Historic Shipwrecks and the Impacts of Climate Change

Deanna Groom

dng20vdh@bangor.ac.uk

Bangor University

Research Article

Keywords: Climate Change, Underwater Archaeology, Photogrammetry, Shipwreck Ecology

Posted Date: May 22nd, 2025

DOI: https://doi.org/10.21203/rs.3.rs-6665362/v1

Additional Declarations: No competing interests reported.

Abstract

This paper presents the results of a four-year research programme exploring the impacts of climate change on historic shipwrecks around the coast Wales. It explored the possibility of creating a network of ‘Sentinel Wrecks’, which would allow research of climate change impacts in relation to specific case studies to be taken forward through international collaboration. The identification of suitable Welsh sites has already begun through the creation of baseline surveys for 17 intertidal sites. 3D digital photogrammetry was used to record sites through annual cycles of uncovering and recovering in response to increasingly severe storm conditions. Analysis of ecological survey data for 52 underwater wreck sites has provide confirmation that several warmer water species are expanding their range northwards in response to rising sea temperatures. Whilst the biodiversity of Welsh shipwrecks has decreased by 7% in the past 30 years. These trends match findings for the wider natural environment of Wales.

This study makes an important contribution, at a nation-wide scale, in reviewing the changes that are already taking place at shipwreck sites during the most critical decade of the climate emergency. The Additionally, it considers the potential of research and policy actions at an international scale that would safeguard underwater and intertidal shipwrecks into the future.

Introduction

Shipwrecks contain a vast and diverse reserve of evidence for our seafaring past and are also unique biodiversity hotspots (Paxton *et al.* 2024). Management insitu is emphasised in both the ICOMOS Charter on the Protection and Management of Underwater Cultural Heritage 1996 (ICOMOS 1997: Article 1) and the 2001 UNESCO Convention on the Protection of Underwater Cultural Heritage (UNESCO 2001: Article 2) along with non-destructive and non-intrusive conservation strategies. This is seen as the best way to safeguard both cultural heritage assets and the natural environment. Excavation and removal of the assets is perceived as necessary only when sites are at risk due to circumstances which cannot be mitigated (Manders 2008: 34).

However, heritage agencies and archaeological practitioners have begun to recognise that many of the marine environmental parameters conducive to good preservation insitu are slowly and relentlessly changing due to climate change. Climate change is bringing rising sea temperatures, decreased salinity, ocean acidification, more low dissolved oxygen (hypoxia) events, and changes to sediment flux chemical exchange processes[1]. These new threats to underwater and intertidal heritage need to be assessed, understood and quantified - especially due to the speed in which the climate emergency is intensifying (Figure 1) (Dunkley 2015; Gearheart *et al.* 2011; Kintisch 2016; Mustow 2021; Stieglitz and Waterson 2013).

Custodians of marine sites have been attempting to document these changes and act for the better safeguarding of sites at risk. For instance, in the UK, articles published in 2008 and 2009 by members of

Historic England's coastal and marine team made suggestions regarding how best to manage the inevitable disintegration and loss of collections of hulked vessels in the intertidal zone. Climate change impacts were identified as accelerated coastal erosion and increased flooding. The decisions being taken now by coastal managers with regard to coastal defences or realigning the coast may significantly affect the survival of such sites. The northwards expansion of non-native and invasive species was also noted as a special concern in England, with presence of the shipworm Lyrodus pedicellatus recorded off Cornwall, in Langstone Harbour in Hampshire, and on the Mary Rose wreck in the Solent (Murphy, Pater and Dunkley 2008; Murphy, Thackray and Wilson 2009).

In more recent years, other academic studies have categorised and identified further risks. For example, Perez-Alvaro in her review paper notes the four main climate-related changes for underwater site as being warming oceans; changes to ocean currents; chemical changes; and sea level rise. Closely associated are human responses to the climate crisis. Such as the exploitation of new fishing grounds to bottom trawling as species change their ranges in response to warming seas. Many of the drivers for finding new oil and gas reserves, offshore renewables developments, and the exploration of deep sea mining opportunities, can be linked back to countries failing to meet the global warming targets of the 2015 Paris Agreement (Jarvis *et al.* 2023; Jarvis 2024).

