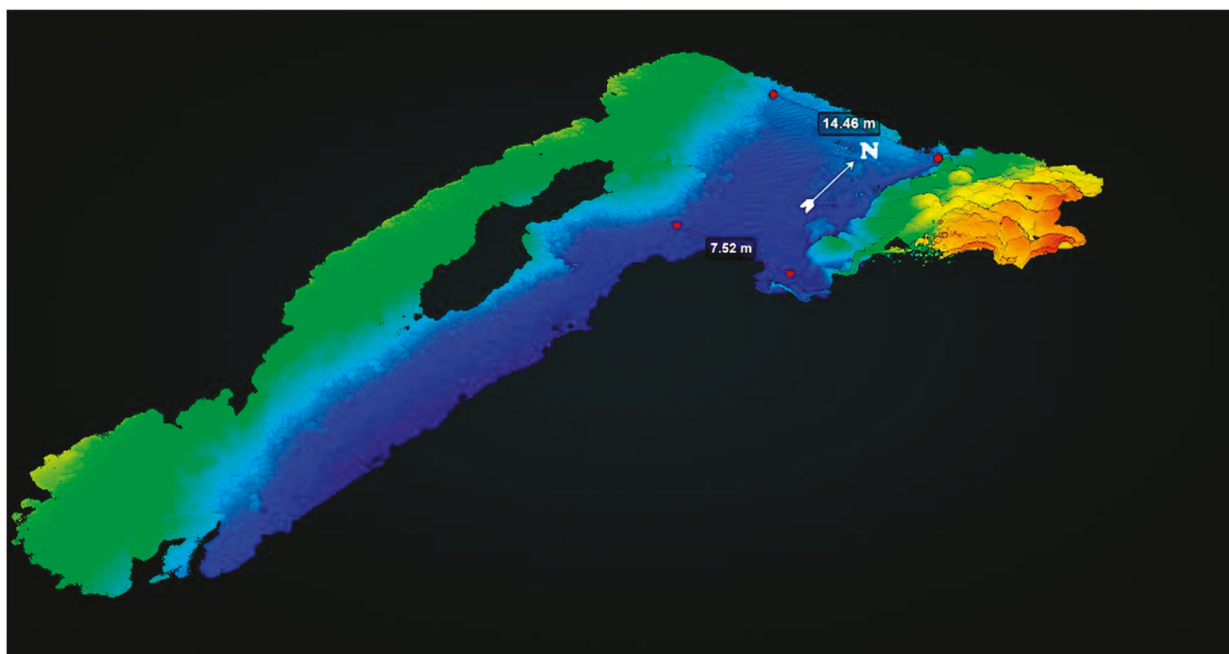


Figure 3. Digital elevation model (DEM) of the harbour entrance channel flanked by the northern (right) and southern (left) breakwaters. Elevation colour scale range from -8.61 m to -2.79 m.

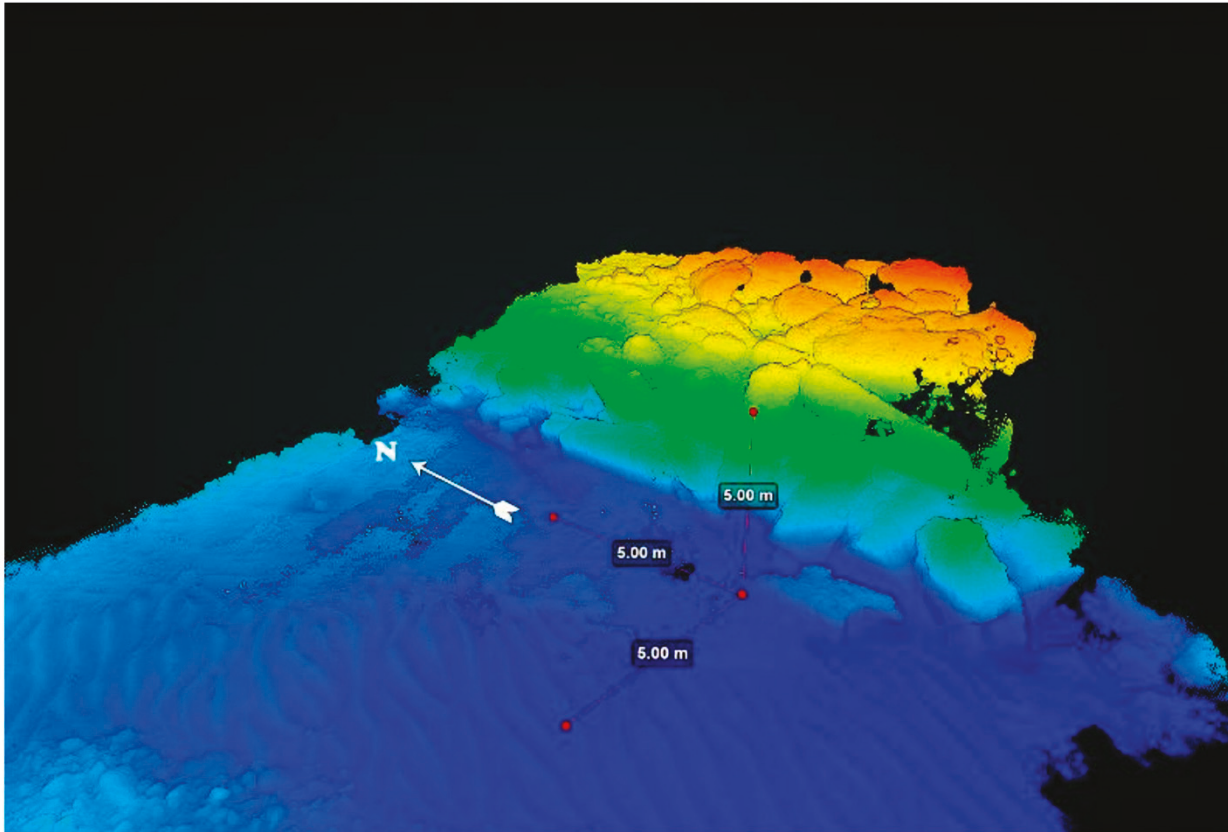


Figure 4. Digital elevation model (DEM) of the northern breakwaters' western extremity. Elevation colour scale range from -8.61 m to -2.79 m.

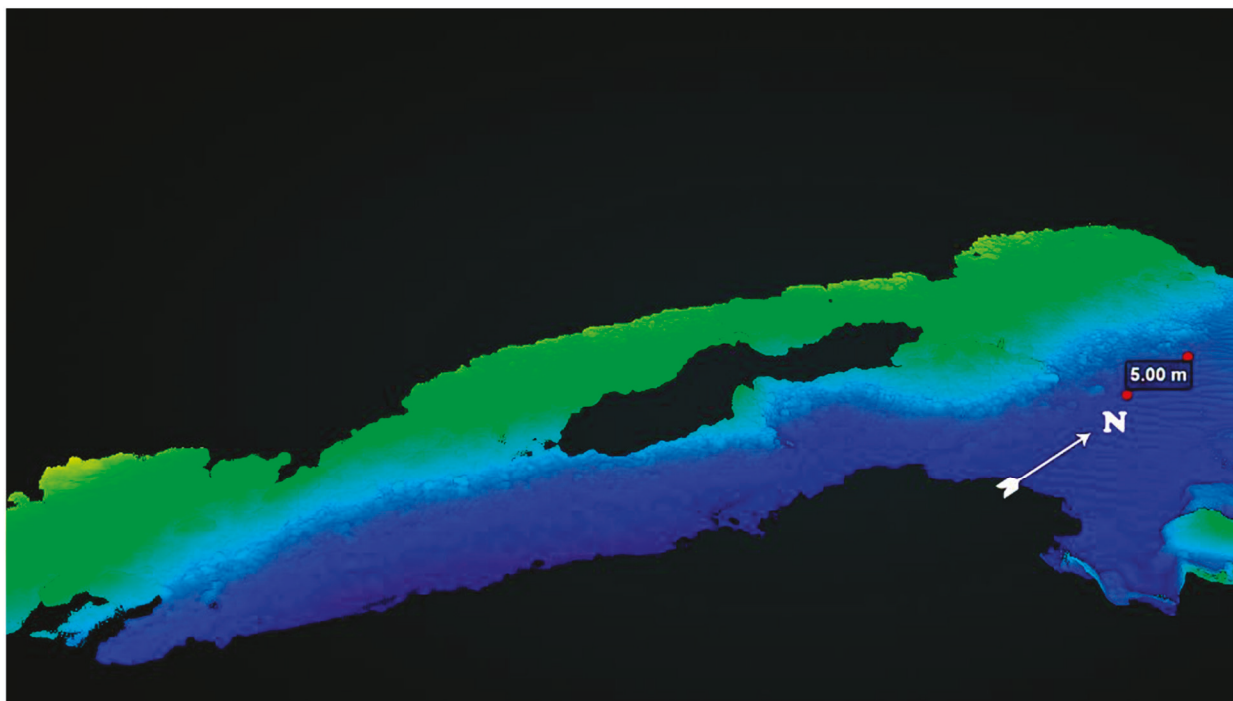


Figure 5. Digital elevation model (DEM) of the southern breakwaters' northern extremity. Elevation colour scale range from -8.61 m to -2.79 m. Actual elevations do not occupy whole range.

The entrance constituted a key area of the Herodian concrete-built outer basin. Historical accounts by Josephus [19] indicate that monumental statues embellished the two

structures standing just outside of the harbour's entrance, extending a salutation to incoming vessels. Our analysis of the three-dimensional model of these structures shows them as presently measuring six by six meters and towering six meters above the seabed, at a depth of 8.6 m (Figure 6). A near 100% coverage of these structures by the bivalve *Spondylus spinosus* is detected through analysis of the model, suggesting novel directions of research into the interaction between artificial structures and the marine environment throughout the ages.

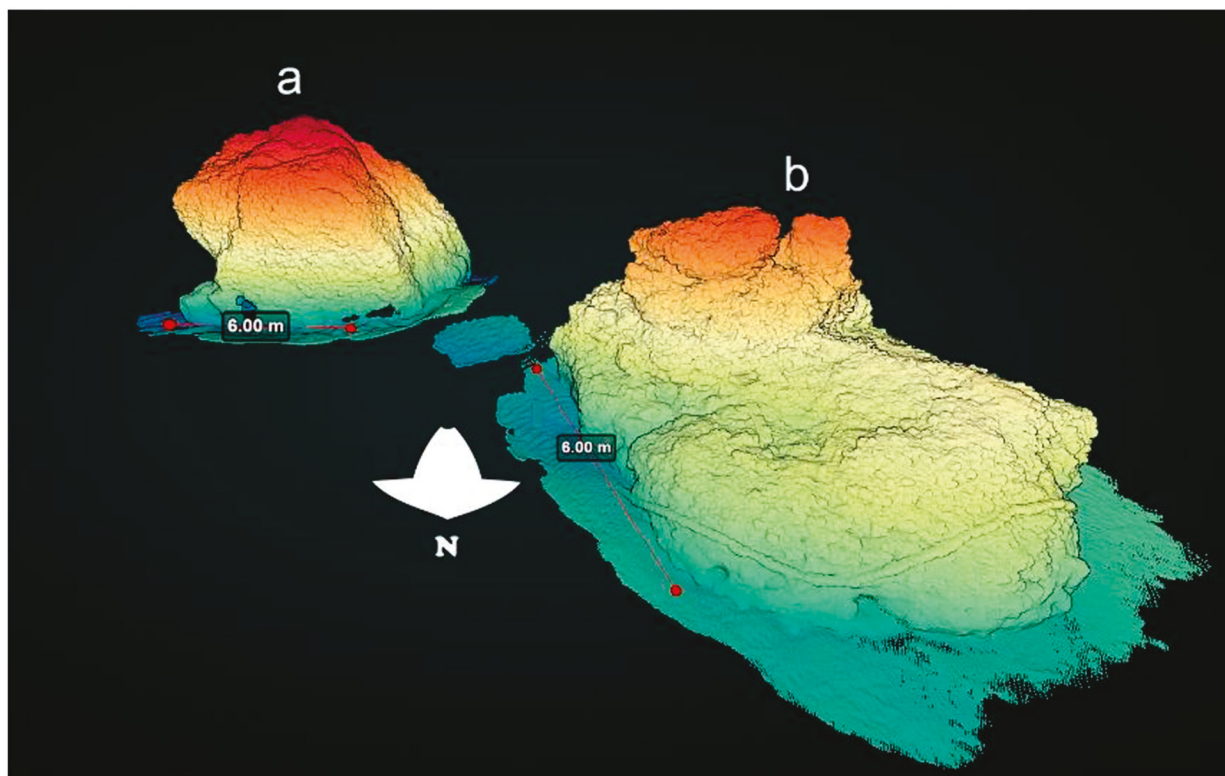


Figure 6. Digital elevation models of the eastern (a) and western (b) columns outside the harbour entrance. Elevation colour scale range from -8.61 m to -2.79 m.

In addition, our volumetric calculations add valuable information for the study of the harbour's entrance. At the westernmost extremity of the northern breakwater, positioned at an average seabed depth of 7.6 m, a spatial expanse of 92.8 square meters is modelled, within which remnants occupy a volume of 221.7 cubic meters (Figure 3). Correspondingly, at the northern extremity of the southern breakwater, where the mean seafloor depth is 7.3 m, the modelled area of 97.3 square meters accommodates remains with a volume of 94 cubic meters (Figure 4). In reference to the remnants of the western structure outside of the entrance, located at an average seabed depth of 7.4 m, a discernible volume of 61.8 cubic meters is evident above the seafloor (Figure 6a). The remains of the eastern structure next to it, positioned at an average seabed depth of 8 m, exhibit an elevated volume of 148.8 cubic meters above the seafloor (Figure 6b). These quantifications may be refined as additional sectors of the harbour's remains undergo modelling.

4. Discussion and Conclusions

The width and the depth of the entrance channel between the extremities of the northern and southern breakwaters were crucial parameters that allowed merchantmen to pass [20,21]. Depth was a critical parameter, as it could prevent large vessels with a significant draught from entering the harbour. Thus, in many instances, they had to moor

offshore and unload their merchandise, like at many other harbours such as Ostia [22,23]. A mosaic found at this port displays a scene showing how difficult this task was—a docker, walking cautiously on a gangway, carries a heavy amphora on his shoulder, from a sea-going freighter onto a *caudicaria*, a craft that sailed along the river Tiber [24]. Although recent investigations have allowed for a better understanding of the harbour system of Ostia, more precisely the capacity of the streams that connected the settlement to the capital city [25], the situation is less clear for Caesarea. The initial study of the remains stated that the depth of the harbour was shallow, preventing vessels with a draught exceeding 2 m from entering [26]. Recent drills and probes have shown that the depth was much more significant, actually reaching 6 m, showing that large merchantmen could enter the Herodian port [27].

Entering harbours was a particularly challenging manoeuvre for unoared sailing vessels, which could potentially cause accidents with devastating consequences, as a shipwreck could obstruct the harbour entrance and suspend traffic, requiring tremendous efforts to remove it. For this reason, commercial vessels required the assistance of smaller oared boats similar to the tugboat displayed in the Rimini mosaic [28,29]. The extremities of breakwaters, protruding into the sea, were exposed to storms. Debris lying on the harbour bottom could likewise obstruct its entrance, which was dangerous for sailing ships. Harbour authorities aiming to mitigate these damages usually reinforced the structures at the entrance. The case is clearly evidenced in Frejus [30]. A recent investigation on a caisson located at the entrance of the Herodian harbour of Caesarea revealed a similar attempt to repair or reinforce the end of the northern breakwater in the second century CE, revealing that the port still enjoyed prosperity in that period [16].

The results presented here provide a new baseline for the mapping of the harbour entrance, which will be expanded to additional areas of the harbour and serve as a basis for gathering further multimodal remote sensing data. A close comparison between the newly identified elements as they appear in Figures 4 and 5 indicates, firstly, that the two main seawalls bracketing the harbour's entrance, and possibly also the superstructure imposed on them, were constructed by employing different architectural styles, and, therefore, were likely constructed during different stages of the harbour's activity. Arguably, the original Herodian structures are represented in the northern breakwater, which employed large-scale ashlar masonry, comprising massive blocks measuring up to three meters in length (Figure 4). This architectural style is familiar from other Roman sites along the local coast, such as elements in the temple platforms of the adjacent Dor. The part of the southern breakwater that formed the western facet of the harbour's entrance, on the other hand, presents far less defined architectural characteristics, defined above as an extensive scatter of rubble, and may be approached as a later renovation project, aiming to solidify a collapsing part of the entrance channel (Figure 5).

Secondly, as far as the functionality of the harbour's entrance is concerned, it is noteworthy that the actual entry channel still remains wide and deep enough today for the passage of larger vessels of antiquity, despite the partial collapse of the walls comprising it on both sides. Together with the possible renovation in antiquity of the northern extremity of the southern breakwater, it may be assumed that the functionality of the harbour was not diminished on account of the deterioration in the condition of the harbour's entrance, but possibly following the collapse of other parts of the breakwaters, most likely the southern one, which was the most exposed to the energy of winter storms attacking it from the southwest. A passage from Procopius Gazaeus [31], dated to the early 6th century, reinforces this notion, as follows:

"The port of the city named after Caesar had fallen into bad condition in the course of time and became exposed to the waves, no longer deserving in fact to be titled a port but

preserving merely its name from its former fortune. But you (Anastasius) did not ignore the city's prayers and laments over the ships which, escaping the sea, were wrecked in the harbour itself. [. . .] Thanks to your decision the city was rejuvenated and receives ships without fear and is provided for its basic requirements."

This passage, which refers to Emperor Anastasius' act of munificence in renovating the dysfunctional Sebastos, clearly refers to ships already passing into the harbour through its entrance, only to be wrecked while in it due to the facility's lack of sufficient protection.

Further investigation is to be carried out on the harbour's original building techniques and resources, function, collapse processes, and possible renovation efforts, centred, among other things, also on the obtainment and transportation of spolia from elsewhere in Caesarea, as well as from neighbouring settlements such as the city of Dor, whose ancient centre on the tell, as well as its coastal structures and facilities, also saw serious decline from the 3rd century onward [32].

