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Archaeological predictive modelling in underwater contexts. Utility and challenges

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***Abstract* – Despite the availability of various remote sensing methods allowing for mapping, monitoring, and studying the underwater cultural heritage at previously unreachable depths, underwater operations remain costly and challenging to sustain in extensive areas. The adoption of formal models indicating where to expect archaeological remains would be extremely beneficial to optimise underwater archaeological investigations. However, whilst archaeological predictive modelling has increasingly been employed in terrestrial contexts, this technique is underdeveloped in the maritime domain, particularly in the Mediterranean basin. While hinting at a mistaken notion of what predictive models should achieve, this underdevelopment also highlights specific caveats, which should be addressed to improve current archaeological predictive modelling approaches, thus promoting their further development in maritime areas. This contribution presents a new GIS-based methodology for the prediction of shipwreck locations in Mediterranean territorial waters (i.e., 12 NM zone); particularly, it focuses on strategies to deal with data biases, model uncertainty and testing.**

Keywords – archaeological predictive modelling, GIS, shipwrecking probability, archaeological risk assessment, cultural heritage management, preventive archaeology, maritime spatial planning

I. INTRODUCTION

Archaeological predictive modelling, prominently defined as a technique enabling to ‘predict, at a minimum, the location of archaeological sites or materials in a region, based either on the observed pattern in a sample or on assumptions about human behaviour’ [1] has been propelled by the endorsement of the 1992 European Convention for the Protection of the Archaeological Heritage [2]. The latter, also known as the ‘Malta Convention’ or ‘Valletta Convention’, has introduced archaeological risk assessment in spatial developmental planning by acknowledging that significant threats to the archaeological heritage are nowadays connected to construction projects rather than unauthorised excavations. Reflecting two sides of the same coin, this risk represents both the possibility for the archaeological record to be damaged and the chance for developers to encounter archaeological remains in the areas involved in developmental plans, with the possibility of facing additional costs for mitigating measures [3]. Knowing in advance where yet unknown cultural heritage remains might be is therefore crucial to minimise the risk and optimise archaeological investigations, cultural heritage management and spatial planning.

Whilst predictive models (PMs) have been increasingly adopted in terrestrial contexts (for a review of theory, methods and cases [4], [5], [6]), they are still underdeveloped in underwater and maritime settings, particularly in the Mediterranean Sea. Among the limited examples in Europe are the second and third generations of the indicative map of archaeological values developed by the Cultural Heritage Agency of the Netherlands (i.e., *De Indicatieve Kaart van Archeologische Waarden*) [7], [8] and the ‘Refining Areas of Maritime Archaeological Potential (AMAPs) for Shipwrecks’ project, which was carried out by the Bournemouth University, in association with the Southampton University, Seazone Solutions Ltd. and the National Museum of Denmark, on behalf of the English Heritage Archaeological Commissions Program [9], [10].

Such underdevelopment of archaeological site location probability models in underwater settings sounds like a paradox in light of the logistics and economic limitations typical of these environments, which impose a prioritisation of the areas to investigate. By indicating where to expect archaeological remains, PMs are handy tools to optimise maritime prospections [11], [12].

Besides the practical applications in cultural heritage management and spatial planning, predictive modelling and formal modelling approaches, more generally, can also foster the understanding of past phenomena since they entail explicit formalisation, hence verification of theoretical hypothesis [13], [14].

However, several methodological challenges and shortcomings still affect archaeological applications of predictive models [15]. Particularly, by looking at those limiting the development of PMs in maritime contexts, and undermining their reliability, are: first, the need to find a balance between the two opposite needs mentioned above, i.e., the necessity to provide, on the one hand, a map indicating the probability of encountering “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” [16], as such, inevitably simplified; on the other hand, a model capable of integrating the archaeological and historical theory and accounting for specificities which are essential to this aim. Connected to the problematic balancing of simplicity and complexity in archaeological modelling [17] is also the tendency to prioritise environmental factors among the input parameters, to the detriment of cultural and cognitive ones [18]. A second limitation relates to the underestimation of the effects of data biases, which is particularly relevant in models based on inductive reasoning, since biased data generate biased results. Last but not least, is the problematic testing of archaeological predictive models and the little to no consideration of the underlining factors of uncertainties [19]. This contribution presents a predictive model for assessing the shipwrecking probability in Mediterranean territorial waters, which was developed by addressing some of the above-mentioned shortcomings [20].