Through a review of studies already published, it became evident that shipwreck research in the 21st century needs to move beyond simply modelling site formation processes. We need to add methods which incorporate climate change into all site assessments. My research project, undertaken at the School of Ocean Sciences, Bangor University from 2021 to 2024, has taken a first step towards addressing these concerns for Wales. The results and observations of this study are presented in the following sections in the hope that it will inspire others to take a closer look at site data they have collated over the years and develop new investigation practices to truly inform the future.

Methodology

The geographical area of the research encompasses an offshore area of 32,000km^2 and 2120km of coastline. Within this area, there are over 830 located shipwrecks, aircraft downed at sea and individual findspots (e.g., isolated cannon finds). Nearly a quarter of these known sites are from the First and Second World Wars. There is potential for an additional 4500 sites to be present. according to documentary sources such as newspaper accounts from the late 18th century onwards. These heritage assets represent the cultural property of 32 nations, which are managed and conserve Through the policies encapsulated in the Welsh National Marine Plan (Welsh Government 2019) (Figure 2).

The first stage of the project involved carrying out an online questionnaire. This was circulated to archaeologists and heritage professionals worldwide through existing research networks. The objective was to obtain an understanding of the various challenges being experienced in shipwreck site management during the climate emergency. Participants were offered the opportunity to suggest the climate change parameters they felt to be most impactful and identify research priorities. Hence gauging the potential to develop universal climate change impact assessment criteria which could be used worldwide. Twenty-seven practitioners took part in this survey from 11 countries including Wales, England, Northern Ireland, Norway, Finland, Belgium, Malta, United States, Tanzania, Australia, and Japan (Figure 3).

In the second stage of the project, an extensive literature review of oceanic climate change predictions and archaeological site formation processes was undertaken. A series of matrices were developed to assess climate change effects (e.g., increased storminess, warming seas and ocean acidification) and their likely impact on the physical, biological and chemical aspects of site formation.

An ArcGIS geodatabase was developed to collate datasets for salinity, temperature, acidity, wave climate, tidal flows, nature of sediments, and speeds of currents under which sediments begin to be entrained (thresholds of motion). A sampling grid was created for the offshore of Welsh waters and was used to create a shapefile which collated information about present conditions and projected changes to the year 2050.

Significant Wave Height (SWH)[2] datasets were also acquired from four semi-permanent wave buoys around the Welsh coast. The average depths of the storm wave base (SWB) during the previous 20 years were calculated.[3] A shapefile was then created to suggest the most common, present extents of storm wave base to and compare with predictions for the storm wave base depths into the future (years 2050-2070).

Coastal vulnerability was also explored through the collation of information about the coast edge, such as beach sediment supply and transport and cliff material and erosion rates. This resulted in the identification of beaches with known histories of draw down and rebuild on an annual basis[4]. These were then correlated with known intertidal wrecks. Thirty-two reconnaissance field visits were undertaken, from which 17 sites were selected and taken forward into the three-year monitoring programme. 3D-digital photogrammetric surveys were combined with the data contained in beach profiles provided by the Welsh Coastal Monitoring Centre.

In the last phase of the project, the Marine Conservation Society supplied ecological surveys for 52 underwater wreck sites from their ‘Seasearch’ initiative. The surveys spanned the years 1995-2013, with some sites having been survey up to 5 times. The species present were collated into a Microsoft Access database, which was enhanced with information about preferred environmental conditions whether they were regarded as invasive non-native species, and whether they had potential to become ‘biomarkers’ for climate change into the future.

Results

Practitioners’ Survey

An online questionnaire was shared with archaeologists and heritage professionals worldwide from April to September 2021. Of the responders, 23% worked in government agencies or national custodian agencies, 53% worked in academia, and 15% were from organisations such as commercial archaeology units and not-for-profit research institutes. A further 4% of respondents were from the recreational sports diving community.

Likert scales allowed participants to rank their agreement to various statements on a five-point scale ranging from 'extremely important' to 'not at all important', with free text boxes allowing participants to provide comments.