Author Contributions: Conceptualization, T.G.; Methodology, G.G., E.A.-S., J.W. and T.G.; Software, E.A.-S. and J.W.; Validation, J.W.; Formal analysis, G.G., E.A.-S., E.N. and T.G.; Investigation, G.G. and E.N.; Resources, G.G. and T.G.; Data curation, E.A.-S. and J.W.; Writing—original draft, G.G., E.A.-S., J.W., E.N. and T.G.; Writing—review & editing, G.G.; Visualization, E.A.-S. and J.W.; Supervision, G.G. and T.G.; Project administration, G.G.; Funding acquisition, G.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Haifa Center for Mediterranean History (*Caesarea SubMaritima* 101); as well as by the European Research Council (CoG, SHIPs, 101088962).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: This project has been made possible thanks to the support of the Haifa Center for Mediterranean History, the Recanati Institute for Maritime Studies, the University of Malta, the Israel Antiquities Authority, Heritage Malta, and the European Research Council. Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hohlfelder, R.L.; Brandon, C.; Oleson, J.P. Constructing the Harbour of Caesarea Palaestina, Israel. *Int. J. Naut. Archaeol.* **2007**, *36*, 409–415. [CrossRef]
2. Galili, E.; Salamon, A.; Gambash, G.; Zviely, D. Archaeological and Natural Indicators of Sea-Level and Coastal Change: The Case of the Roman Harbor of Caesarea. *Geosciences* **2021**, *11*, 306. [CrossRef]
3. Yasur-Landau, A.; Shtienberg, G.; Gambash, G.; Spada, G.; Melini, D.; Arkin-Shalev, E.; Tamberino, A.; Reese, J.; Levy, T.E.; Sivan, D. New Relative Sea-Level (RSL) Indications from Archaeological Constructions in Dor, the Carmel Coast, Israel—From the Middle Bronze Age to the Roman period (~3500–1800 yBP). *PLoS ONE* **2021**, *16*, e0251870. [CrossRef] [PubMed]
4. Raban, A. Sebastos: The royal harbour at Caesarea Maritima—A short-lived giant. *Int. J. Naut. Archaeol.* **1992**, *21*, 111–124. [CrossRef]
5. Gambash, G. Caesarea Maritima and the Grand Strategy of the Roman Empire. *Skyllis* **2013**, *13*, 53–58.
6. Holum, K.G.; Hohlfelder, R.L.; Raban, A.; Bull, R.J. *King Herod's Dream: Caesarea on the Sea*; W. W. Norton & Co.: New York, NY, USA, 1988.
7. Ringel, J. Literary sources and numismatic evidence of maritime activity in Caesarea during the Roman period. *Mediterr. Hist. Rev.* **1988**, *3*, 54–62. [CrossRef]
8. Hohlfelder, R.L. Byzantine coin finds from the sea: A glimpse of Caesarea Maritima's later history. In *Harbour Archaeology*; Raban, A., Ed.; BAR International Series 257; British Archaeological Reports: Oxford, UK, 1985; pp. 179–184.
9. Ramsay, J. Trade or trash: An examination of the archaeobotanical remains from the Byzantine harbour at Caesarea Maritima, Israel. *Int. J. Naut. Archaeol.* **2010**, *39*, 376–382. [CrossRef]

10. Raban, A. The lead ingots from the wreck site (area K8). *J. Rom. Archaeol. Suppl. Ser.* **1999**, *35*, 179–188.
11. Marcus Vitruvius Pollio. *De architectura*.
12. Raban, A. *The Harbours of Caesarea Maritima, Parts i and ii: Results of the Caesarea Ancient Harbour Excavation Project, 1980-1985. Volume I: The Site and the Excavations*; BAR Publishing: Oxford, UK, 1989.
13. Caruana, J.; Wood, J.; Nocerino, E.; Menna, F.; Micallef, A.; Gambin, T. Reconstruction of the collapse of the ‘Azure Window’s natural arch via photogrammetry. *Geomorphology* **2022**, *408*, 108250. [CrossRef]
14. Georgiou, N.; Dimas, X.; Fakiris, E.; Christodoulou, D.; Geraga, M.; Koutsoumpa, D.; Baika, K.; Kalamara, P.; Ferentinos, G.; Papatheodorou, G. A multidisciplinary approach for the mapping, automatic detection and morphometric analysis of ancient submerged coastal installations: The case study of the ancient Aegina Harbour Complex. *Remote Sens.* **2021**, *13*, 4462. [CrossRef]
15. Lazar, M.; Basson, U. Frequency domain electromagnetic methods for coastal archaeology—A new(ish) approach for the detection of ancient settlements. In Proceedings of the EGU General Assembly 2023, Vienna, Austria, 24–28 April 2023; pp. EGU23–5919. [CrossRef]
16. Sharvit, J.; Buxton, B.; Kushnir, U. Caesarea from Building to Destruction: New Results from Survey and Excavation Seasons 2015–2022 (Heb.). *BaMerkaz* **2023**, *3*, 183–206.
17. McCarthy, J.; Benjamin, J.; Winton, T.; van Duivenvoorde, W. (Eds.) The Rise of 3D in Maritime Archaeology. In *3D Recording and Interpretation for Maritime Archaeology: 1–10*; Coastal Research Library, 31; Springer: Berlin/Heidelberg, Germany, 2019.
18. Levy, T.E.; Papatheodorou, G.; Geraga, M.; Christodoulou, D.; Georgiou, N.; Kordella, S.; Gkionis, P.; Spondylis, I.; Michalis, M.; Dimas, X.; et al. Digital underwater technologies in the methoni bay cultural heritage project, Greece: Interdisciplinary approaches and sustainability. *Sci. Cult.* **2023**, *9*, 51–88. [CrossRef]
19. Flavius Josephus. *The Jewish War*.
20. Nantet, E. *Phortia: Le Tonnage des Navires de Commerce en Méditerranée: Du VIII^e Siècle av. l’Ère Chrétienne au VII^e Siècle de l’Ère Chrétienne*; Presses Universitaires de Rennes: Rennes, France, 2016.
21. Nakas, I.D. The Construction, Use and Evolution of the Hellenistic and Roman Harbours of the Aegean. Ph.D. Thesis, University of Birmingham, Birmingham, UK, 2022.
22. Dionysius of Halicarnassus. *Roman Antiquities*.
23. Strabo. *Geographica*.
24. Mosaic of Ostia, Piazzale delle Corporazioni, Statio 25, 2nd cent.
25. Salomon, F.; Keay, S.; Carayon, N.; Goiran, J.-P. The Development and Characteristics of Ancient Harbours—Applying the PADM Chart to the Case Studies of Ostia and Portus. *PLoS ONE* **2016**, *11*, e0162587. [CrossRef] [PubMed]
26. Reinhardt, E.G.; Raban, A. Site Formation and Stratigraphic Development of Caesarea’s Ancient Harbor. In *Caesarea Reports and Studies: Excavations 1995–2007 Within the Old City and the Ancient Harbor*; BAR International Series 1784; Holum, K.G., Stabler, J.A., Reinhardt, E.G., Eds.; BAR Publishing: Oxford, UK, 2008; pp. 155–181.
27. Sharvit, J.; Planner, D.; Barkai, O. Caesarea, the Inner Harbour. *Hadashot Arkheologiyot* **2022**, *135*, 1–8.
28. Mosaic of Museo della Città di Rimini, 2nd cent–3rd cent.
29. Ugolini, F. *Visualizing Harbours in the Classical World: Iconography and Representation around the Mediterranean*; Bloomsbury Publishing: London, UK, 2020.
30. Morhange, C.; Gébara, C. *Fréjus (Forum Julii): Le Port Antique/The Ancient Harbour Portsmouth, R.I.*; Cambridge University Press: Cambridge, UK, 2010.
31. Procopius Gazaeus. *Panegyricus in Imperatorem Anastasium*.
32. Arkin, E.; Gambash, G.; Yasur-Landau, A. Disheveled Tenacity: The North Bay of Roman and Byzantine Dor. *J. Marit. Archaeol.* **2019**, *14*, 205–237. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

Article

Exploring the Mediterranean: AUV High-Resolution Mapping of the Roman Wreck Offshore of Santo Stefano al Mare (Italy)

Christoforos Benetatos ^{1,*}, Stefano Costa ², Giorgio Giglio ¹, Claudio Mastrantuono ³, Roberto Mo ⁴, Costanzo Peter ¹, Candido Fabrizio Pirri ^{4,5}, Adriano Rovere ¹ and Francesca Verga ¹

¹ Politecnico di Torino, Department of Environment, Land and Infrastructure Engineering (DIATI), Corso Duca degli Abruzzi 24, 10129 Torino, Italy; giorgio.giglio@polito.it (G.G.); costanzo.peter@polito.it (C.P.); adriano.rovere@polito.it (A.R.); francesca.verga@polito.it (F.V.)

² Superintendence of Archaeology, Fine Arts and Landscape for Liguria, Italian Ministry of Culture, Via Balbi 10, 16126 Genova, Italy; stefano.costa@cultura.gov.it

³ Museo Relitto Romano (MURR) di Santo Stefano al Mare, Piazza della Stazione 1, 18010 Santo Stefano al Mare, Italy; murr.santostefano@gmail.com

⁴ Politecnico di Torino, Department of Applied Science and Technology (DISAT), Corso Duca degli Abruzzi 24, 10129 Torino, Italy; roberto.mo@polito.it (R.M.); fabrizio.pirri@polito.it (C.F.P.)

⁵ Italian Institute of Technology—CSFT, via Livorno 60, 10144 Torino, Italy

* Correspondence: christoforos.benetatos@polito.it

Abstract

Historically, the Mediterranean Sea has been an area of cultural exchange and maritime commerce. One out of many submerged archaeological sites is the Roman shipwreck that was discovered in 2006 off the coast of Santo Stefano al Mare, in the Ligurian Sea, Italy. The wreck was dated to the 1st century B.C. and consists of a well-preserved cargo ship of Roman amphorae that were likely used for transporting wine. In this study, we present the results of the first underwater survey of the wreck using an Autonomous Underwater Vehicle (AUV) industrialized by Graal Tech. The AUV was equipped with a NORBIT WBMS multibeam sonar, a 450 kHz side-scan sonar, and inertial navigation systems. The AUV conducted multiple high-resolution surveys on the wreck site and the collected data were processed using geospatial analysis methods to highlight local anomalies directly related to the presence of the Roman shipwreck. The main feature was an accumulation of amphorae, covering an area of approximately 10×7 m with a maximum height of 1 m above the seabed. The results of this interdisciplinary work demonstrated the effectiveness of integrating AUV technologies with spatial analysis techniques for underwater archaeological applications. Furthermore, the success of this mission highlighted the potential for broader applications of AUVs in the study of the seafloor, such as monitoring seabed movements related to offshore underground energy storage or the identification of objects lying on the seabed, such as cables or pipelines.

Keywords: AUV; Roman shipwreck; seabed monitoring; geospatial analysis; marine archeology; underwater cultural heritage; underground energy storage

1. Introduction

During historic times, the Mediterranean Sea was an important area of commerce and cultural exchange among the surrounding countries, connecting the civilizations of Europe, Africa and Asia (e.g., [1]). According to [2], during the Roman era, the Mediterranean is believed to have been more interconnected than at any other time until modern transportation developed in the 19th century.

Shipwrecks are some of the most valuable sources to gain an insight into the maritime economy in the Mediterranean area. Until 1984, there were almost 800 shipwrecks reported in the Mediterranean area and the Black Sea [3], while to date, almost 1784 ancient shipwrecks have been identified [4], many dating from the Hellenistic and Roman periods, a time when maritime commerce was very active due to relatively stable political conditions. Many wrecks that lie in shallow waters are easily accessible to potential looters, while others, especially those sunk in deeper locations, are more difficult to reach and remain relatively intact.

These shipwrecks provide valuable and rare evidence of the goods and materials that were traded across the sea in ancient times. The goods in most cases were transported in amphorae, ceramics and other types of cargo, which, when discovered, offer valuable information regarding the economic patterns, production centers, and consumption habits of the communities of that time [3]. The reasons for the maritime disasters that caused the ships to sink were diverse. Sometimes, heavy storms or navigational errors could lead to the ship sinking, while other times, the causes can be linked to piracy or even to deliberate beaching.

In the Italian region, one of the discoveries that has enriched our knowledge of maritime trade in Roman times is the wreck of a Roman merchant vessel located off the coast of Santo Stefano al Mare in the Ligurian Sea (Figure 1). The wreck was discovered in 2006, and it is a well-preserved example of a mid-sized cargo ship that was transporting amphorae. The wreck offers valuable information regarding shipbuilding techniques and logistical practices in the 1st century B.C. The site where the wreck was found is relatively undisturbed and thus has allowed researchers to document the spatial organization and preservation state of the cargo with high precision. In addition, a museum dedicated to the wreck, the Roman Shipwreck Museum (MURR), was established in the area of the former railway station of Santo Stefano al Mare, with the aim of bringing the public closer to history and underwater archaeology and offering a unique opportunity to virtually explore the wreck to those who cannot dive into the depths of the Ligurian Sea.

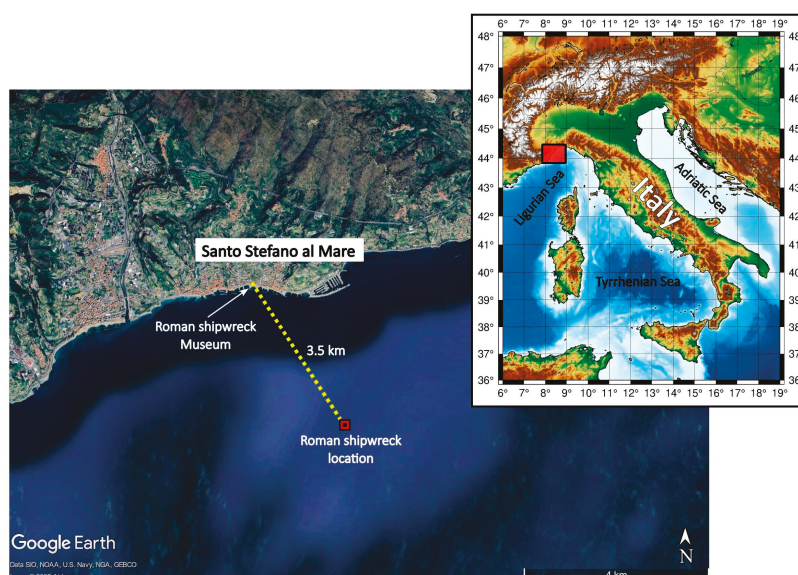


Figure 1. Location of the Roman shipwreck in the Ligurian Sea, close to the city of Santo Stefano al Mare (IM), Italy; the red square on the top right map identifies the position of the wreck site in the Ligurian Sea, North-West Italy.

In recent years, Autonomous Underwater Vehicles (AUVs) have become an important tool used in a wide range of marine exploration applications. This has been achieved

by introducing state-of-the-art technologies that minimize human contribution and allow accurate mapping of large areas that are difficult to access directly.

AUVs are extensively used for seabed mapping due to their high-resolution scan capability. Bathymetric studies have been conducted by [5], who employed an AUV to map undiscovered fields of high-temperature hydrothermal vents. Ref. [6] used an AUV to survey bathymetry and water mass properties at Glover's Reef atoll in Belize as part of a multidisciplinary study of population connectivity of Nassau grouper. Ref. [7] exploited high-resolution multibeam scans for sea floor mapping, while [8] used AUVs for iceberg positioning and orientation. AUVs have also been used for environmental monitoring and the mapping and detailed characterization of geological structures. Ref. [9] focused their research on monitoring coral reefs and fisheries. Ref. [10] used images at selected reference stations on the Australian continental shelf for the identification of changes in benthic assemblage composition and cover derived from registered maps collected at regular intervals. Ref. [11] used an AUV to record aquatic life. Ref. [12] focused on the study of hydrothermal fields on the submarine ridges. Ref. [13] adopted AUV technology for studying large-scale, deep-sea geological structures such as mid-ocean ridges, seamounts and back-arc basins. In recent years, surveys and inspections of subsea infrastructures and sites have also benefited from AUVs because they can work efficiently and safely in a cost-effective way. Ref. [14] utilized an AUV for real-time simultaneous localization and mapping (SLAM) to inspect a 3D subsea infrastructure within a water tank, whereas [15] focused their work on pipeline inspection for tracking and monitoring spilled oil and gas in an offshore environment. AUVs have also been used for military applications such as intervention activities, logistics, search and rescue operations [16–18]. Recently, ref. [19] presented advancements in Unmanned Underwater Vehicle (UUV) technology, leading to increased capabilities and reduced costs, and making underwater archaeological sites more accessible, thereby reducing the need for human diving.

AUVs are particularly valuable for conducting archaeological studies by mapping underwater sites with high precision and minimizing human intervention, which could damage the archaeological findings [20,21]. Ref. [4] studied 11 known shipwrecks in the Ionian Sea (Greece), ranging from ancient times to the 20th century, using marine remote sensing tools such as side-scan sonars, sub-bottom profilers, and multibeam echo-sounders.

The considerable interest of the scientific community in a broad spectrum of underwater operations to investigate offshore historical artifacts as well as industrial marine structures is well documented in recent research. Ref. [22] performed geophysical surveys off the ancient port of Myos Hormos in the Red Sea; they detected a Roman shipwreck using a side-scan sonar and AUV-based high-resolution mapping, highlighting the value of advanced acoustic methods for underwater archaeology. Ref. [23] offers a review of recent advances in underwater robotics and analyzes their potential to improve inspection and monitoring of critical undersea infrastructures. Ref. [24] highlights the potential of using artificial intelligence for the detection and classification of underwater findings and how interdisciplinary approaches can assist in the preservation and valorization of cultural heritage.

For the study of the offshore area of Santo Stefano al Mare, recent technological advancements were employed for an accurate mapping of the wreck site and its amphorae. At the end of 2023, an AUV was deployed by Graal Tech to explore the area and collect detailed bathymetric data about the ancient cargo ship lying on the seabed. The AUV provided a high-resolution 3D map of the wreck site, which helped identify key geomorphological and anthropogenic features. In this work, we collected and analyzed the available data derived from the AUV acquisitions. Data were elaborated using geostatistical techniques, including

a variogram model and spatial interpolation analysis. The main detected features were a substantial amphorae concentration and a separate anomaly, identified as a mine cart.