II. A SHIPWRECKING PROBABILITY MODEL

The shipwrecking probability model indicates which areas within the Mediterranean territorial waters (i.e., the 12 NM zone as defined by the 1982 United Nations Convention on the Law of the Sea) have a higher probability than others of shipwreck events (i.e., it specifies a relative probability rather than an absolute one). The model is based on cost-surface analysis in geographic information systems (GIS) and it is developed following a deductive, i.e., theory-driven, approach [21] [22], [23]; indeed, due to the many biases affecting the distribution of the underwater archaeological record, which risked generating a biased prediction, the observed sites are used to test and validate the model rather than as input-data after taking several measures to limit the effects of data limitations in the phase of testing. In order to cater to the requirements, on the one hand, of maritime spatial planning and cultural heritage management, and on the other hand, of in-depth archaeological and historical analysis, the model was developed at two different scales of analysis following slightly different procedures. The Regional-scale (RS) model focuses on navigation dynamics in the area between Cap Bon (present Tunisia) and Alexandria (present Egypt) in Roman times, and it is based on a systematic screening of textual evidence from Classical times. The Global-scale (GS) model is extended to all Mediterranean territorial waters without chronological limitations by employing a big-data approach (Fig.1).

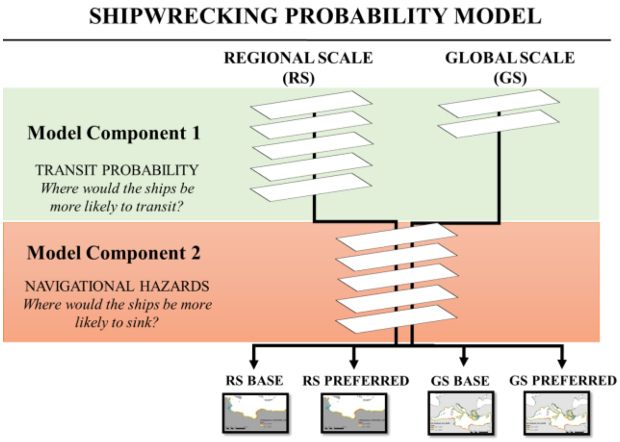

Fig. 1. Shipwrecking Probability models' structure.

Two research questions are addressed to identify shipwrecking probabilities, corresponding to two separate model components: where ships are more likely to transit and where ships are more likely to sink. Sinking probabilities are calculated by considering environmental factors (i.e., mean wind speed, mean wave height, bathymetry, and the effects of storminess along the coast of the Mediterranean Sea, in terms of increasing mean sea level and storm return value that have never been included in archaeological models before [24]. Transit probabilities are derived by considering pulling and pushing factors attracting or averting mariners' movement; particularly, the model considers shelters, landing sites, anchorages and ports, whose attractiveness varies based on environmental conditions, proximity to the inland transport system and further socio-cultural attractors. The model also takes into account the twofold implication of coastal sight in terms of orientation aid and risk connected to assault probability and environmental hazards; particularly, differently from other nautical models assigning a seafaring preference to the entire area in sight of land, in the shipwrecking probability model the preference is assigned at the seaward edge of the land range of visibility (i.e., the sea spaces placed as far as possible from the shore but from which the land is still visible). At both scales two outcomes are produced: a ‘BASE’ and a ‘PREFERRED’ model. In the former all factors have equal weight; in the latter the input factors are assigned different weights based on their alleged relevance following the Analytical Hierarchy Process by Saaty [25].