Of foremost interest, participants identified the impact of more frequent severe storms as a major threat to shipwreck sites, with other priority areas for research being as follows (Figure 4):

- gaining fuller understanding of the range and scale of sites being impacted;
- gaining a better understanding of changes in shipwreck ecosystems from warming seas;
- gaining a better understanding of the impact of climate change on the interrelationships between the physical, biological, and chemical processes of archaeological site formation;
- expanding our understanding of the impacts of ocean acidification on metal wrecks and corrosion processes;
- gaining a better understanding of the impact of storms on shipwrecks situated in medium sea depths (15m-50m);
- developing new holistic interdisciplinary approaches which involve marine and social sciences;
- developing a broader standardisation for marine survey data collection for climate change purposes, so that to determine best practice standards that could be shared and applied internationally.

The responses to the survey guided the scope of the research to be taken forward. A decision was made to focus on three key climate change factors: the impact of more frequent severe storms, ocean acidification, and warming seas.

Development of Matrices

Three matrices were formulated for assessment of these climate change phenomena. The first matrix exploring the impacts of severe storms on shipwreck sites, considering the Couple Model Intercomparison Project 5 (CMIP 5). This model has produced a plausible extreme scenario of a 50–80% increase in days of strong winds in the United Kingdom by 2070–2100, compared to the weather experienced in the period 1975–2005. Larger extreme wave heights will also be experienced on Atlantic facing coasts and within the Irish Sea (Bricheno and Wolf 2018). The second matrix explored the impacts of increasing sea temperatures on shipwrecks given a projected increase of 4-6˚C in the sea's surface waters (Tinker and Howes 2020: 30) and a 1-2˚C rise in temperature averaged through the full depth of the Welsh coastal waters (Sharples *et al.* 2020; Young and Holt 2007). The third matrix reviewed the impact of rates at which our oceans are absorbing excess carbon dioxide (CO_2). The concentration of this greenhouse gas now exceeds 400 parts per million (ppm) Welsh coastal waters. Over the past 10 years, this concentration has increased 2.3ppm annually. Consequently, a prediction for a drop in mean pH across the northwestern European continental shelf of about 0.0036 per year by 2010 is expected, with significant spatial variation such as 0.005 per year in Bristol Channel and 0.002 per year in the Celtic Sea (Humphreys et al. 2020: 54). However, there is still uncertainty regarding CO_2 uptake and magnitude of pH change in low and medium salinity waters such as estuaries and near-coastal waters (Howarth 2005), where many Welsh shipwrecks are located.

Exploring climate change impacts from the viewpoint of shipwreck site formation processes proved challenging. For example, the matrix reviewing the potential impacts of increased sea temperature identified increases in corrosion rates as likely but also identified the potential buffering effect that might be created by lower dissolved oxygen (hypoxia) events. Hypoxia events affect the life cycles of colonizing organisms. So, will this lead to a degrading of the abrasion protection biofilm gives the surface of shipwrecks in the water column? Will increases in sea temperature and ocean acidification reduce or increase the abundance of bacteria? The enzymes secreted by bacteria on the surface of iron and steel wrecks exert a major influence on the kinetics of corrosion as well as on the nature of the corrosion products (Gjelstrup Bjordal *et al.* 2011: 95).

More than anything, the matrices flagged where cross-disciplinary research is desperately needed. Particularly regarding identifying thresholds for potentially rapid change in preservation states from changing ocean parameters.

Results of GIS Mapping

A 4km x 4km sampling grid was generated in ArcGIS to cover the study area. Sediment type was combined with a Sediment Mobilisation Index (SMI) to assign a value to represent the likely preservation qualities of the sedimentary regime (Coughlan et al. 2021). Ninety-seven sites fell within grid squares where the best preservation conditions might normally be found comprising finer sediments (sand and/or mud). Theses grid squares also featured low average currents at seabed level (up to 0.5knots) and with annual mobilisation frequencies of less than 20%. Currents were found to be the mobilisation cause for the sediments for the vast majority of these grid squares.