Our results show that the acquisition process and methodology were adequate for accurately locating the amphorae accumulation and measuring its dimensions and, more generally, that current AUVs, equipped with proper instrumentation, have a good performance for underwater archaeological exploration. The successful outcome of this mission confirmed the AUV's potential for the identification and localization of objects lying on the seabed, such as communication cables or pipelines, as reported in [15], but their use could be effectively extended to monitoring seabed movements related to anthropogenic activities, as suggested in [25,26].

2. The Roman Shipwreck

The waters of the Ligurian Sea are rich in ancient shipwrecks, with the discovery of the Albenga A in 1950 being the first and possibly most famous find [27]. Crucially, most discoveries are the result of fishing or diving activity and not of systematic research, as is the case of the Santo Stefano Romano shipwreck that was found off the coast of Santo Stefano al Mare, a small coastal village in the province of Imperia, Italy [28–30].

In 2006, at a depth of about 58 m, the sea returned the remains of a Roman merchant ship, that once sailed the Mediterranean transporting amphora-borne foodstuffs. This wreck, dating back to the 1st century BC, is one of several examples of this period along the coast of Liguria.

The vessel, likely of medium size, around 15–20 m long and 5–8 m wide, was probably a corbita (Figure 2), a sailing ship with a rounded bow and stern that had a large load capacity. This ship typically had one mast, even if the presence of a second mast cannot be excluded. The existence of a deck is doubtful because in other cases it was found that such ships had only narrow footbridges for access, leaving the entire hull free for cargo, covered only by tents in case of rain or rough sea. It is also believed that since the cargo was full of a single type of amphora, this proves that the ship was performing a cabotage route rather than coastal trade with intermediate stops ([31] and references therein). The presence of amphorae (Figure 3), of Roman Republican type 1B according to the Dressel classification [31], suggests that the ship was transporting wine (or, less likely, oil), valuable goods that were traded along the commercial routes connecting the Italian peninsula to Gallia and Hiberia further to the west.

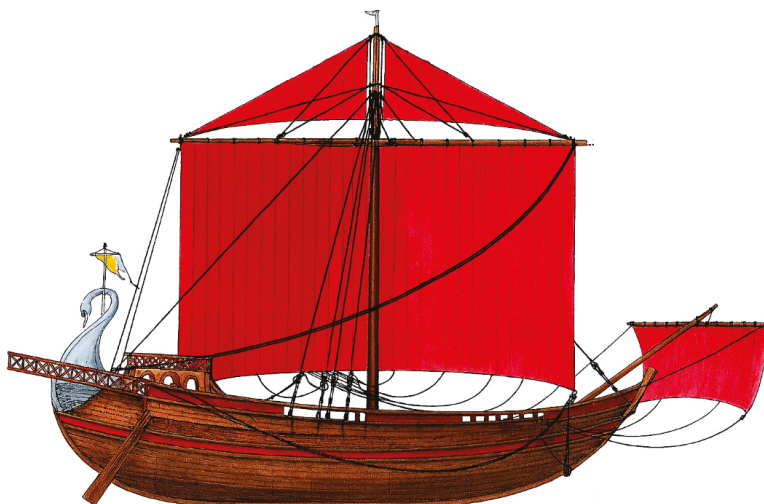


Figure 2. Artistic depiction of a Roman corbita vessel (mod. from [32]).



Figure 3. Underwater photo of an amphora from the Santo Stefano al Mare shipwreck (**left**); representation of a Dressel 1B amphora [33] (**right**). (Underwater photo courtesy of: Superintendence for Archaeology, Fine Arts and Landscape for Liguria Soprintendenza Archeologia Belle Arti e Paesaggio per la Liguria/Nautilus Technical Diving Center).

While the ship's wooden planks are worn by time and salt, the cargo of amphorae is still well-preserved. It is believed that the cargo capacity was about 3000 amphorae. The amphora accumulation is covered with sponges and has an elliptical shape, rising about 70 cm above the seabed (Figure 4). Video analysis shows mostly intact amphorae, scattered on the seabed, possibly due to trawl nets, with only around 5% of the amphorae having been damaged. The absence of other materials, such as ceramic pieces, stones, etc., around the amphorae suggests the good state of preservation of the wreck [31]. Dives conducted by the team from the Superintendence (Soprintendenza) and the Nautilus Technical Diving Center have documented the state of the wreck and carried out detailed surveys, allowing researchers to reconstruct the history and hypothesize the causes of the sinking of the ship, which likely sunk due to a sudden storm, a common event for sailors of the time who, despite their expertise, lacked modern technology to predict the whims of the sea.



Figure 4. Underwater photos of the amphorae accumulation of the Santo Stefano al Mare shipwreck. (Underwater photos courtesy of Superintendence for Archaeology, Fine Arts and Landscape for Liguria—Soprintendenza Archeologia Belle Arti e Paesaggio per la Liguria/Nautilus Technical Diving Center).

This extraordinary discovery became the focus of a French documentary series dedicated to Roman trade in the Mediterranean named “Histoires englouties” (PLANÈTE+/myCANAL), episode “Les naufrages de l’Empire romain”. In this episode, director-diver Kevin Sempé explores several sites across Italy and France, including the Roman shipwreck off Santo Stefano al Mare (Liguria) as well as wrecks in the Camargue. The series was broadcast during December 2022 and produced by Imagissime (Mediawan). High-definition underwater footage offered the public fascinating images of what lies on the seabed, revealing the beauty and historical value of the wreck.

3. Underwater Exploration with the AUV

3.1. AUV Equipment

The exploration of submerged archaeological sites presents complex challenges and requires advanced methods to achieve high-quality data acquisition. Several challenges, such as the depth of investigation, limited visibility, unpredictable sea currents, and the need for precise data acquisition without direct visual confirmation, need to be addressed; thus, the use of advanced technology is mandatory. AUVs equipped with high-precision sensors have become essential for the real-time collection of detailed, georeferenced subsea data (e.g., [4,19] and references therein).

In the present study, an AUV assembled by Graal Tech was deployed for the inspection of the Roman shipwreck off the coast of Santo Stefano al Mare, at a depth of approximately 58 m. The employed platform was based on the X300 model, equipped with instruments for high-resolution bathymetric mapping and imaging and georeferenced localization of the AUV.

The NORBIT WBMS multibeam sonar was the core of the system. This device emits fan-shaped acoustic waves toward the seabed and measures the time it takes for the echoes to return after striking submerged objects. The result is a detailed 3D bathymetric map that offers a precise reconstruction of the underwater terrain that is crucial for identifying anthropogenic structures such as wrecks or objects lying on the sea floor. Alongside the multibeam sonar, a 450 kHz side-scan sonar was also employed. Unlike the multibeam, which focuses on vertical depth, this instrument performs lateral scans, providing high-resolution images of the seabed on both sides of the vehicle. It is especially useful for detecting the shapes and contours of submerged objects, allowing researchers to clearly distinguish man-made elements from natural formations. To accurately determine where data is being collected, the AUV is equipped with an inertial navigation platform integrated with a Doppler Velocity Log (DVL). The former uses gyroscopes and accelerometers to detect the vehicle's movement and orientation, while the DVL measures velocity relative to the seabed. Together, these systems allow for precise georeferencing of each point, even in the absence of GPS signals, which cannot be received underwater.

The entire system is managed by a synchronization software that enables autonomous navigation and real-time data acquisition. Additionally, a radio communication link with the ground station allows remote monitoring of the mission, with the possibility of receiving updates on the vehicle position and issuing corrective commands, if necessary.

3.2. AUV Specifications and Instrumentation

The X-300 is a multimode AUV that can operate under different configurations, as a classic AUV, glider or profiler, while in some cases also as a ROV-like system with real-time operator control. It is 2.2 m long with a diameter of its cylindrical body of 15.5 cm, a weight of approximately 29 kg, and it is capable of operating down to a depth of 300 m below sea level.

The general structural layout includes a nose section, hosting navigation sensors and optional sonar or cameras. The payload bay (middle part) hosts scientific equipment or side-scan sonar. The core suite of sensors includes:

- Inertial Measurement Unit (IMU) with gyroscopes and accelerometers used for navigation;
- Depth-meter and pressure sensor;
- Doppler Velocity Log (DVL) for underwater dead-reckoning;
- GPS (only at surface);
- Acoustic modem and WiFi for underwater and surface communications.

Optional payloads may include different frontal or side-scan sonars and environmental sensors (e.g., fluorometer, magnetometer)

The AUV buoyancy system is controlled by a variable buoyancy chamber. Its thruster system includes two pairs of vectored thrusters plus a rear propulsor for the main forward thrust that offers a maximum speed of 5 knots. The tail is equipped with antennas or tether connection devices. The AUV is powered by 24 V Li-ion batteries.

The resolution of side-scan sonars depends on the frequency and the depth of investigation. Sonars operating in low frequencies (100–300 kHz) offer longer range and deeper penetration, but lower resolution. Higher-frequency sonars (600–1200 kHz) offer higher resolution but are limited to shallow waters. The 450 kHz sonar employed for the surveys is an intermediate solution. It is effective at the depths of the Roman shipwreck site since it is specifically designed for continental shelf waters or coastal surveys. Its optimal operation depth range is 50–150 m, with a lateral coverage of 100–400 m while offering a resolution between 20 and 50 cm.

The X-300 model uses an inertial navigation system and a Doppler Velocity Log (DVL) to maintain accurate positioning when operating underwater in the absence of GPS access. Its Inertial Measurement Unit (IMU) continuously monitors acceleration and angular rates, and the on-board computer analyzes the data to estimate position or orientation changes with time. This system keeps track of the navigation path once the last GPS measurement is taken, just before the submersion of the AUV. Additional systems, such as the Doppler Velocity Log (DVL), are used to measure the AUV's velocity relative to the seabed using acoustic pulses, providing precise 3D velocity data, which significantly enhances positional accuracy when used in conjunction with IMU data.

3.3. AUV and Equipment Testing Phases

The mission followed a multiphase approach that is described below and is illustrated in the pictures shown in Figure 5.

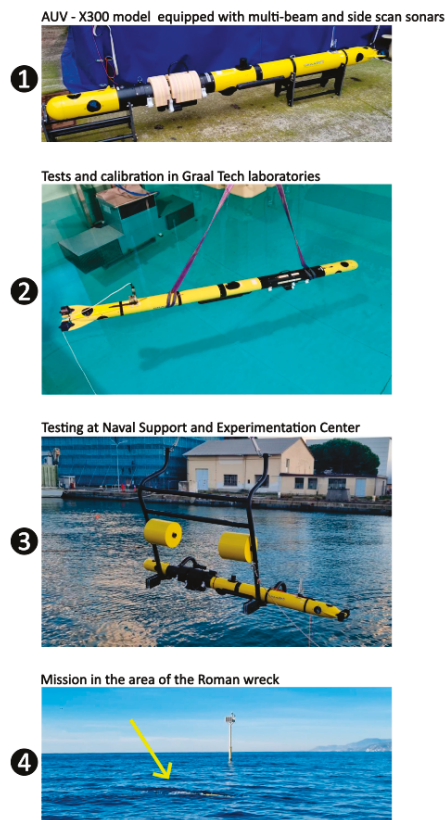


Figure 5. Visual narration of the journey of the AUV from assembly to open-sea deployment, starting with the installation of the sonar systems (1), followed by preliminary testing in a controlled pool

environment (2), then seawater trials at the Naval Support and Experimentation Center in La Spezia (3), and finally the actual inspection of the archaeological site (4).

The development of this underwater archaeological mission adhered to rigorous protocols. Initially, a system calibration and validation were conducted at Graal Tech's laboratories, where the autonomous vehicle was configured with the multibeam sonar system and integrated data management software. Extensive testing of each of the individual components and the overall system stability was performed in controlled pool environments to simulate operational conditions. These preliminary tests ensured functional integrity before deployment.

The second phase involved conducting sea trials at the Naval Support and Experimentation Center (CSSN) in La Spezia. The objectives included refining navigation algorithms to achieve precise georeferencing and validating data fusion methods between the navigation system and multibeam sonar. Trial data acquisition facilitated the iterative adjustments to optimize sensors synchronization and positional accuracy under open-sea conditions.

Following laboratory and sea trial validation, the operational phase was initiated. Pre-deployment procedures included system checks, instrumentation functionality verification, and logistical preparations such as loading the AUV and supporting equipment onto the deployment vessel. The mission was executed through three autonomous surveys at specific depths:

1. Survey 1: Depth of 40 m.
2. Survey 2: Same trajectory as Survey 1, but at 45 m.
3. Survey 3: Navigation at 48 m with a vertical distance of 7 m from the seabed.

Each survey was designed to generate high-resolution, layered datasets of the archaeological site.

4. Statistical Analysis of Data Recorded by the AUV

The data collected during the AUV surveys were downloaded and processed to examine the methodology applied during the acquisition process and to analyze the findings related to the remains of the Roman shipwreck on the sea floor. Initial analysis of the collected data was used to demonstrate its operational effectiveness. The on-board sensors produced detailed 3D reconstructions of the wreck site, revealing the structural features and the positioning of artifacts such as amphorae, while the integrated navigation algorithms maintained precise georeferencing. The combined application of multibeam and side-scan sonar methodologies facilitated the interpretation of the submerged archaeological site.

The area surveyed by the AUV is approximately 65 m × 50 m wide, covering a larger area with respect to the one where the Roman shipwreck is located (Figure 6), with depths below sea level varying from 54 m to 62 m. The acquisition route of the AUV was in the NW-SE direction with a sampling rate frequency of approximately 1 data point/15 cm along the route. The average spacing between adjacent trajectories was approximately 10 cm, covering the area of investigation with a high point density. Each stripe of data points reflects the trajectory followed by the AUV to cover the study area. An intentional overlap between stripes was designed to ensure complete spatial coverage and the absence of gaps.

The data were initially imported into a specialized software for statistical analysis to visualize them and perform an analysis focused on revealing the details of sea floor geometry and the objects lying on the seabed.

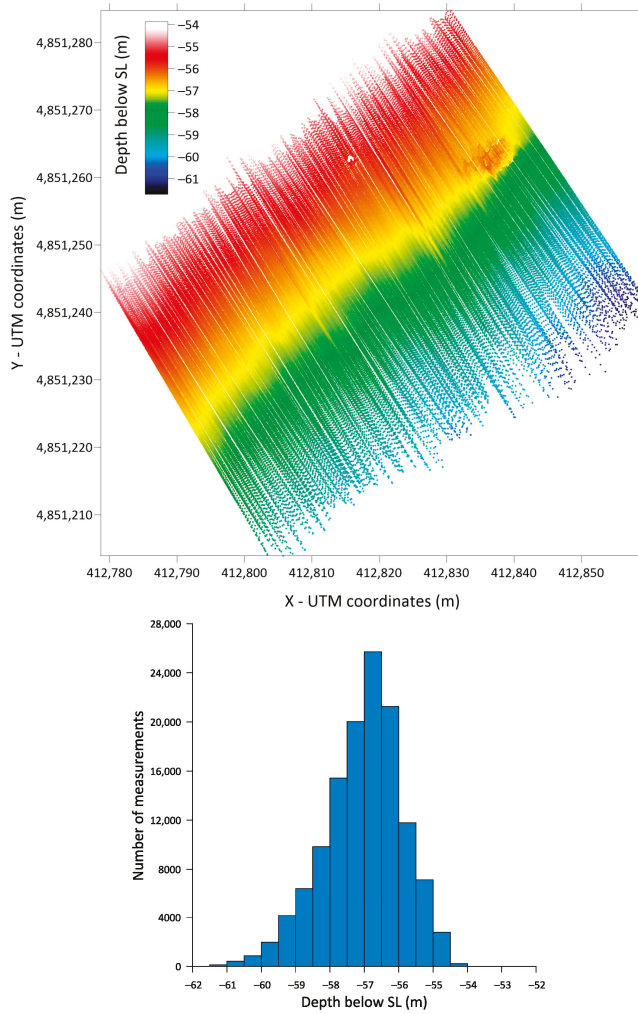


Figure 6. Measurement points of the depth of the seabed below sea level (SL) acquired by the AUV in the area of the Roman shipwreck (**top**) and corresponding histogram distribution of the depth values (**bottom**). The route of the AUV followed parallel NW–SE trajectories coinciding with the direction of the data point stripes displayed in the top map.

Before any interpretation, it was necessary to recognize possible trends that are related to the geometry of the sea floor. In this pre-processing phase, a geostatistical analysis (e.g., [34–37]) was performed in order to identify the spatial characteristics of the dataset (including spatial variation or degree of discontinuity). For this reason, it was necessary to calculate the variogram, a useful tool to identify various spatial features of a dataset, such as spatial continuity, cyclicity, or trend. For observations collected in nature (data points within a specific area), the variogram (or semi-variogram) is defined as the half variance of two observations that are separated in space by a specific distance (lag distance). In this case, the experimental variogram was calculated as follows:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{x=1}^{N(h)} [Z(x+h) - Z(x)]^2 \quad (1)$$

where h is the lag distance between the two data points $Z(x+h)$ and $Z(x)$ and $N(h)$ is the number of pairs of data points for this specific lag distance (e.g., [34]).

A conceptual example of an experimental variogram analysis is presented in Figure 7.

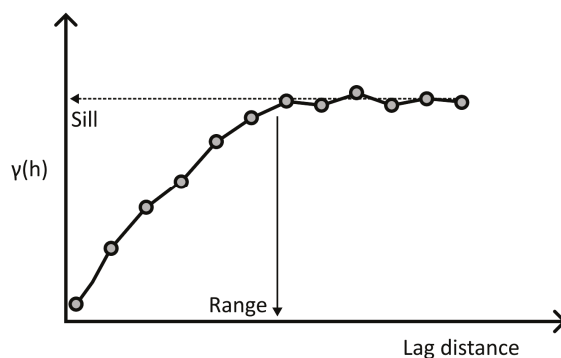


Figure 7. Typical example of an experimental variogram showing the maximum data variability (sill) and the maximum correlation distance (range); the horizontal axis represents the lag distance (distance between pairs of data points).