III. MODEL EVALUATION

The shipwrecking probability model was tested against the shipwreck evidence (Fig. 2) using Kvamme's Gain statistics (Kgain) [26] and the Pearson chi-squared goodness of fit test [27]. To this aim, an integrated shipwreck database was set up by combining the shipwreck data provided by the University of Oxford within the Oxford Roman Economy Project (OXREP) and the Digital Atlas of Roman and Medieval Civilisations (DARMC) set up by the University of Harvard.

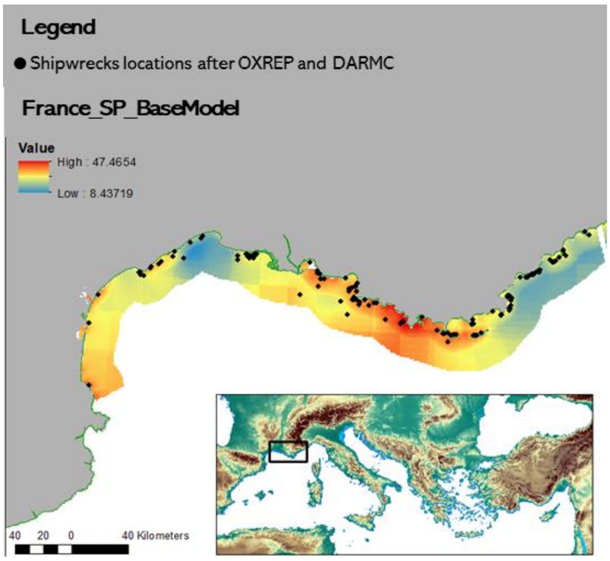

Fig. 2. Shipwreck locations (after OXREP and DARMC) and Shipwrecking Probability in French waters produced by the Global Scale Base Model (map by Ritondale).

The objective was to determine if the high-probability areas identified by the model indeed had a higher shipwreck density compared to the overall density of the entire research area. Additionally, the statistical significance of this distribution pattern was examined to assess whether it occurred by chance.

In terms of the Kgain statistic, previous research suggests that a minimum value of 0.7 is necessary to achieve significant precision and accuracy, thereby reducing the possibility of substantial errors and ensuring applicability in most cultural heritage management contexts. The Global-scale model satisfies this requirement with a Kgain value of 0.72 in the preferred scenario (Fig. 3).

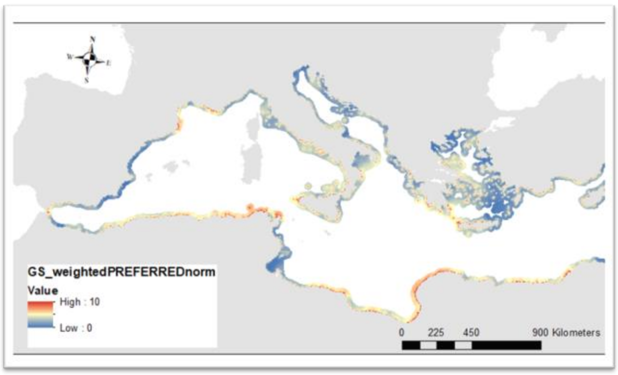

Fig. 3. Global Scale Preferred SP model

At the regional scale, the chi-squared value was calculated, confirming the significance of the results by highlighting the substantial difference between expected and observed values across all scenarios. At the Regional scale, the application of the same statistical testing procedure was rendered infeasible due to the limited number of documented shipwrecks within the designated area. Instead, the model's performance was assessed by contrasting the density of shipwrecks categorised in the highest risk class as predicted by the model against the overall shipwrecks density within the specified region. The model was deemed valid when the former exceeded the latter. In the Regional study area, both the Global and Regional models were utilised, facilitating comparative analysis of the outcomes generated by these two distinct modelling approaches. Notably, the Regional model (RS) exhibited superior performance in comparison to the Global model (GS), indicating the potential value of accounting for factors such as shelter attractiveness and visibility analysis, which are absent from the Global model. The Kgain statistic was chosen for testing the predictive capability of the model since it is the most commonly employed method in archaeological predictive modelling worldwide (e.g., in the Dutch IKAW) and therefore, it has the advantage of enabling the comparison of predictive performance in different models. However, it must be acknowledged that the Kgain statistic is particularly susceptible to data biases, and further alternative testing methods are ongoing to better evaluate the model performance through Bayesian statistics.