The above results were checked against calculations of the present storm wave base. Wave data was acquired from the four semi-permanent WaveNet buoys to explore minimum, maximum and average depths for the storm wave base (i.e. depth at which a passing wave begins to agitate and mobilise seabed sediment in storm conditions). The four datasets span seventeen years, from 2005-2022. A fifth percentile of the largest SWH were used for the calculations. The results confirmed that topography of the Welsh coast creates very distinct wave climates. For example, South Wales is fully exposed to the longest fetch of the prevailing winds (southwest) and swell waves from the Atlantic. This is in contrast to the largest waves and surges which occur in Liverpool Bay due to westerly and north-westerly winds.

Liverpool Bay is sheltered from swell waves from the Atlantic (Brown *et al.* 2010: 119). One depth does not easily fit the entire Welsh coast as, of course, it varies with configuration of each prevailing wave climate. The storm wave vase was found to vary from 27m in Liverpool Bay in the north, to 33m off northwest Wales and Anglesey, 42m in Cardigan Bay, 50m off south Pembrokeshire coast, and 33m in the Bristol Channel in the south. Using these depths, 370 wrecks were subsequently identified as most frequently being in a state of increased sediment mobilisation during storm conditions (Figure 5). Into the future, mean significant wave heights are projected to slightly decrease, but the mean of maximum wave heights may increase by 0.5m (Wolf et al. 2020). This will increase the storm wave base depth and bring additional sites into more frequent sediment mobilisation.

The data structure of the sampling grid facilitated the mapping of further attributes relating to present-day environmental parameters (e.g. annual average salinity, winter and summer temperatures, etc) and for predictions for changes to these to the year 2050. For example, by 2050, annual average salinity is projected to decrease by 0.11-0.19ppm (Dye et al. 2020); tidal amplitude to increase by 10%, and sea-levels by 0.19-0.24m (Horsburgh et al. 2020) and acidity to increase by pH 0.15 (Humphreys et al. 2020). The most common biotopes present in each grid square were also recorded, with initial analysis of their resistance to climate change from the work carried out by the Marine Life Information Network (MarLIN).

To identify beaches, where significant drawn-down in response to storms is a regular occurrence, the following geomorphological and marine environment characteristics were mapped to produce a new shapefile:

- the character of the coastline and foreshore;
- the source of sediment (e.g. nature of cliffs or whether the sediment was a reworking of glacial tills or surface deposition in the nearshore);
- annual mean SWH;
- offshore fetch;
- predictions for sea-level rise;
- net sediment transport;
- beach conditions;
- availability of beach profiles to provide evidence of trends.

This led to the effective identification of 77 beaches with a history of seasonal drawn-down. Seventeen wrecks within 10 of these beaches were prioritised for the monitoring (Figure 6).

Results of Photogrammetric Field Survey

The monitoring programme was designed to capture intertidal wrecks in their ‘winter’ profile. That is, after a prolonged period of successive severe weather events (i.e., visited in February-April and/or after single particularly severe weather event). These surveys were then followed up by surveys in their ‘summer’ profile to provide comparative data (i.e., visited in August-early October after the prolonged summer period of calmer weather).

Photogrammetry was selected as the best methodological approach for these surveys, given the consistency of the methodology in depicting and reconstructing heritage assets, but also its efficiency in gathering data during short tidal windows (e.g., Lesgidi 2020; McCarthy 2014; McCarthy *et al.* 2019; Whitehead 2019). The images for photogrammetric alignment were taken with four low-cost waterproof cameras, which were tested for their results[5]. Agisoft Metashape software was chosen for image processing and the generation of 3D digital models. An outer circle of images was gathered, every 5 paces, at approximately 10m distance from the wreck or further away to capture the full extent of scour patterns. Then an inner circle of images was taken at 1-2 pace intervals and at a distance of 1-1.5m from the wreck and again from beach level. A minimum image overlap of 70% was observed to ensure the creation of successful photogrammetric 3D models. The number of images gathered for each site ranged between 160-760 (Figures 7 and 8). The site shown in the illustrations that follow is believed to be the Vittoria, an Italian-registered sailing barque, which drove ashore on 26 January 1872. However, research into other possibly identities continues.