During the variogram analysis, the values of the variogram are plotted for several lag distances. If the dataset shows correlation in a specific direction, it is expected that the variogram values will flatten out, at a certain distance, when the maximum data variability (sill) is reached. This lag distance is called range and indicates the maximum distance, in a given direction, for which the values remain correlated. To evaluate the full spatial correlation, the variogram can also be calculated for different directions, investigating the presence of anisotropy effects. If the dataset exhibits higher spatial continuity in a certain direction, a longer correlation range is expected in that direction. In several cases, the dataset may be characterized by the presence of a trend; in such cases, the variogram analysis will show a continuous increase with larger lag distances never reaching the “sill” point.

During the pre-processing phase, we performed the variogram analysis on the data gathered by the AUV. The variogram map created by calculating the experimental variogram for different directions is shown in Figure 8. As expected, the trend in the data due to the deepening of the seafloor was clearly identified (direction parallel to the AUV route), while the variogram shows a constant behavior in the direction perpendicular to the AUV route, which is typical for a variable that does not present any spatial continuity.

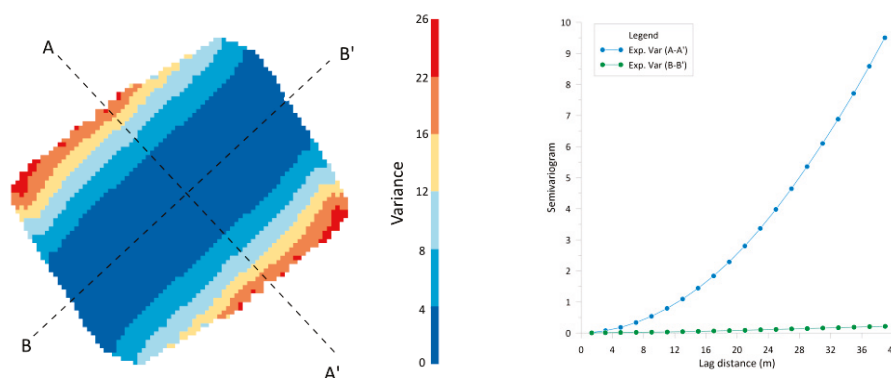


Figure 8. Variogram map and experimental variograms relative to the directions parallel (A-A') and perpendicular (B-B') to the AUV route.

Then, we performed an interpolation over the available data points and created a surface that represents the detected regional trend (Figure 9) by using a polynomial regression approach applied to the original bathymetric data. As clearly visible from the regional trend, the investigated area shows a constant deepening of the sea floor when moving from NW towards SE, which we expected to identify during the variogram analysis.

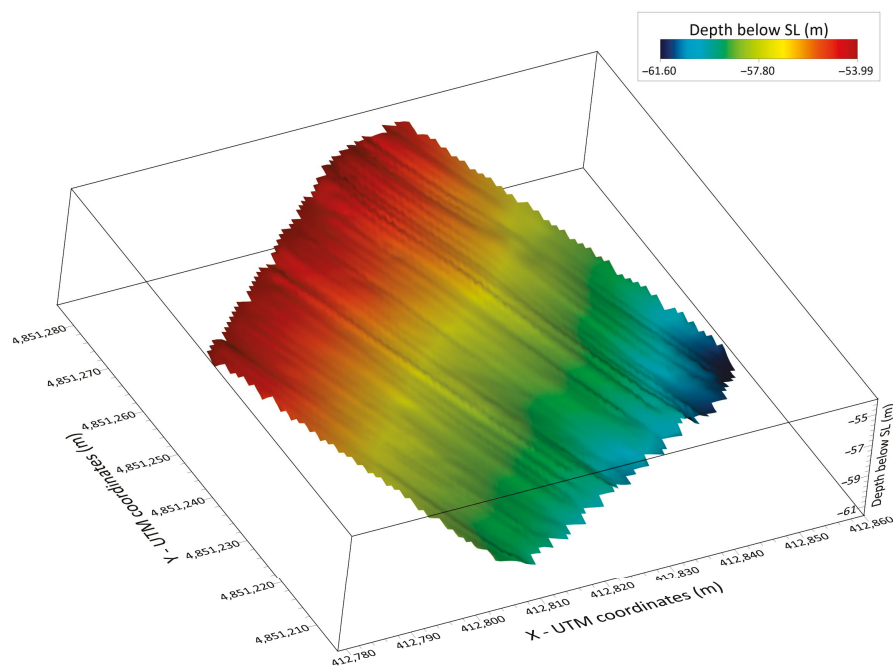


Figure 9. Regional surface trend obtained from the original seabed depth map.

This trend was subsequently subtracted from the data points to create a detrended dataset of the bathymetric data suitable for further analysis. The detrended data, interpolated using the Kriging interpolation technique, along with the corresponding histogram distribution of the residual depth values, are presented in Figure 10. In this case, the Kriging interpolation was adequate for producing accurate maps because the point density was extremely high (a few centimeters distance between points and a total number of more than 128,000 measured points), and different methods would not have generated substantially different results.

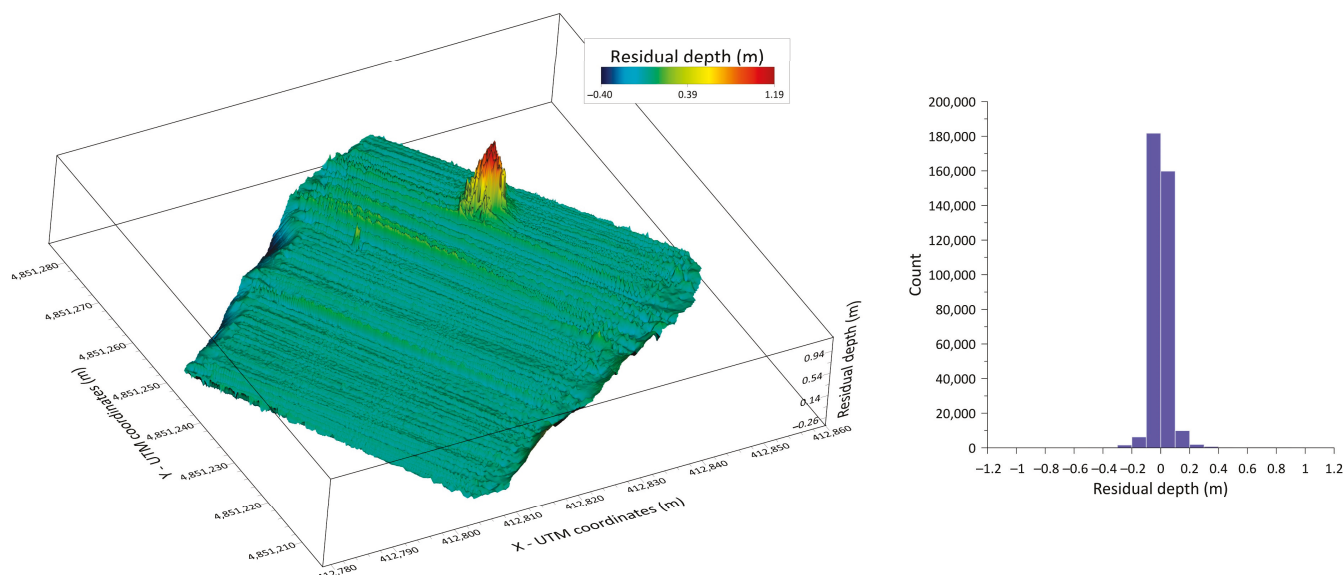


Figure 10. Residual surface of the seabed elevation points after removing the regional surface trend and corresponding histogram distribution of the residual depth values.

The area covered by the AUV surveys shows two anomalies, which are highlighted in Figure 11. The first anomaly of large dimensions corresponds to the Roman shipwreck site. It covers an area of approximately 10 m × 7 m and highlights the accumulation of amphorae

related to the cargo of the Roman ship that sank in that region. The maximum height of the amphorae accumulation reaches almost 1 m. The second anomaly has dimensions of approximately 1.5 m × 1.5 m and corresponds to a mine cart.

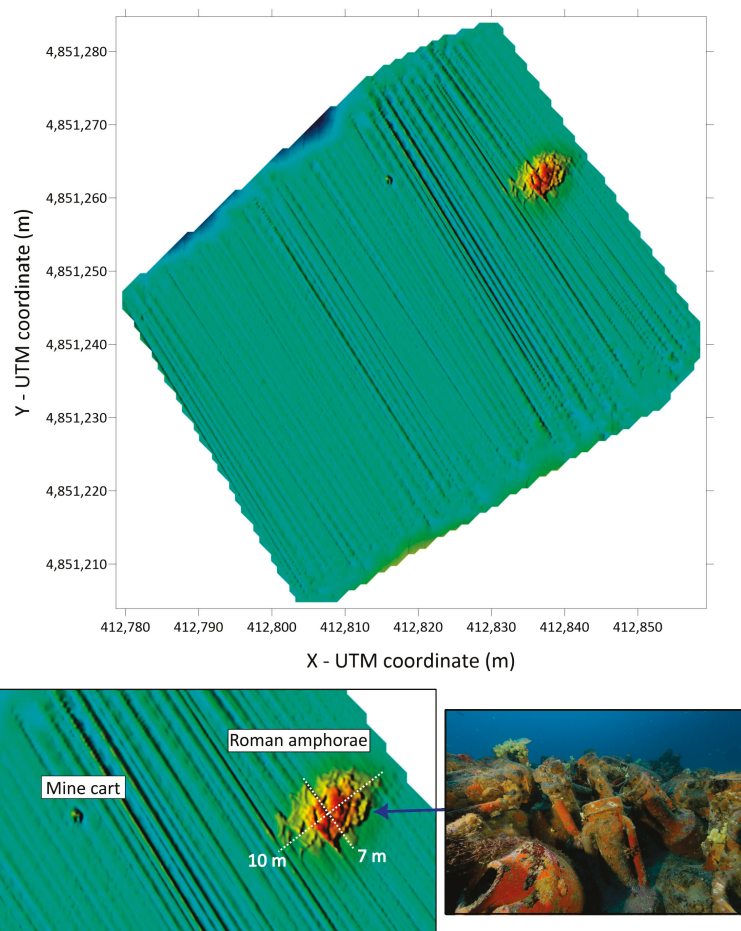


Figure 11. Identification and measurements of significant anomalies recognized on the seabed: Roman amphorae accumulation and mine cart. (Underwater photo courtesy of: Superintendence for Archaeology, Fine Arts and Landscape for Liguria Soprintendenza Archeologia Belle Arti e Paesaggio per la Liguria/Nautilus Technical Diving Center).

5. Discussion and Conclusions

In this work, we presented an integrated methodology for the acquisition and analysis of underwater elevation data related to a Roman shipwreck site offshore of the town of Santo Stefano al Mare in the Liguria region of northern Italy, using an Autonomous Underwater Vehicle (AUV). This was the first time that an AUV was deployed in that area to document the shipwreck. The result of this work is an example of interdisciplinary collaboration between archaeology and engineering, combining advanced monitoring techniques, geostatistical analysis, and knowledge of maritime archeology. The outcome of this joint effort from researchers with such different backgrounds contributes to revealing the complexities of ancient maritime networks and enriches our understanding of the economic and social framework that characterized the Mediterranean basin during the Roman era. Furthermore, the collaboration with the Roman Shipwreck Museum (MURR) proved the importance of bringing scientific discoveries and public interest to raise awareness of cultural heritage preservation.

The combined use of multibeam and side-scan sonars proved to be a highly effective solution for surveying submerged archaeological sites, ensuring minimum disturbance of the site under investigation. The collected data interpretation has demonstrated that the

use of high-quality equipment and the application of geostatistical techniques can provide precise and reliable results in identifying relatively small objects lying on the seabed, with dimensions ranging from the centimeter to meter scale. The methodology that is presented in this work proves how advanced technological integration and systematic operational planning can bring underwater exploration to a rigorous scientific discipline, showing its potential for applications beyond archaeology surveys. Bathymetric variations and the presence of submerged artifacts, cables or pipelines can be detected and mapped, reducing the need for diving interventions. The ability to detect and map seabed anomalies can also be applied to offshore infrastructure inspection, environmental monitoring, and geostorage risk assessment.

Author Contributions: Conceptualization, C.B., F.V., C.F.P., C.M., G.G. and R.M.; methodology, C.B.; formal analysis, C.B.; investigation, R.M.; resources, A.R.; writing—original draft preparation, C.B. and C.P.; writing—review and editing, C.B., C.P., F.V., G.G., S.C. and A.R.; supervision, F.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. The original data collected by the AUV and used in this study are available at the following link: <https://zenodo.org/records/17281322>, accessed on 2 October 2025. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors acknowledge the Ministry of the Environment and Energy Safety (MASE) for their support in developing the methodology for seabed investigation with Autonomous Underwater Vehicles. Furthermore, the authors wish to thank the Ministry of Culture (MiC)—Superintendency of Archaeology, Fine Arts and Landscape of Liguria, and the Port Authority for granting permission to explore the Roman shipwreck with the AUV.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AUV	Autonomous Underwater Vehicle
UUV	Unmanned Underwater Vehicle
MURR	Roman Shipwreck Museum
SLAM	Simultaneous Localization and Mapping

References

1. Abulafia, D. *The Great Sea: A Human History of the Mediterranean*; Oxford University Press: Oxford, UK, 2011; p. 783. ISBN 0195323343.
2. Whitewright, J. Sailing and sailing rigs in the ancient Mediterranean: Implications of continuity, variation, and change in propulsion technology. *Int. J. Naut. Archaeol.* **2018**, *47*, 28–44. [CrossRef]
3. Parker, A.J. Shipwrecks and ancient trade in the Mediterranean. *Archaeol. Rev. Camb.* **1984**, *3*, 99–113. [CrossRef]
4. Geraga, M.; Christodoulou, D.; Eleftherakis, D.; Papatheodorou, G.; Fakiris, E.; Dimas, X.; Georgiou, N.; Kordella, S.; Prevenios, M.; Iatrou, M.; et al. Atlas of Shipwrecks in Inner Ionian Sea (Greece): A Remote Sensing Approach. *Heritage* **2020**, *3*, 1210–1236. [CrossRef]
5. German, C.R.; Yoerger, D.R.; Jakuba, M.; Shank, T.M.; Langmuir, C.H.; Nakamura, K.I. Hydrothermal exploration with the autonomous benthic explorer. *Deep Sea Res.* **2008**, *55*, 203–219. [CrossRef]
6. Shcherbina, A.Y.; Gawarkiewicz, G.G.; Linder, C.A.; Thorrold, S.R. Mapping bathymetric and hydrographic features of Glover’s Reef, Belize, with a REMUS autonomous underwater vehicle. *Limnol. Oceanogr.* **2008**, *53*, 2264–2272. [CrossRef]
7. Thompson, D.; Caress, D.; Paull, C.; Clague, D.; Thomas, H.; Conlin, D. MBARI mapping AUV operations: In the Gulf of California. In Proceedings of the 2012 Oceans Conference, Hampton Roads, VA, USA, 14–19 October 2012; pp. 1–5. [CrossRef]