Given the many factors of uncertainty embodied in the model procedures, which is a rather unheeded problem in most archaeological computational models [28], [29] sensitivity and uncertainty analysis were performed. Particularly, following Evans [30], the factors of errors and uncertainty were first identified and distinguished into three groups: a) input data uncertainty, b) model choice uncertainty, and c) model mechanics uncertainty. Afterwards, several scenarios were produced following the OAT method (i.e., One Factor At Time) to verify how the model behaves under variation and which of these impacts the model most. Fig. 4 and Fig. 5 show the scenarios produced in the Regional-scale and Global scale model by removing one factor per model run. On the x-axis is the normalised cost, i.e., the relative shipwreck-probability value (RSP value), resulting from the weighted addition of the input raster surfaces. On the y-axis are the % of cells in the raster surface presenting the relative shipwrecking probability (RSP) value specified on the x-axis.

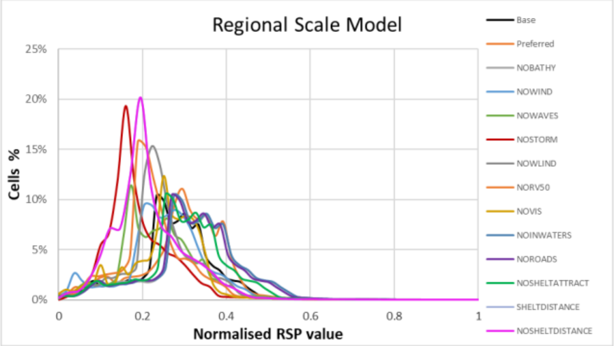

Fig. 4. Regional-scale Model scenarios produced by removing one factor per model run.

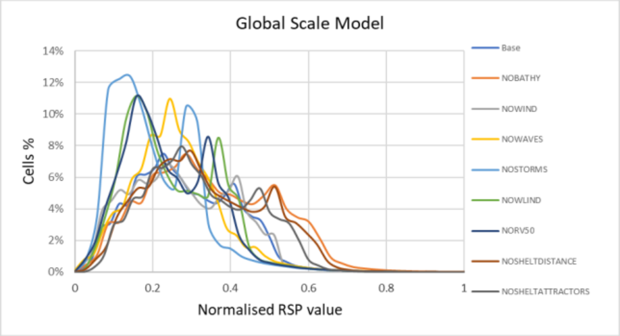

Fig. 5. Global-scale Model scenarios produced by removing one factor per model run.

IV. MODEL APPLICABILITY AND FURTHER DEVELOPMENT

Being the first archaeological predictive map to be developed in Mediterranean territorial waters, this model serves as a foundational framework, which may be expanded with additional data to explore more intricate processes and address specific research inquiries in the future. For instance, while currently being limited to the assessment of shipwreck *events* (i.e., seafaring probability and sinking probability), it could be integrated with the inclusion of preservation conditions and post-depositional dynamics to better ascertain the shipwreck *remains potential*.

However, by knowing in advance which maritime regions present higher shipwrecking probability than others, it is already possible to optimise underwater surveys, e.g., not only by prioritising areas to investigate but also and foremost by supporting the selection of the most suitable operating settings employed in remote sensing surveys. Indeed, since higher frequencies, e.g., of acoustic tools, that ensure better resolutions correspond to proportionally inverse swath widths, i.e., limited surveyed areas [31], it is helpful to know beforehand where higher frequencies are needed.

Besides the practical utility that has been emphasised here, the model also contributes to evaluating the impact of a factor in ancient seafaring, which formal modelling approaches tend to underestimate, namely the effect of risk perception in shaping the ancient seaborne movement. The comprehensive documentation of the ArcGIS procedure enables easy replication, testing, and customisation by other researchers.

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