8. Norgren, P.; Skjetne, R. A multibeam-based SLAM algorithm for iceberg mapping using AUVs. *IEEE Access* **2018**, *6*, 26318–26337. [CrossRef]
9. Vasilescu, I.; Kotay, K.; Rus, D.; Dunbabin, M.; Corke, P. Data collection, storage, and retrieval with an underwater sensor network. In Proceedings of the 3rd International Conference on Embedded Networked Sensor Systems, San Diego, CA, USA, 2–4 November 2005; pp. 154–165. [CrossRef]
10. Williams, S.B.; Pizarro, O.R.; Jakuba, M.V.; Johnson, C.R.; Barrett, N.S.; Babcock, R.C.; Kendrick, G.A.; Steinberg, P.D.; Heyward, A.J.; Doherty, P.J.; et al. Monitoring of benthic reference sites: Using an autonomous underwater vehicle. *IEEE Robot. Autom. Mag.* **2012**, *19*, 73–84. [CrossRef]
11. Katzschmann, R.K.; DelPreto, J.; MacCurdy, R.; Rus, D. Exploration of underwater life with an acoustically controlled soft robotic fish. *Sci. Robot.* **2018**, *3*, eaar3449. [CrossRef]
12. Wu, T.; Tao, C.; Zhang, J.; Wang, A.; Zhang, G.; Zhou, J.; Deng, X. A hydrothermal investigation system for the Qianlong-II autonomous underwater vehicle. *Acta Oceanol. Sin.* **2019**, *38*, 159–165. [CrossRef]
13. Zhu, Z.; Tao, C.; Wu, T.; Schneider von Deimling, J.; Zhang, J.; Zhang, G. Seafloor Classification by Fusing AUV Acoustic and Magnetic Data: Toward Complex Deep-Sea Environments. *IEEE Trans. Geosci. Remote Sens.* **2025**, *63*, 4203215. [CrossRef]
14. Palomer, A.; Ridao, P.; Ribas, D. Inspection of an underwater structure using point-cloud SLAM with an AUV and a laser scanner. *J. Field Robot.* **2019**, *36*, 1333–1344. [CrossRef]
15. Kimura, R.; Choyekh, M.; Kato, N.; Senga, H.; Suzuki, H.; Ukita, M.; Kamezuka, K. Guidance and control of an autonomous underwater robot for tracking and monitoring spilled plumes of oil and gas from seabed. In Proceedings of the 23rd International Offshore and Polar Engineering Conference, Anchorage, AK, USA, 30 June–5 July 2013.
16. Hamilton, M.J.; Kemna, S.; Hughes, D. Antisubmarine warfare applications for autonomous underwater vehicles: The GLINT09 sea trial results. *J. Field Robot.* **2010**, *27*, 890–902. [CrossRef]
17. Sanz, P.J.; Ridao, P.; Oliver, G.; Casalino, G.; Insaurralde, C.; Silvestre, C.; Melchiorri, C.; Turetta, A. TRIDENT: Recent improvements about autonomous underwater intervention missions. *IFAC Proceeding* **2012**, *45*, 355–360. [CrossRef]
18. Casalino, G.; Caccia, M.; Caselli, S.; Melchiorri, C.; Antonelli, G.; Caiti, A.; Indiveri, G.; Cannata, G.; Simetti, E.; Torelli, S.; et al. Underwater intervention robotics: An outline of the Italian national project MARIS. *Mar. Technol. Soc. J.* **2016**, *50*, 98–107. [CrossRef]
19. Diamanti, E.; Ødegård, Ø.; Mentogiannis, V.; Koutsouflakis, G. Underwater Drones as a Low-Cost, yet Powerful Tool for Underwater Archaeological Mapping: Case Studies from the Mediterranean. *J. Comput. Appl. Archaeol.* **2025**, *8*, 10–24. [CrossRef]
20. Bingham, B.; Foley, B.; Singh, H.; Camilli, R.; Delaporta, K.; Eustice, R.; Mallios, A.; Mindell, D.; Roman, C.; Sakellariou, D. Robotic tools for deep water archaeology: Surveying an ancient shipwreck with an autonomous underwater vehicle. *J. Field Robot.* **2010**, *27*, 702–717. [CrossRef]
21. Allotta, B.; Costanzi, R.; Ridolfi, A.; Salvetti, O.; Reggiannini, M.; Kruusmaa, M.; Salumae, T.; Lane, D.M.; Frost, G.; Tsiogkas, N.; et al. The ARROWS project: Robotic technologies for underwater archaeology. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *364*, 012088. [CrossRef]
22. Hamouda, A.; El-Gharabawy, S.; Fekry, A.; Nassar, M. Exploration and identification of ancient Roman shipwreck located at Quseir, Red Sea. *Egypt. J. Aquat. Res.* **2024**, *50*, 17–22. [CrossRef]
23. Ioannou, G.; Forti, N.; Millefiori, L.M.; Carniel, S.; Renga, A.; Tomasicchio, G.; Binda, S.; Braca, P. Underwater inspection and monitoring: Technologies for autonomous operations. *IEEE Aerosp. Electron. Syst. Mag.* **2024**, *39*, 4–16. [CrossRef]
24. Ababneh, A. Review Future Technologies in Underwater Cultural Heritage. *J. Gen. Union Arab. Archaeol.* **2024**, *9*, 1–19. [CrossRef]
25. Benetatos, C.; Catania, F.; Giglio, G.; Pirri, C.F.; Raeli, A.; Scaltrito, L.; Serazio, C.; Verga, F. Workflow for the Validation of Geomechanical Simulations through Seabed Monitoring for Offshore Underground Activities. *J. Mar. Sci. Eng.* **2023**, *11*, 1387. [CrossRef]
26. Carpignano, A.; Gerboni, R.; Mezza, A.; Pirri, C.; Sacco, A.; Sassone, D.; Suriano, A.; Ugenti, A.C.; Verga, F.; Viberti, D. Italian Offshore Platform and Depleted Reservoir Conversion in the Energy Transition Perspective. *J. Mar. Sci. Eng.* **2023**, *11*, 1544. [CrossRef]
27. *La Nave Romana di Albenga: Studi, Progetti e Ricerche per il Nuovo Museo*; Gandolfi, D., Trigona, S.L., Eds.; Rivista di Studi Liguri: Bordighera-Albenga, Italy, 2022; ISBN 978-88-86796-87-3.
28. Trigona, S.L. Archeologia subacquea in Liguria: Un progetto integrato per la tutela e la valorizzazione. In *Proceedings e Report*; Bonora, L., Carboni, D., De Vincenzi, M., Eds.; Firenze University Press: Florence, Italy, 2020; Volume 126, pp. 137–146. ISBN 978-88-5518-146-4.
29. Trigona, S.L. Archeologia Subacquea in Liguria. L'attività Dello STAS Nel 2014–2015. In *Archeologia Liguria Nuova Serie*; De Ferrari Editore: Genova, Italy, 2018; Volume 6, pp. 2014–2015. ISBN 9788864059631.
30. Trigona, S.L. Archeologia Subacquea in Liguria: L'attività Dello STAS Nel Triennio 2016–2018. In *Archeologia Liguria*; De Ferrari Editore: Genova, Italy, 2021; Volume 7, pp. 11–29, ISBN 9788855034388, ISSN 2499-927X.

31. Martino, G.P. Relitto di Santo Stefano al Mare (IM). *Archaeol. Marittima Mediterr.-Int. J. Underw. Archaeol.* **2007**, *7*, 45–52, ISSN 1724-6091. [CrossRef]
32. Westphalen, N. Roman Warfare, Ships and Medicine. *J. Mil. Veterans Health* **2020**, *28*, 11–22.
33. Gaba, E. Wikimedia Commons User: Sting. Antic Roman Wine Amphora of the Dressel 1B Type, Wikimedia Commons. 2007. Available online: https://commons.wikimedia.org/wiki/File:Amphora_Dressel_1B.svg (accessed on 2 October 2025).
34. Ma, Y.Z. *Quantitative Geosciences: Data Analytics, Geostatistics, Reservoir Characterization and Modeling, Quantitative Geosciences: Data Analytics, Geostatistics, Reservoir Characterization and Modeling*; Springer International Publishing: Berlin/Heidelberg, Germany, 2014. [CrossRef]
35. Matheron, G. Principles of Geostatistics. *Econ. Geol.* **1963**, *58*, 1246–1266. [CrossRef]
36. Stein, M.L. Minimum Norm Quadratic Estimation of Spatial Variograms. *J. Am. Stat. Assoc.* **1987**, *82*, 765–772. [CrossRef]
37. Zakeri, F.; Mariethoz, G. A review of geostatistical simulation models applied to satellite remote sensing: Methods and applications. *Remote Sens. Environ.* **2021**, *259*, 112381. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

Article

Sub-Bottom Profiler in Underwater Archaeology: Comparative Analysis for Non-Intrusive Surveying and Documentation of Underwater Cultural Heritage in Spain

Soledad Estrella Solana Rubio ^{1,*}, Felipe Cerezo Andreo ², Sebastián Federico Ramallo Asensio ³, Francisco López-Castejón ⁴, Darío Bernal-Casasola ², Miguel Ángel Cau Ontiveros ⁵, Rafael Sabio González ⁶ and Emilio Gamo Pazos ⁷

¹ Department of Prehistory and Archaeology, University of Granada, 18011 Granada, Spain

² University of Cádiz; felipe.cerezo@uca.es (F.C.A.); dario.bernal@uca.es (D.B.-C.)

³ University of Murcia; sfr@um.es

⁴ Cartagena Oceanographic Research Institute; francisco@cori.institute

⁵ ICREA and University of Barcelona, ERAAUB-IAUB; macau@ub.edu

⁶ National Museum of Underwater Archaeology (ARQVA); rafael.sabio@cultura.gob.es

⁷ National Archaeological Museum (MAN); emilio.gamo@cultura.gob.es

* Correspondence: ssrubio@ugr.es

Abstract

In this paper, the results of several geophysical surveys developed with a Sub-Bottom Profiler in different regions of Spain are presented. This research forms part of a broader project aimed at developing innovative non-invasive methodologies for documenting Underwater Cultural Heritage (UCH). The 2001 UNESCO Convention on the Protection of the Underwater Heritage recommends the use of non-destructive techniques, in situ conservation, and prioritising exploration over recovery. Geophysical techniques allow the non-invasive documentation of UCH without altering archaeological remains. The Sub-Bottom Profiler was tested in several underwater archaeological surveys under different objectives, depths, and environmental conditions. The research questions addressed the amount of information obtainable without intrusion and the optimal use of the equipment for methodological innovation. Based on the results, methodological conclusions are drawn regarding the influence of seabed composition on acoustic performance, the importance of controlling navigation speed and vessel stability, and the strong impact of sea state on data quality. The need for frequency and motion-correction optimisation to balance resolution and penetration is also highlighted, as well as the usefulness of SBP for anomaly detection, site monitoring, and palaeolandscape reconstruction. These findings contribute to establishing a transferable methodological framework applicable to other case studies.

Keywords: non-invasive techniques; geophysical survey; Sub-bottom profiler; monitoring UCH; new technologies; Spain

1. Introduction

Underwater Cultural Heritage (UCH), as defined in the 2001 UNESCO Convention for the Protection of the Underwater Cultural Heritage, comprises “all traces of human existence having a cultural, historical or archaeological character which have been partially or totally under water, periodically or continuously, for at least 100 years, such as sites, structures, buildings, artefacts, ships or human remains, together with their archaeological and natural context” [1,2] (Art. 1(1)(a)). This definition explicitly includes and recognizes that

the context (including sediment and environment) is an integral part of the scientific value of the site. The Convention also affirms that Underwater Cultural Heritage is a ‘particularly vulnerable’ asset and that its preservation contributes to understanding phenomena such as climate change and sea level rise [2] (Convention summary). A fundamental principle of the Convention is that in situ preservation—meaning the conservation of Underwater Cultural Heritage in its original location and context—must be regarded as the preferred option before any intrusive intervention is authorised [2] (Art. 2(5)). This approach implicitly acknowledges the scientific value of surrounding sediments and environmental context as integral components of conservation. The Annex to the Convention establishes detailed rules requiring that archaeological activities avoid unnecessary disturbance, prioritise non-destructive techniques, and ensure that any intervention does not compromise the long-term preservation of the site. These provisions reinforce the obligation to safeguard sedimentary deposits and maintain the integrity of the archaeological context [2] (Annex—Rules 1, 3 and 4).

Spain has implemented the UNESCO 2001 Convention on the Protection of the Underwater Cultural Heritage through a combination of pre-existing heritage legislation and specific policy instruments aligned with its principles. The core legal framework is provided by the Ley 16/1985 de Patrimonio Histórico Español [3], complemented by extensive regional legislation and, crucially, by the National Plan for the Protection of Underwater Cultural Heritage, which implements the Convention after Spain’s ratification in 2005. The Green Paper was prepared in 2009 to guide Spanish implementation of UNESCO’s Convention management principles [4].

Since ratification, Spain has achieved significant advances, including the institutional consolidation of research and conservation through the Museo Nacional de Arqueología Subacuática (ARQUA), the development of comprehensive inventories, and its leadership in UNESCO’s Register of Best Practices, where it holds the highest number of recognized initiatives. Notable projects conducted in accordance with the Convention’s Annex include the excavation of the Deltebre I wreck (Tarragona) [5,6], the Bou Ferrer Roman shipwreck (Villajoyosa) [7–9], and the study of Cala Cativa I and Cap del Vol (Girona) [5,10,11], as well as the Nuestra Señora de las Mercedes project [12–14]; all of them constitute relevant examples within Spain’s application of the Convention, focusing on balancing the degree of intervention at the heritage site with the value of the historical and archaeological information obtained, public dissemination, and long-term conservation. In addition, the Illes Formigues II project [15] has been formally designated in 2025 by UNESCO as an example of best practice under the framework of the 2001 Convention [16].

Despite the significant progress achieved in Spain in the implementation of the 2001 UNESCO Convention, several structural challenges continue to constrain the effective documentation and management of Underwater Cultural Heritage. One of the main difficulties is the unequal distribution of technical and financial resources among regions, which leads to heterogeneous levels of survey coverage, site monitoring, and research continuity. In addition, the increasing exposure of submerged archaeological sites to natural and anthropogenic pressures—such as coastal development, illegal recoveries, anchoring, and climate change-driven seabed dynamics—poses a persistent threat to the UCH preservation.

At the operational level, underwater archaeological fieldwork in Spain shows that although a common archaeological methodology is followed—prioritising minimal impact approaches—each investigation requires adaptation depending on site-specific conditions, including sediment characteristics, preservation state, and environmental factors. Consequently, while the Convention provides clear overarching principles, its practical application often requires methodological flexibility to address the variability of under-

water contexts. Within this framework, these operational constraints, together with the methodological challenges described above, highlight the need for reliable and adaptable non-destructive survey strategies capable of improving site detection and interpretation.

In response to these limitations, marine geophysical methods gain increasing relevance. Their integration with archaeological fieldwork has become a widely adopted approach for the detection and initial characterization of underwater archaeological sites, enabling their broad classification and preliminary spatial assessment [17,18]. However, progressing from general survey outputs to detailed, site-specific interpretation continues to present methodological limitations, as the resolution and interpretative potential of combined datasets remain uneven across different environmental and archaeological contexts [19,20].

Multibeam echo sounder (MBES) and side-scan sonar (SSS) are widely used geophysical tools for the detection and morphological characterization of seabed features, providing high-resolution acoustic imagery of exposed or partially exposed archaeological remains [17,18]. Photogrammetry has also become an established technique for the generation of high-resolution digital elevation models (DEMs), enabling detailed three-dimensional documentation of visible structures and supporting precise spatial analyses of archaeological features [21]. However, recent comparative studies highlight that its application is strongly constrained by environmental conditions such as water turbidity and light penetration, which limit its effectiveness in non-ideal underwater contexts [22]. Within this set of non-destructive testing (NDT) approaches, these surface-oriented acoustic and optical methods are therefore primarily effective for exposed remains, as their sensing capabilities are limited to the seafloor interface.

However, addressing buried archaeological deposits requires analytical approaches capable of extending beyond surface detection. In this sense, Sub-Bottom Profiler (SBP) extends the analytical capacity of marine geophysical surveys by allowing acoustic penetration into sedimentary layers and the identification of subsurface stratigraphic anomalies [19,20]. It enables the non-contact detection and positioning of buried archaeological deposits beneath the seabed. This subsurface capability enhances the detection potential of surface-based methodologies and provides a more complete understanding of underwater archaeological contexts, improving the interpretative capacity of geophysical survey data. It also represents a complementary tool for enhancing regional survey coverage and supporting more systematic and efficient documentation of archaeological sites, particularly in areas where traditional visual or diver-based methods are constrained, while remaining aligned with non-destructive survey principles.

2. Geographical Setting

In this paper we present the geophysical survey work developed in four different underwater contexts, as part of four research projects, in four regions of Spain (Figure 1): Algeciras (Cádiz), Cartagena (Murcia), Palma de Mallorca (Balearic Islands), and the River Tagus (Guadalajara, Castilla-La Mancha).

2.1. Algeciras (Cádiz): The “Herakles” Project

Located on the northern shore of the Strait of Gibraltar, Algeciras (Figure 1(1)) boasts a wide bay that has served as an anchorage, refuge, water source and trading post at this crossroads of nautical routes since ancient times [23]. This unique geographical setting provides a privileged environment for analysing seafaring in the area, which prompted the “Herakles” project¹, led by the University of Cadiz and developed between 2020 and 2023. The research objectives of the Herakles project aimed to identify nautical activity in Algeciras Bay from a diachronic perspective, as well as to identify anthropogenic and natural threats to the conservation of the UCH and to highlight the significance of some

of the documented archaeological sites [24]. Furthermore, it provided the framework for the development of a non-invasive methodology in line with UNESCO's principles, adaptable to the study of archaeological sites of diverse natures, situated across a range of environmental contexts and shaped by varying research questions, resource constraints, and operational challenges [25].

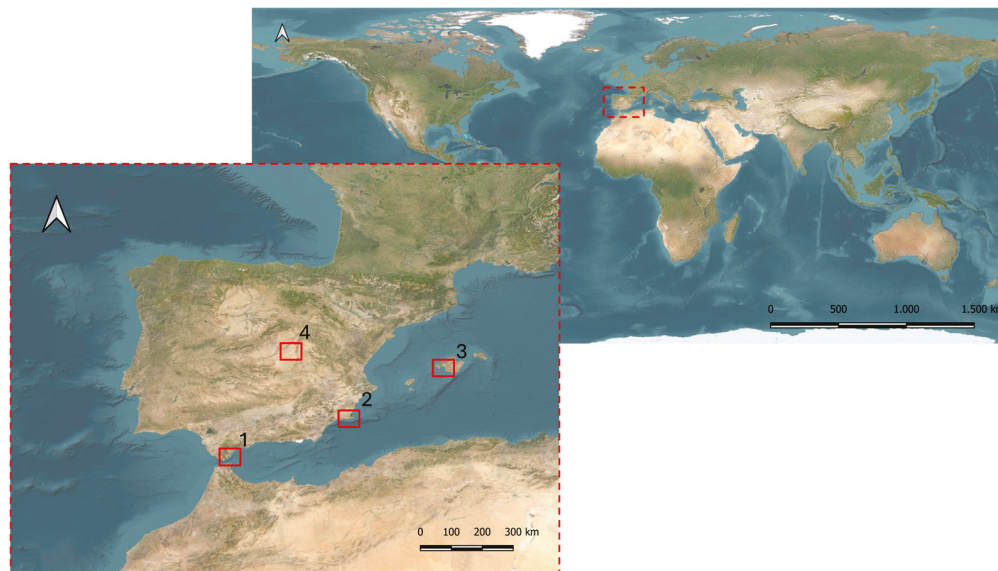


Figure 1. Location of the case studies in Spain. (1) Algeciras (Cádiz); (2) Cartagena (Murcia); (3) Palma de Mallorca (Balearic Islands); (4) River Tagus (Guadalajara, Castilla-La Mancha). Source: Authors' own elaboration.

2.2. Cartagena (Murcia): The “Aladroque” Project

The second case study focused on the harbour area of Cartagena and its surroundings (Figure 1(2)), an area notable for the abundance and diversity of archaeological material recorded over more than three decades [26–33]. The High-Level Isolated Low-Pressure System (known in Spain as DANA) that affected the Region of Murcia in September 2019 caused a series of significant consequences on land. One of the most direct consequences was the rise in water levels in the dry riverbeds, with many of them overflowing and causing large quantities of sediment and rubbish to be washed out to sea. In view of the need to assess the scale of the environmental impact caused by this meteorological event on the marine environment and to evaluate its potential effect on underwater cultural heritage, the ‘Aladroque’ project² was undertaken. To address the research question concerning the impact of the 2019 flood on the submerged natural and cultural heritage of the area, the objectives were to assess the rate of sedimentation associated with such an event and to monitor burial processes resulting from the flooding of riverbeds at known archaeological sites [34].

2.3. Palma de Mallorca (Balearic Islands): The “ARQUEOMALLORNAUTA” Project

The island of Palma de Mallorca, in the Balearic Islands (Figure 1(3)), provided the third setting for this methodological study. The archipelago preserves a rich corpus of underwater archaeological remains associated with its maritime and commercial history, which extends back to antiquity [35,36]. A further example is the Ses Fontanelles shipwreck, discovered in 2019 off the south-west coast of the island in shallow sandy seabed conditions. The “ARQUEOMALLORNAUTA” project³ aimed to document and excavate this Late Roman shipwreck [37,38]. The methodological approach to geophysical surveying as a preliminary activity was adopted in order to gather as much information about the

site as possible before proceeding with the excavation and to identify anomalies in the surrounding area for subsequent archaeological interpretation.

2.4. Driebes (Guadalajara): The “Caraca” Project

Finally, the fourth case study provided an opportunity to implement this methodology within a fluvial context for the first time. Conceived as a pilot project, the survey was undertaken in the waters of the River Tagus in the vicinity of the archaeological site of *Caraca*, located on the Cerro de la Virgen de la Muela (Driebes, Guadalajara) (Figure 1(4)). This terrestrial archaeological site has been under investigation since 2016 through an interdisciplinary research project that has enabled the assessment of its archaeological potential, the identification of its general characteristics, chronology, and phases of occupation, as well as its relationship with the Roman road linking *Complutum* and *Carthago Nova* [39]. However, the relationship between the settlement and the River Tagus, particularly regarding its function as a navigable corridor, defensive frontier, and water resource remains a developing line of enquiry within current research. As part of this research framework, the integration of the National Museum of Underwater Archaeology and the University of Cádiz into the project⁴ for the geophysical survey was aimed at delineating the river’s ancient course, identifying potential crossing points such as fords or bridges, structures associated with its navigational use, evidence of military conflicts, and other movable artefacts linked to human activity along the river [40].

3. Materials and Methods

A Sub-Bottom Profiler is a marine geophysical instrument used to investigate sediments and geological layers beneath the seabed. It emits low-frequency acoustic pulses that penetrate the sea floor, recording reflected signals to produce detailed images of subsurface structures, which can then be analysed archaeologically to determine whether or not they are anomalous [41]. In marine geophysics, a Sub-Bottom Profiler is used to map and analyse sediment layers and buried geological features beneath the seabed. It supports maritime construction planning, cable and pipeline routing, environmental assessments and archaeological research by providing high-resolution images of structures buried beneath the sediment, as well as those on the seabed [42].

The resources available to conduct this work include a Sub-Bottom Profiler (SBP) model SES-2000 standard, manufactured by INNOMAR Technologie⁵. Its parametric nature allows a high resolution in the detection of strata and sediment layers, and the signal penetrates, on average, to a depth twice the distance between the sensor and the seabed. The equipment also includes an SMC IMU-108 Motion Reference Unit (MRU)⁶ to correct and refine the spatial location of the signal and a Leica GS18 GNSS Mobile RTK GNSS Antenna, which ensures positioning of data readings with a millimeter error margin⁷ (Figure 2).

The Sub-Bottom Profiler is particularly well-suited to meeting UNESCO’s standards for Underwater Cultural Heritage management because it enables detailed, non-invasive mapping of buried archaeological deposits. By revealing sedimentary layers and subsurface structures without physically disturbing them, it allows researchers to assess site stratigraphy, monitor stability, and plan interventions responsibly. This capacity for precise, in situ evaluation supports informed decision-making, ensures the integrity of fragile contexts, and aligns with the principle of minimising intervention while maximising knowledge acquisition [17–20].

Accurate transect planning (Figure 3) is essential for reliable data interpretation, requiring the definition of survey grids and the density of the recording. This planning

takes place prior to the survey, taking into account the research-specific objectives, the nature of the archaeological site, environmental conditions and available resources.

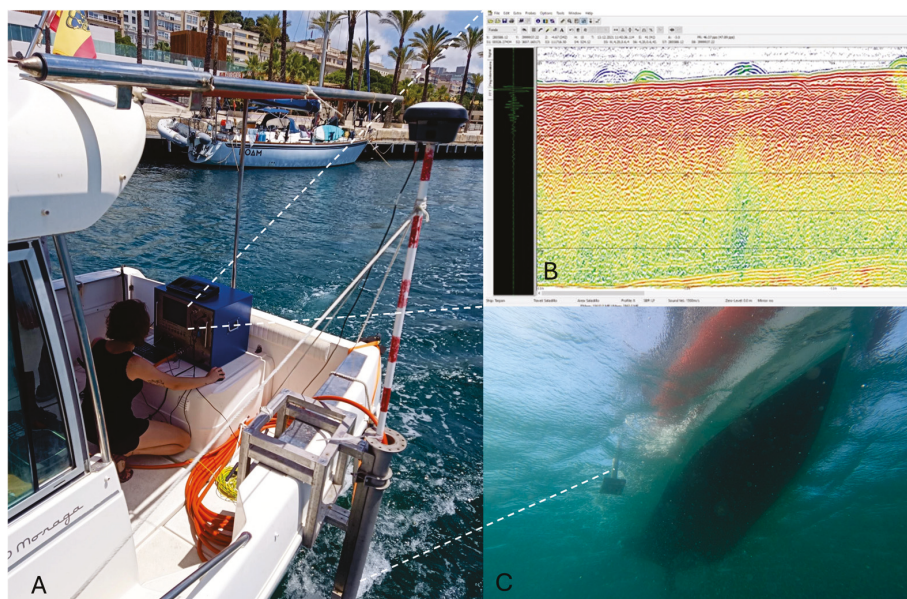


Figure 2. Equipment used on board the vessel for fieldwork. (A) Vessel-mounted acoustic profiling system, including transceiver, GNSS receiver, and data acquisition unit; (B) Example of returned acoustic signal displayed in real time; (C) Submerged transducer emitting acoustic pulses towards the seabed. Source: Authors' own elaboration.

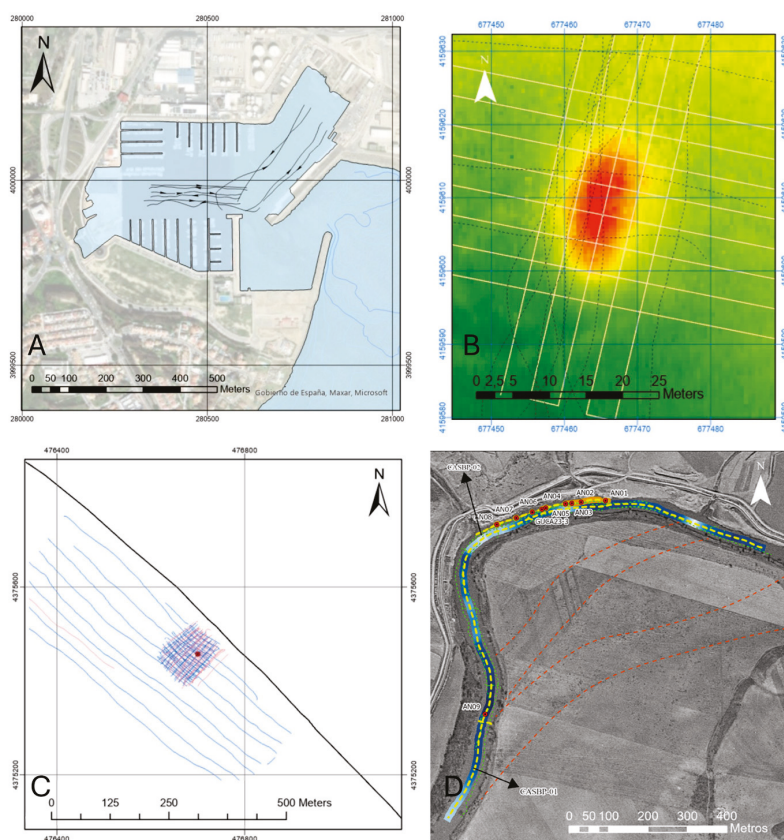


Figure 3. Examples of transects surveyed in each case study. (A) "El Saladillo" harbour area; (B) Anomaly at the Cartagena 1 shipwreck; (C) The Ses Fonanelles shipwreck and its surrounding area; (D) The Tagus meander facing the ancient city of Caraca. Source: 3A–C Authors' own elaboration; 3D from [40].

Taken together, the technical characteristics of the SBP system and the operational parameters outlined above define the methodological framework within which its application must be understood. Beyond its instrumental configuration, the effectiveness of SBP is contingent upon survey design, environmental conditions, and the specific research questions guiding data acquisition. The discussion now moves from this technical basis to its implementation across the selected case studies, where its performance, adaptability, and interpretative potential are assessed in relation to distinct archaeological and geomorphological contexts.

Sub-Bottom profiler techniques were applied within framework of the ‘Herakles’ Project, with the survey focusing on a sector of the harbour area known as ‘El Saladillo’ (Figure 3A). Intensive port development and dredging works have significantly altered this area over time [43], presenting a particular challenge, as the surface layers of the seabed yielded no archaeological information. The constraints inherent in the surface-oriented acoustic and optical techniques discussed in the previous section rendered them of little applicability, given that any archaeological remains, if present, would most likely be located beneath the seabed. In this context, the Sub-Bottom profiler emerged as the most suitable technique for addressing the central research question, namely whether undisturbed deposits survived at greater depths and what forms of archaeological evidence might be identified within them. In this regard, the main objective was to examine the general stratigraphic sequence of the area in order to assess the extent to which anthropogenic interventions have influenced natural sedimentation processes and the preservation of underwater cultural heritage (UCH). As noted previously, the Herakles project provided the initial framework for the development of the methodology. Given that ‘El Saladillo’ constitutes a port setting characterised by relatively stable environmental conditions, an additional line of enquiry concerned the extent to which SBP could reliably fulfil the project’s research objectives.

A two-day survey was conducted across the central sector of ‘El Saladillo’ (Figure 3A), comprising approximately ten transects of roughly 200 m each, oriented along an east–west axis and its reciprocal direction. While vessel vibrations occasionally complicated data acquisition, the muddy seabed allowed signal penetration exceeding 10 m, revealing detailed identification of stratigraphic layers, paleolandscape features, and ancient harbour deposits. As the results proved satisfactory and yielded relatively clear acoustic returns, the survey was subsequently extended to include several transects exceeding 300 m in length, oriented along a north-east to south-west alignment and its reverse.

Following this successful survey with SBP in Algeciras, it was agreed to use it in Cartagena, where the main objective of the “Aladroque” project was to assess the DANA-type climate event of 2019 impact on the UCH. From a methodological perspective, SBP was selected on the basis that its acoustic signal penetrates below the sediment–water interface, thereby offering greater analytical potential than alternative techniques restricted to the detection of seabed surface features [17,18]. In addition, the team had access to the results of a geophysical survey carried out by the Aurora Trust and the National Museum of Underwater Archaeology in 2007 and 2008, involving multibeam echo sounder (MBES), side-scan sonar (SSS) and Sub-Bottom Profiler (SBP) [27]. The results of the first two methods were used to identify sites of archaeological interest where the assessment was to be performed. Comparing the stratigraphic profiles obtained using SBP in 2007 with those recorded by the ‘Aladroque’ project offered a unique opportunity to assess the rate of sedimentation following the DANA.

The two-week survey covered several areas of the port of Cartagena, including the mouth of the Benipila Rambla and Algameca Chica down to a depth of around –50 m, characterised by a detrital and rocky seabed rich in archaeological material. To evaluate

burial and exposure processes affecting underwater cultural heritage (UCH), several archaeological sites were selected as pilot cases; however, only one is included in this study, as it proved most suitable for the purposes of methodological comparison. The Cartagena I shipwreck was documented in 2008 at a depth of 63 m near the entrance to the port of Cartagena. Using previous side-scan sonar (SSS) and multibeam echosounder (MBES) imagery, the 'Aladroque' team was able to determine its orientation and approximate dimensions (16×7 m). This information was highly valuable for the accurate planning of the transect over the shipwreck anomaly (Figure 3B). Five transects, each approximately 20 m in length, were surveyed along the shipwreck's presumed longitudinal axis, oriented at an angle of approximately 60° and its reciprocal bearing of 240° . Eight transects were then surveyed perpendicular to the first set, following bearings of 150° and 330° .

The effectiveness of SBP in documenting burial mound-type archaeological sites, as demonstrated in Cartagena, led to its application in the survey of the Ses Fontanelles shipwreck. The objectives were to obtain stratigraphic images of the tumulus that formed the shipwreck in order to visualise its structure and characterise its sedimentary layers. The surrounding area was surveyed to gain a better understanding of the stratigraphy and sediment dynamics of the zone and to identify the location of any anomalies potentially associated with the archaeological site.

Given that the mound was located at shallow depth and in close proximity to the coast, it was readily accessible through a diver-based methodological approach. Moreover, as it was buried, surface documentation using alternative techniques such as multibeam echosounder or photogrammetry was of limited relevance. As the primary objective was to understand the internal stratigraphy of the tumulus, SBP constituted the most appropriate analytical tool.

The survey was conducted over a one-week period in two phases: initially, data acquisition focused on the shipwreck itself, followed by coverage of the surrounding area (Figure 3C). A total of 57 transects were acquired over the wreck site, of which 33 were oriented parallel to the coastline and 24 perpendicular to it. In the adjacent area, 10 transects of approximately 550 m in length were undertaken, all aligned parallel to the coastline. The seabed, predominantly sandy with a substantial muddy component, allowed signal penetration to several metres, reaching -5.5 m in some profiles.

Once the reliability of the SBP had been established for surveys in both harbour and shipwreck archaeological maritime contexts, it was resolved to test the methodology in a riverine environment, as part of the Caraca project archaeological activity. Preliminary documentation undertaken prior to the geophysical survey yielded evidence that the River Tagus, in its course through the Caraca area, had undergone anthropogenic modification, notably through the construction of the Estremera Canal. This appeared to present a situation comparable to that of 'El Saladillo', insofar as such human-induced alteration suggested the absence of archaeological material within the upper sedimentary layers, at least in primary depositional context. This consideration led to the selection of SBP over alternative geophysical methods oriented towards the detection of anomalies on the riverbed surface.

The aim of the geophysical study was to assess the applicability of subsurface profiling techniques in riverine environments, where hydrodynamic processes and sediment composition differ significantly from those observed in coastal and marine environments. Furthermore, the purpose was to determine the presence of a palaeochannel and to identify early river fording points (ancient crossing points) or submerged structures associated with the river's navigational use in antiquity.

A total of eleven longitudinal transects following the river channel and fourteen transverse profiles were acquired (Figure 3D), covering an overall distance of 4806 km

and ensuring full coverage of the meander. Particular attention was paid to the area adjacent to the ancient settlement, as well as to several structures identified during previous diving surveys undertaken by the project's underwater archaeologists. The riverbed was predominantly composed of silts and muds, which provided favourable acoustic penetration conditions. However, dense riparian vegetation along both margins locally affected signal quality. The average water depth was approximately 7 m, and optimal results in terms of penetration and resolution were obtained using a frequency range of 12–15 kHz, at a mean navigation speed of 2–3 knots [40].

In all cases, the decision was taken to utilise equipment with a single pulse per frequency, thereby mitigating noise in the signal caused by airborne particles and wave motion in the case of marine environments, or by currents in the case of the river environment. It is also noteworthy that a range of solutions were formulated in response to the circumstances and resources available to each vessel (Figure 2A–C), with the aim of mitigating the impact of engine vibrations on the Sub-Bottom profiler's acoustic signal (Figure 2B). Without going into detail—as this is a matter that depends on each individual case—it should be noted that, to reduce noise in the acoustic signal, it is important to position the transducer as far away as possible from the boat's engine, in conjunction with the dynamics of waves and current, must be taken into account.

4. Results: The Development of a Method

Across the four case studies, this research has explored the capabilities and constraints of the Sub-Bottom profiler for surveying and documenting the UCH. All the data collected was processed using the SES2000 software, the operating license for which was purchased from INNOMAR and is owned by the Laboratory of Archaeology and Prehistory at the University of Cádiz. The processing time is relatively short, especially when compared to other methods such as multibeam echosounder, although it depends on the quality of the data collected. In other words, if data are collected with the highest possible precision—through appropriate adjustment of parameters according to depth, the boat's speed and the desired level of detail—the resulting acoustic signals are of superior quality, thereby reducing post-processing time. Line length and acquisition duration are also determining factors, as is the overall strategy employed for the organisation and management of the recorded data.

Multiple types of anomalies were detected in each survey and subsequently verified using complementary approaches, including historical records, magnetic data, test excavations, and visual inspections. This process has enabled the development of a consolidated catalogue of anomalies for use in future SBP applications. Analysis of the results obtained in each of the SBP surveys enables the anomalies detected to be classified and some general observations to be made about the use of the equipment, which will be useful for future research in similar environments.

Within the El Saladillo research area, our survey has successfully delineated a paleochannel originating from the Last Glacial Maximum (see Figure 4A). This previously undocumented geomorphological feature appears to have resisted sediment infill over extended periods, thereby preserving its depth and likely explaining its persistent function as a maritime anchorage throughout history. The geophysical surveys further allowed the identification of the basal layers of Isla Verde, currently swallowed up by the modern harbour, but which was once one of the main landmarks on the maritime landscape in the ancient Algeciras Bay. Among the notable breakthroughs, our analyses revealed multiple anchoring zones characterised by muddy sediments, alongside numerous reefs and hazardous rocky outcrops situated proximal to the paleosurface. By integrating stratigraphic data derived from our SBP surveys with eighteenth-century bathymetric information ob-

tained from historical cartography, it was possible to discriminate between sectors where harbour sediments had been removed by anthropogenic or natural processes and those that have remained largely preserved. This approach has significantly facilitated the acquisition of novel insights into historical nautical practices, providing a robust framework for future underwater archaeological research in the Algeciras Bay [23,24].

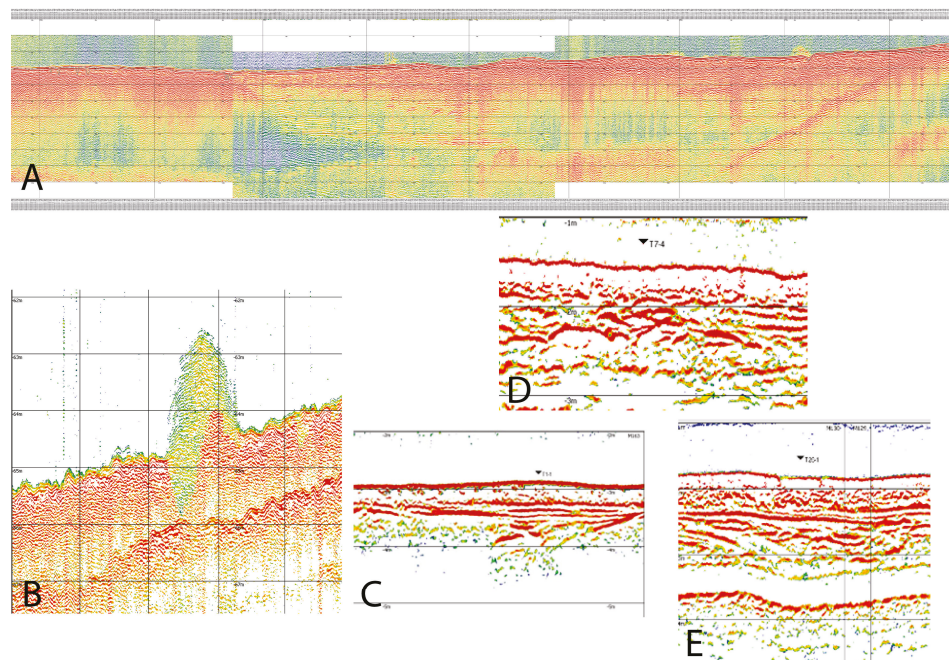


Figure 4. Examples of types of anomalies recorded. (A) Paleochannel with continental sedimentation; (B) Shipwreck; (C) Pipeline; (D) Buried object (in this case an amphora); (E) Natural anomaly corresponding to the bottom of a paleochannel. Source: Authors' own elaboration.

In the port of Cartagena, application of Sub-Bottom profiler techniques has generated stratigraphic profiles with remarkable resolution, which have made it possible to document in detail the effects of the 2019 DANA flood on Underwater Cultural Heritage. This dataset provides a crucial foundation for improving both monitoring and conservation strategies. By observing the differences between the results of different surveys the “Aladroque” team detected new anomalies and enabled assessment of burial or exposure changes, as well as sediment redistribution caused by flooding, including displacement of large objects and debris. Located anomalies were subsequently documented either through diver-led research, in the case of those located at accessible depths, or by means of a Remotely Operated Vehicle (ROV) for those situated in deeper waters, with their archaeological potential evaluated and a monitoring protocol established.

A particular focus has been the evaluation of burial and erosion dynamics at several archaeological sites, especially the Cartagena 1 shipwreck, located at -63 m depth and recognised as one of the best-preserved 2nd-century BC shipwrecks in the Iberian Mediterranean. Through comparison of the 2008, 2021, and 2022 survey data, it was confirmed that the tumulus has been partially exposed, with between 70 and 80 cm of material now unearthed. The cargo has become dispersed over an area roughly double its size in 2008, indicating progressive destabilisation of the site (see Figure 4B). At the same time, other areas have undergone significant sediment deposition, which has obscured archaeological elements identified in the 2008 surveys. While this burial process can contribute positively to preservation, it simultaneously restricts direct access to the material, complicating study and documentation. Complementary diving inspections of selected anomalies revealed the presence of anthropogenic debris that is compromising the structural integrity of certain

artefacts. Large-format plastics—including segments of drip irrigation hoses, nylon ropes, and crop-covering plastics—have proved particularly damaging. These materials adhere to exposed heritage objects, resisting water currents and thereby exerting mechanical stress that fractures artefacts and disperses fragments across the seabed.

The outcomes of the “ARQUEOMALLORNAUTA” Project survey successfully provided detailed stratigraphic visualisation of the Ses Fontanelles shipwreck and its surrounding area. Among the anomalies deemed significant, those presenting particular archaeological or stratigraphic relevance were selected for further consideration. These were subsequently categorised into three levels of intervention priority, based on accessibility, size, morphology, and depth beneath the seabed.

Following a second round of signal processing and comparative anomaly analysis, three features were associated with paleochannels, one corresponded to the Ses Fontanelles shipwreck, five offered critical stratigraphic information, and six were interpreted as a pipeline (see Figure 4C). To verify these interpretations, eight archaeological test pits were excavated, though only one yielded archaeological material—a fragment of a pre-Roman amphora produced in the island of Ibiza—located beneath a layer of shells and coarse gravel and overlain by dead seagrass. Hyperbolic reflections observed in the acoustic data coincided with the burial locations of this material (see Figure 4D).

Anomalies of natural origin were identified as a layer of rubble, coarse gravel, and pebble deposits, interpreted as the seabed of a paleochannel with evidence of continental sedimentation phases (see Figure 4E), offering valuable insights into the pre-Holocene palaeolandscape.

Regarding the anomaly corresponding to the Ses Fontanelles shipwreck, documented across 53 stratigraphic profiles, it was made possible to characterise the distinct layers composing the protective tumulus, the cargo and the construction elements.

From the survey of the River Tagus, the identification of several possible submerged structures is particularly noteworthy. The first group appears to comprise a series of walls located on the right bank of the river, downstream from the Roman site of Caraca, and aligned at a slight angle to the direction of the current. Among the stone blocks forming these walls, a fragment of a Roman roof tile bearing finger-impressed decoration was recovered. Visual and geophysical surveys identified a total of eight rocky outcrops in front of the ancient city, spaced at irregular intervals, most of which face 25° North.

In addition, it has been possible to document the stratigraphy of the area, as well as the banks of the river’s palaeochannels. These data contribute to a better understanding of the river’s evolution, particularly within a context of meanders and former fording points, which is now significantly altered by the construction of the Estremera Canal and the dams, which have created a calmer and deeper river than would have existed in earlier periods.

Finally, the location of former river fording points was confirmed in three areas, one of which appears to run directly in front of the ancient city itself. This finding is of considerable interest, as it lies directly opposite the *Complutum–Carthago Nova* road, and may help to explain why the road was routed from the city towards the river [39,40].

5. Discussion and Conclusions

The evidence gathered from the four case studies substantiates the methodological reliability of the Sub-Bottom profiler in Underwater Cultural Heritage surveys.

Its application has enabled the acquisition of high-resolution stratigraphic datasets, refined seabed morphological characterisation, and systematic detection of subsurface anomalies. Collectively, these outcomes underscore the effectiveness of SBP technology in supporting accurate, non-invasive assessment of submerged archaeological contexts.

Methodological differences among the four SBP surveys are primarily related to acquisition strategy, data comparability, and validation procedures. In Algeciras, the methodology was oriented towards broad-area coverage and interpretative correlation, relying on single-phase acquisition and subsequent integration with external datasets. In Cartagena, the approach was inherently longitudinal, based on strictly comparable survey configurations across different campaigns to enable diachronic analysis. The Balearic survey introduced a more iterative workflow, combining acoustic acquisition with successive processing stages and selective ground-truthing to test the reliability of anomaly detection. In contrast, the Tagus River required methodological adjustment at the acquisition stage itself, with survey parameters adapted to shallow, low-energy fluvial conditions and complemented by direct observational inputs. Collectively, these differences illustrate how SBP methodology shifts between extensive mapping, temporal monitoring, iterative validation, and environment-driven adaptation depending on survey constraints and objectives.

Based on the results of these four surveys, SBP can be regarded as particularly effective in contexts where the upper sedimentary layers have been disturbed, such that visual inspection or surface-oriented acoustic techniques produce limited or negative results. It is likewise particularly suited to investigations of submerged palaeolandscapes, where the research questions are oriented towards the reconstruction of stratigraphic sequences and sedimentary dynamics within a diachronic framework.

With regard to its application in shipwreck contexts, this study has applied the method to two case studies characterised by differences in size, depth, and sedimentary dynamics. The development of a method applicable to other shipwrecks with similar conditions of preservation has been facilitated by the aforementioned findings. The proposed method is intended to distinguish their cargo, constructive structure, ballast, scattered parts or other surrounding objects, without altering the UCH in any way. In addition, identifying the dimensions of the shipwreck, its sediment cover, and the dispersion of archaeological materials can provide valuable information for planning the excavation and understanding site formation processes.

Experience on the River Tagus indicates that fluvial environments impose constraints that differ substantially from those encountered in coastal and open marine settings; consequently, methodological adjustments were required with respect to data acquisition parameters, signal penetration, and criteria for data interpretation. Compared to the marine surveys, where more stable conditions allowed for consistent signal propagation and clearer stratigraphic definition, the riverine application demanded greater caution in profile interpretation due to increased heterogeneity in sediment composition and the presence of weaker or less continuous acoustic interfaces. Furthermore, reduced water depth and variable flow conditions influenced both survey design and data quality, limiting the continuity of acoustic reflectors. In areas where survey density was increased through closely spaced transects, vessel speed had to be reduced, thereby increasing exposure to wave action, currents, and drift, which in turn affected data quality and signal stability. Similar constraints were observed in zones with restricted navigation, particularly along near-bank sections of the Tagus River and areas with dense aquatic vegetation, where manoeuvrability limitations further impacted survey consistency.

Although this analysis has focused on surveys in which SBP was used in isolation, this does not imply that it should not be complemented by other documentation techniques. On the contrary, the integration of SBP surveys with additional tools such as side-scan sonar or multibeam echosounder is likely to enhance the interpretative value of the results. As noted above, in this study SBP was employed as a standalone method in order to address questions related to buried sediments and to achieve highly specific research objectives

embedded within broader investigative frameworks, for which complementary techniques were also applied.

By way of conclusion, several general observations (Table 1) may be outlined regarding its application in UCH surveys. Nevertheless, it must be emphasised that the site-specific geomorphological context, the technical configuration of the equipment, and the particular aims of each research project ultimately shape both methodological choices and the interpretative scope of the results.

Table 1. Best practice recommendations for sub-bottom profiling in underwater archaeology. Source: Authors' own elaboration.

Category	Aspect	Considerations	Recommendations
Environmental conditions	Seabed composition	Substrate affects signal penetration and noise levels	Higher penetration into fine-grained sediments
	Water conditions	Wave action reduces the reliability of the data and increases noise	Avoid acquisition under rough water conditions (waves > 0.3–0.4 m).
Survey operations	Navigation speed	Lower speed improves clarity but increases survey time and disturbance (waves, vibration, drift).	Maintain low speeds (2–2.5 knots; max ~4 knots).
	Signal penetration	Penetration may reach up to twice the water column under theoretical conditions.	Adjust acquisition parameters to water depth (optimal ~10–20 m).
Technical setup	Vessel configuration	Instability and vibration degrade signal quality	Use a stable and manoeuvrable vessel and minimise engine vibration.
	Motion correction	Vessel motion may generate spurious hyperbolic reflections	Incorporate a motion correction sensor
	Frequency settings	Resolution and penetration are inversely related	Calibrate frequency to site conditions and survey objectives
Research applications	Archaeological and environmental use	Buried anomaly detection, site monitoring, palaeolandscapes reconstruction, sediment dynamics and anthropogenic impact assessment	Complement with geotechnical coring and seabed mapping methods (e.g., multibeam bathymetry).

Seabed conditions

Acoustic performance is strongly influenced by substrate composition. Muddy environments allow deeper and cleaner signal penetration, whereas sandy seabeds tend to produce greater acoustic noise. Consolidated rocky bottoms generally inhibit penetration, except in cases of loosely compacted sandy rock formations.

Survey platform requirements

The vessel should be compact enough to ensure manoeuvrability while maintaining sufficient stability. A rigid gunwale, positioned as vertically as possible relative to the water surface, is recommended. Particular attention must be given to preventing engine-induced vibrations from being transmitted to the SBP system, as this directly affects data quality.

Navigation speed

Operational speeds should remain below 4 knots, with optimal results consistently obtained between 2 and 2.5 knots. Although reduced speeds enhance signal clarity, they

increase survey duration and exposure to environmental disturbances, including wave action, vessel vibration, and reduced capacity for course correction.

Sea state limitations

Data accuracy is highly dependent on environmental conditions. Wave heights exceeding 30–40 cm have been observed to significantly compromise signal reliability. Surveys undertaken in such conditions risk producing distorted or unusable datasets and should therefore be avoided.

Signal penetration parameters

Under theoretical conditions, penetration depth may reach approximately twice the water column beneath the transducer. At greater depths, pulse frequency must be increased to account for longer return times. Empirically, the most reliable results have been achieved within a depth range of 10–20 m.

Frequency optimisation

Frequency adjustment involves a trade-off between resolution and penetration. Higher frequencies provide enhanced detail but reduced depth reach, while lower frequencies increase penetration at the expense of resolution. Optimal configuration requires case-specific calibration through systematic testing.

Motion correction

The integration of a motion sensor substantially improves interpretative reliability. Without correction, vessel movement can generate acoustic artefacts in the form of hyperbolic reflections that may be erroneously interpreted as archaeological anomalies.

Research applications

SBP methodology is particularly effective for anomaly detection and long-term monitoring of known sites. It enables diachronic comparison of datasets to assess sedimentation dynamics, supports palaeolandscape reconstruction, and assists in evaluating anthropogenic impacts such as dredging. For comprehensive stratigraphic analysis, however, SBP data should be complemented by geotechnical coring [44].

6. Future Research Directions

Future research applying SBP technology in environmental and archaeological contexts distinct from those examined in this study will be essential for validation, refining and expanding the conclusions presented here. Surveys conducted under different geomorphological, sedimentological, or operational conditions may identify alternative technical configurations better suited to scenarios beyond our empirical experience. Furthermore, the integrated use of SBP alongside complementary geophysical instruments—such as multibeam echosounders, magnetometers, or side-scan sonar—has considerable potential to clarify the specific conditions and research objectives under which SBP deployment proves most effective. Such multidisciplinary approaches will contribute to a more nuanced and context-sensitive methodological framework for UCH research.

Notwithstanding, the findings presented herein constitute a substantive contribution to the methodological development of SBP applications in UCH surveying. The analytical framework and technical considerations outlined provide an empirically grounded foundation upon which subsequent investigations may expand. Rather than representing a definitive model, this study establishes a structured point of departure for further refinement, comparative testing, and interdisciplinary advancement within the field. The consolidation of a structured SBP-based methodology has the potential to advance knowledge of UCH while enhancing the international visibility and scientific impact of this research field.

Author Contributions: Conceptualization, S.E.S.R.; methodology, S.E.S.R. and F.C.A.; software, F.C.A. and S.E.S.R.; validation, F.C.A. and S.E.S.R.; formal analysis, S.E.S.R. and F.C.A.; investigation, S.E.S.R. and F.C.A.; resources, F.C.A.; data curation, S.E.S.R. and F.C.A.; writing—original draft preparation, S.E.S.R.; writing—review and editing, S.E.S.R.; visualization, S.E.S.R. and F.C.A.; supervision, F.C.A.; project administration, F.C.A., S.F.R.A., F.L.-C., D.B.-C., M.Á.C.O., R.S.G. and E.G.P.; funding acquisition, F.C.A., S.F.R.A., F.L.-C., D.B.-C., M.Á.C.O., R.S.G. and E.G.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by: The project that gave rise to these results received the support of a fellowship from the “la Caixa” Foundation (ID 100010434). The fellowship code is LCF/BQ/DR23/ 12000015. The work in the Bay of Algeciras has been co-financed by the 2014–2020 ERDF Operational Programme and by the Department of Economy, Knowledge, Business and University of the Regional Government of Andalusia. Project reference: FEDER-UCA18-107327. The Cartagena case study has been co-financed by CORI and the ARQUEOTOPOS III Project, Grant HAR2017-85726-C2-1-P (Carthago Nova desde su entorno litoral: Paleotopografía y evolución medioambiental del Sector central del Sureste Ibérico. Dinámica poblacional y productiva) funded by MCIN. The case of Ses Fontanelles is part of the activities of the research group ERAAUB of the Institute of Archaeology of the University of Barcelona (IAUB), Consolidated Group (2021 SGR 00696), thanks to the support of the Comissionat per a Universitats i Recerca del DIUE de la Generalitat de Catalunya. Some of the activities have been possible thanks to the synergies created with the projects “Arqueología y Arqueometría aplicadas al estudio de la cerámica y el poblamiento de la ciudad romana de Pollentia y su hinterland (Mallorca, islas Baleares)” (ARQCERPOL) (PID2021-123223NB-I00) (ARQCERPOL) (PID2021-123223NB-I00), funded by MCIN/AEI/ 10.13039/501100011033 and by “ERDF A way of making Europe”, GARVM IV (PID2022- 138814OB-I00/MCIN/AEI), Gobierno de España/FEDER; MEDUSA (PCM_00031), Plan Complementario de Ciencias Marinas de la Junta de Andalucía; BARBATECET and CRiPTHA, of the Programa Programa Operativo FEDER Andalucía 2021-2027, Consejería de Universidad, Investigación e Innovación de la Junta de Andalucía. The financial provision for the Tagus survey and the archaeological work in Caraca was facilitated by an agreement approved between Ayuntamiento de Driebes and the Excma. Diputación Provincial de Guadalajara. With the support of Ayuntamiento de Brea de Tajo and the Asociación de Amigos del Museo de Guadalajara.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: Thanks to the four projects, the four universities, the two museums and the LABAP-UCA, which provided us with the equipment. To the owners and captains of the boats. To all the researchers who seek knowledge underwater.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

UCH	Underwater Cultural Heritage
UNESCO	United Nations Educational, Scientific and Cultural Organization
MBES	Multibeam echo sounder
SSS	Side-scan sonar
DEM	Digital elevation model
NDT	Non-destructive testing
SBP	Sub-Bottom Profiler
DANA	Depresión Aislada en Niveles Altos/High-Level Isolated Low-Pressure System
ERDF	European Regional Development Fund
MRU	Motion Reference Unit
GNSS	Global Navigation Satellite System

RTK	Real-Time Kinematic
ROV	Remotely Operated Vehicle

Notes

- ¹ “Entre las Columnas de Hércules, Arqueología Subacuática de un espacio privilegiado. La bahía de Algeciras” (HERAKLES). This work has been co-funded by the 2014–2020 ERDF Operational Programme and by the Department of Economy, Knowledge, Business and Universities of the Regional Government of Andalusia. Project reference: FEDER-UCA18-107327.
- ² “Aladroque: The impact of DANA-type weather events on the conservation of the underwater environments around the approaches to the port of Cartagena (Spain)” an initiative of the Cartagena Oceanographic Research Institute (CORI), in collaboration with the University of Murcia (UM), the University of Cadiz (UCA) and the Navy Diving Centre (CBA).
- ³ Joint project of the Consell de Mallorca and the universities of Barcelona, the Balearic Islands and Cádiz.
- ⁴ Excavation project of the late antique necropolis at Caraca and the Carpetan layers in the same area, as well as a survey of a sector to the east of Cerro de la Virgen de la Muela (Driebes, Guadalajara). Project authorised by Confederación Hidrográfica del Tajo, Ministerio de Cultura y Deporte and Dirección General de Patrimonio Cultural y Bellas Artes (JCCM File No.: 23.1889-P1 and AA-008-2023).
- ⁵ Innomar Technologie GmbH, Schutower Ringstraße 4, 18069 Rostock, Germany.
- ⁶ SMC Ship Motion Control Ltd., 203 Rue D’Argens, Area 2A, GZR1368 Gzira, Malta.
- ⁷ All this equipment is owned by the Laboratory of Archaeology and Prehistory at the University of Cádiz (Spain).

References

1. Maarleveld, T.; Guérin, U.; Egger, B. *Manual para Actividades Dirigidas al Patrimonio Cultural Subacuático: Directrices para el Anexo de la Convención de la UNESCO de 2001*; UNESCO: Paris, France, 2013. Available online: <https://unesdoc.unesco.org/ark:/48223/pf0000220716> (accessed on 12 March 2026).
2. UNESCO. Convention on the Protection of the Underwater Cultural Heritage (Adopted 2 November 2001, Paris). UNESCO. Official Text of the Convention. 2001. Available online: <https://unesdoc.unesco.org/ark:/48223/pf0000126065> (accessed on 12 March 2026).
3. Ley 16/1985, de 25 de Junio, del Patrimonio Histórico Español. Boletín Oficial del Estado, 29 de Junio 1985, Núm. 155, pp. 20343–20352. Available online: <https://www.boe.es/eli/es/1/1985/06/25/16/con> (accessed on 12 March 2026).
4. Working Group of the Technical Coordination Committee of the Historical Heritage Council. *Green Paper: National Plan for the Protection of the Spanish Underwater Cultural Heritage (Bilingual Edition in Spanish and English)*; Ministerio de Cultura: Madrid, Spain, 2010. Available online: <https://www.cultura.gob.es/dam/jcr:c7d03625-58ee-499f-90d8-efccd6733947/libro-verde-plan-nacional-de-proteccion-del-patri.pdf> (accessed on 12 March 2026).
5. Mayoral Peñalva, J. Comparativa Entre el Modelo Tradicional de Documentación Arqueológica y la Fotogrametría Subacuática: Pecios Deltebre I y Cala Cativa I. 2017. Available online: <http://hdl.handle.net/10498/21967> (accessed on 12 March 2026).
6. Geli, R.; Ciarlo, N. On Defining the Identity of Vessels: An In-terim Report and Critical Approach to the Deltebre I (1813) Site, Spain. *Int. J. Hist. Archaeol.* **2024**, *28*, 667–697. [CrossRef]
7. De Juan, C.; Cibecchini, F. Initial construction evidence of the Bou Ferrer shipwreck. *Archaeonautica* **2021**, *21*, 153–159. [CrossRef]
8. Moya, J.A.; Muñoz, F.J. Underwater photogrammetry of the Bou Ferrer archaeological site. *Sci. J. Appl. Soc. Clin. Sci.* **2022**, *2*, 1–9. [CrossRef]
9. De Juan, C.; Gibecchini, F.; Espinosa i Moya, J.A. (Eds.) El Derelict Bou Ferrer (la Vila Joiosa, Comunitat Valenciana, Espanya). Investigació, Conservació i Divulgació d’un Jaciment Subaquàtic Excepcional (2012–2019). *Revista PH*, 109, pp. 208–209. 2023. Available online: <https://hdl.handle.net/11532/395358> (accessed on 12 March 2026).
10. Nieto, F.J. El pecio del Cap del Vol. Nuevas aportaciones. *Cypsela Rev. Prehist. Protohist.* **1982**, *4*, 165–168.
11. Raurich, X. El jaciment de Cala Cativa: Notes sobre el primer treball d’arqueologia subaquàtica realitzat a Catalunya. *Ann. Inst. Estud. Empord.* **1994**, *27*, 261–271.
12. Negueruela, I.; Recio, P.; Castillo, R.; Sierra, J.L. *Nuestra Señora de las Mercedes: Recuperación, Estudio y Puesta en Valor de un Yacimiento Subacuático*; Ministerio de Cultura: Madrid, Spain, 2024. Available online: https://libreria.cultura.gob.es/libro/nuestra-senora-de-las-mercedes_11893/ (accessed on 12 March 2026).
13. Mateo, S.P. Documentar el patrimonio arqueológico en un museo: El caso de la fragata Nuestra Señora de las Mercedes en el Museo Nacional de Arqueología Subacuática ARQVA. *Rev. Gen. Inf. Doc.* **2024**, *34*, 251–266. [CrossRef]
14. Ministerio de Cultura. Proyecto Nuestra Señora de las Mercedes. 2024. Available online: <https://www.cultura.gob.es/mnarqua/en/investigacion/proyectos/nsm.html> (accessed on 12 March 2026).
15. Núñez, S.B.; Galí, G.M.; Mayoral, J.; Mauri, R.G. Salvando las distancias: La excavación del pecio profundo Illes Formigues II (Palamós–Palafrugell, Girona). *PH Boletín Inst. Andal. Patrim. Histórico* **2025**, *115*, 266–279. [CrossRef]

16. UNESCO. Best Practices—Spain. 2025. Available online: <https://www.unesco.org/en/underwater-heritage/best-practice-spain> (accessed on 12 March 2026).
17. Grøn, O.; Boldreel, L.O. Sub-bottom profiling for large-scale maritime archaeological survey: An experience-based approach. In *2013 MTS/IEEE OCEANS—Bergen*; IEEE: Piscataway, NJ, USA, 2015. [CrossRef]
18. Grøn, O.; Boldreel, L.O.; Cvikel, D.; Kahanov, Y.; Galili, E.; Hermand, J.P.; Nævestada, D.; Reitana, M. Detection and mapping of shipwrecks embedded in sea-floor sediments. *J. Archaeol. Sci.* **2015**, *4*, 242–251. [CrossRef]
19. Winton, T. Quantifying Depth of Burial and Composition of Shallow Buried Archaeological Material: Integrated Sub-bottom Profiling and 3D Survey Approaches. In *3D Recording and Interpretation for Maritime Archaeology*; McCarthy, J.K., Benjamin, J., Winton, T., van Duivenvoorde, W., Eds.; Springer: Cham, Switzerland, 2019; pp. 155–174. [CrossRef]
20. Winton, T. Application of Parametric Sub-Bottom Profilers for Responsible in Situ Management of Underwater Shallow-Buried Archaeological Materials. *Hist. Archaeol.* **2023**, *57*, 188–208. [CrossRef]
21. Calantropio, A.; Chiabrando, F. Underwater Cultural Heritage Documentation Using Photogrammetry. *J. Mar. Sci. Eng.* **2024**, *12*, 413. [CrossRef]
22. Solana Rubio, S.; Salas Romero, A.; Cerezo Andreo, F.; González Gallero, R.; Rengel, J.; Rioja, L.; Callejo, J.; Bethencourt, M. Comparison between the Employment of a Multibeam Echosounder on an Unmanned Surface Vehicle and Traditional Photogrammetry as Techniques for Documentation and Monitoring of Shallow-Water Cultural Heritage Sites: A Case Study in the Bay of Algeciras. *J. Mar. Sci. Eng.* **2023**, *11*, 1339. [CrossRef]
23. Cerezo Andreo, F.; Solana Rubio, S.; Salas Romero, A.; González Gallero, R.; Ciarlo, N.C. Fondeo y tráfico marítimo. Avances del estudio de contextos subacuáticos de época antigua en el litoral de Carteia. In *Carteia y el Ciclo Haliéutico Reflexiones y Novedades en el Marco del Fretum Gaditanum*; Expósito Álvarez, J.A., Bernal Casasola, D., Eds.; UAM: Madrid, Spain, 2024; Volume 7, pp. 253–266.
24. Andreo, F.C.; Gallero, R.G.; Mañas, C.P.R.; Rubio, S.S.; Romero, A.S.; Ciarlo, N.C.; Tudela, E.F.; Muñoz, H.S.; Bettencourt, J.; Lapiedra, M.G.; et al. Entre las columnas de Hércules, arqueología subacuática de un espacio privilegiado. La bahía de Algeciras. Primeros resultados del Proyecto Herakles. In *CIANYS 2021. Actas del I Congreso Iberoamericano de Arqueología Náutica y Subacuática: Cádiz, del 20 al 23 de octubre de 2021*; Andreo, F.C., Mañas, C.P., Rubio, S.S., Eds.; Editorial UCA: Cádiz, Spain, 2025; pp. 145–158. Available online: <http://hdl.handle.net/10498/38556> (accessed on 12 March 2026).
25. Solana Rubio, S. Underwater Cultural Heritage in the Strait of Gibraltar: A State of the Art. In *Maritime Archaeology Graduate Symposium*; Short Report Series; Honor Frost Foundation: London, UK, 2024. [CrossRef]
26. Mas, J. *El Puerto de Cartagena*; Athenas: Cartagena, Spain, 1979. Available online: <https://www.cultura.gob.es/mnarqua/dam/jcr:207e2e72-56d8-44ff-9bc4-c6c07f90b1da/librojuliomas.pdf> (accessed on 12 March 2026).
27. Castillo Belinchón, R.; Gambin, T.; Miñano Domínguez, A.I.; Munuera Navarro, D.; Rodríguez Iborra, J. Memoria del Proyecto de Prospección Arqueogeofísica y Documentación con ROV en la Bahía de Cartagena. Campañas 2007 y 2008 (MANS, Vol. 3). Ministerio de Cultura. 2025. Available online: <https://www.cultura.gob.es/dam/jcr:4230b4f6-10fb-4588-88f8-1b7fa280b457/mans-03-m.pdf> (accessed on 12 March 2026).
28. Reyes, J.P. Inventario de yacimientos arqueológicos subacuáticos del litoral murciano. *Cuad. Arqueol. Marítima* **1996**, *4*, 57–90.
29. Gañán, I.A.; Bravo, M.G.; Domínguez, A.I.M.; Reyes, J.P. Informe preliminar de la Prospección arqueológica Subacuática realizada en los Accesos al puerto de Cartagena y Puerto e Isla de Escombreras. In *Memorias de Arqueología*; Lechuga Galindo, M., Sánchez González, M.B., Eds.; Consejería de Educación y Cultura: Murcia, Spain, 1997; pp. 295–302. Available online: <https://dialnet.unirioja.es/servlet/articulo?codigo=8186745> (accessed on 12 March 2026).
30. Reyes, J.P. Actuaciones arqueológicas submarinas en nueva dársena deportiva “Marina de Curra”. In *Actas de las Jornadas de ARQUA 2011*; Ministerio de Educación Cultura y Deporte: Madrid, Spain, 2012; pp. 47–51. Available online: <https://dialnet.unirioja.es/servlet/articulo?codigo=8174894> <https://es.calameo.com/read/000075335bfa5f6cd7b5e>; (accessed on 12 March 2026).
31. Miñano Domínguez, A. Informe del Proyecto de Prospección arqueológica en el Puerto de Cartagena. In *Memorias de Arqueología*; Lechuga Galindo, M., Sánchez González, M.B., Eds.; Consejería de Educación y Cultura: Murcia, Spain, 2012; pp. 86–139. Available online: <https://patrimoniocultural.carm.es/inicio> (accessed on 12 March 2026).
32. Domínguez, A.I.M.; Belinchón, R.C. Últimas campañas arqueológicas subacuáticas del Museo Nacional de Arqueología Subacuática (2011–2012). In *Arqueología Subacuática Española: Actas del I Congreso de Arqueología Náutica y Subacuática Española, Cartagena, 14, 15 y 16 de Marzo de 2013*; Nieto Prieto, X., Bethencourt Núñez, M., Eds.; UCA Editores: Cádiz, Spain, 2014; Volume 2, pp. 221–228. Available online: <http://dialnet.unirioja.es/servlet/articulo?codigo=5001810> (accessed on 12 March 2026).
33. Matallana, F.F. Prospección subacuática en la Marina de Curra (Cartagena). In *XIX Jornadas de Patrimonio Cultural de la Región de Murcia*; Lechuga Galindo, M., Collado Espejo, P.E., Sánchez González, M.B., Eds.; Tres Fronteras: Murcia, Spain, 2008; pp. 381–383. Available online: <http://dialnet.unirioja.es/servlet/articulo?codigo=2884071> (accessed on 12 March 2026).

34. Cerezo Andreo, F.; Solana Rubio, S.; López-Castejón, F.; Ramallo Asensio, S.F. El Impacto de los Eventos Climáticos tipo DANA en la Conservación de los Entornos Subacuáticos de los Accesos al Puerto de Cartagena (España). Primeros Datos del Proyecto Aladroque. *NANS: Noticiario de Arqueología Náutica y Subacuática*. 2022, pp. 4–18. Available online: <https://www.cultura.gob.es/mnarqua/publicaciones/publicaciones-seriadas/nans/2022.html> (accessed on 12 March 2026).
35. Bost, J.-P.; Campo, M.; Colls, D.; Guerrero, V.M.; Mayet, F. *L'épave Cabrera III (Majorque). Échanges Commerciaux et Circuits Monétaires au Milieu du IIIe Siècle Après J.-C.*; Centre Pierre: Paris, France, 1992; Volume 23, Available online: <https://hal.science/hal-01798862> (accessed on 12 March 2026).
36. Aragón, E.; Rodríguez, J.; Munar, S. Investigación y gestión del Patrimonio Cultural Subacuático en las Islas Baleares: La Carta Arqueológica Subacuática de Formentera y el pecio romano de Porto Cristo. *RIPARIA* **2016**, *2*, 21–53. [CrossRef]
37. Cau-Ontiveros, M.A.; Bernal-Casasola, D.; Pecci, A.; Fantuzzi, L.; Picornell-Gelabert, L.L.; Valenzuela Oliver, A.; Retamosa Gámez, J.A.; Portillo-Sotelo, J.L.; Cardell Perelló, J.; Munar Llabrés, S.; et al. Multianalytical approach to the exceptional Late Roman shipwreck of Ses Fontanelles (Mallorca, Balearic Islands, Spain). *Archaeol. Anthropol. Sci.* **2024**, *16*, 58. [CrossRef]
38. Bernal-Casasola, D.; Cau-Ontiveros, M.A.; De Juan Fuertes, C.; Munar Llabrés, S.; Cardell Perelló, J.; García Ríaza, E.; Moya Montoya, J.A.; Oviedo Callealta, J.; Portillo Sotelo, J.L.; Retamosa Gámez, J.A.; et al. Repensando el comercio marítimo de Carthago Spartaria: Acerca del pecio tardorromano de Ses Fontanelles (Mallorca). *Drassana* **2023**, *31*, 156–185. [CrossRef]
39. Ortea, J.F.; Pazos, E.M. *La Ciudad Romana de Caraca. Historia y Territorio*; La Ergástula: Madrid, Spain, 2020; Available online: <https://www.laergastula.com/producto/la-ciudad-romana-de-caraca-historia-y-territorio/> (accessed on 12 March 2026).
40. Sabio, R.; Cerezo, F.; Solana, S.; Gamo, E.; Fernández, J.; Martín, S. Intervención Arqueológica en el Río Tajo, en el Entorno de la Antigua Ciudad de Caraca (Driebes). *NANS: Noticiario de Arqueología Náutica y Subacuática*. 2024. Available online: <https://www.cultura.gob.es/mnarqua/publicaciones/publicaciones-seriadas/nans/2024.html> (accessed on 12 March 2026).
41. Zhu, J.; Zhou, T.; Li, T.; Chen, B.; Meng, X.; Mazhar, S. High-resolution sub-bottom profiling technology using parametric array and vector hydrophone. *Appl. Acoust.* **2024**, *223*, 110077. [CrossRef]
42. Saleh, M.; Rabah, M. Seabed sub-bottom sediment classification using parametric sub-bottom profiler. *NRIAG J. Astron. Geophys.* **2016**, *5*, 87–95. [CrossRef]
43. Gallero, R.G. La arqueología subacuática en la bahía de Algeciras. Estado de la cuestión y avance de una carta arqueológica de la bahía. In *Arqueología Subacuática Española: Actas del I Congreso de Arqueología Náutica y Subacuática Española. Cartagena, 14, 15 y 16 de Marzo de 2013*; Prieto, X.N., Núñez, M.B., Eds.; Editorial UCA: Cádiz, Spain, 2014; Volume II, pp. 173–178. Available online: <https://www.cultura.gob.es/mnarqua/dam/jcr:f950bde1-5116-480e-8087-7d0e595e2f81/librocongreso.pdf> (accessed on 12 March 2026).
44. Torres, T.; Ortiz, J.E.; Ramallo, S.; Ros, M.; Sánchez-Palencia, Y.; Blázquez, A.; Cerezo, F.; López-Cilla, I.; Galán, L.A.; Borrego, Á.G.; et al. Development of the marine Holocene environment in a drowned paleovalley with final anthropic influence in the Cartagena Bay (Murcia, SE Spain). *Holocene* **2022**, *32*, 554–568. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

MDPI AG
Grosspeteranlage 5
4052 Basel
Switzerland
Tel.: +41 61 683 77 34

Journal of Marine Science and Engineering Editorial Office

E-mail: jmse@mdpi.com
www.mdpi.com/journal/jmse



Disclaimer/Publisher's Note: The title and front matter of this reprint are at the discretion of the Guest Editors. The publisher is not responsible for their content or any associated concerns. The statements, opinions and data contained in all individual articles are solely those of the individual Editors and contributors and not of MDPI. MDPI disclaims responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.



Academic Open
Access Publishing

mdpi.com

ISBN 978-3-7258-8668-5