A Holystone HS720E 4K EIS drone (still resolution 4K - 3840 x 2160) was also purchased to facilitate access to locations where the foreshore conditions were uncertain. The drone was flown in straight line grid pattern at 2m intervals to gather video and stills at a height of approximately 10m. These aerial views proved particularly useful in the case of two new sites identified on the western bank of Sandy Haven. These were not immediately visible from the ground level as they were heavily covered by seaweed but were confirmed from the overhead views gathered by the drone.

During the 3D modelling process, photo alignment issues occurred in the Agisoft software, where the surfaces of the scour pools were constantly in motion with wind ripples. To deal with this issue, a system of ‘benchmark views’ for each wreck was established to include views of a folding 1m rules measuring the depths of scour. In other surveys, where the scour pool surfaces were still, Agisoft was able to provide an approximation of the depth and shape of the scour. Through a combination of these methods, it was found that scour depths varied seasonally across the 17 sites, from 0mm (infilled) in late summer to 480mm deep after the winter storms. Cloud Compare software was used to assess height changes in beach sediment – i.e., where sediment was scoured out and where sediment was built up inside and outside the wreck (Figure 9).

The beach profile data provided by the Welsh Coastal Monitoring Centre (WCMC) was able to confirm trends of lowering and changes in slope across a wider area beach in the vicinity of the wrecks. Sites were subsequently located along the profile to establish the zone in which they fell (e.g., stable zone or primary area of beach drawn down/rebuild). The results of beach profiles analysis at Pembrey are shown in Figure 10 with the relative locations of shipwreck sites marked along their lengths. The WCMC has instigated a national system of beach profile monitoring locations, hence the beach profiles utilised for this research will continue to be resurveyed on a regular basis. Sediment levels and beach profile changes around the wrecks can continue to be quantified into the future.

To take research into the wave climates experienced at the monitored sites one step further, the National Oceanographic Data Centre, Liverpool, supplied data from their UK-wide coastal modelling and forecasting system. The data provided significant wave heights[6] for three locations around the Welsh coast for the years 2005-2070. The data was divided into periods to represent the recent past and present (2005-2025) and a 20-year projected sequence into the future for the years 2050-2070. Subtle differences are observable in the bar chart distribution plots (Figure 11). The plots suggest more SWHs above 3.5m (i.e. more storm events in the 2050-2070 period). Increases are also evident in the wave climates up to 0-1m, suggesting fewer calm days.

The net result must be that intertidal archaeological sites will be subject to increased erosion and physical force during autumn, winter, and spring. With a shorter, calm period in the summer for sediment to move back onshore, this means that sites will be uncovered and vulnerable to degradation for longer, year on year, into the foreseeable future.

Analysis of Ecological Surveys

The ecological surveys analysed for 52 permanently underwater wreck sites were carried out by members of the Marine Conservation Society as part of their Seasearch initiative. Five hundred and twenty-six ecological records were subsequently created in a MS Access database linked to the 52 archaeological site records. The ecological records comprised 478 individual species and 48 biotopes (i.e., habitats associated with a particular community of species). The archaeological records were enhanced by a programme of archive research into the history of each vessel, and ecological records were enhanced with species information gleaned from a variety of published and online sources.

Fourteen shipwrecks were found to feature one or more of seven non-native/invasive species (Figure 12). The presence of two of these species, the *Ciona robusta* (yellow-ringed sea squirt) and the *Aplidium glabrum* (honeycomb sea squirt), is attributed to climate change and warming seas (Picton and Morrow 2023). A World War II landing craft (Coflein, NPRN 240258), which foundered in 1951 within the port of Milford Haven, had the highest number of identified non-native/invasive species (five in total).

In the UK, the Joint Nature Conservation Committee (JNCC) has promoted a unified system for recording the abundance of marine benthic flora and fauna in ecological surveys. Known as the SACFOR system, it uses quadrants to undertake species counts and the descriptive scale which has given the system its name (**S**uper-abundant, **A**bundant, **C**ommon, **F**requent, **O**ccasional, and **R**are)(Hiscock 1996). The widespread adoption of SACFOR provides a means to compare both the presence and density of species from one survey to the next. Analysis of the SACFOR abundance identified 87 of the 478 species with abundances in decline. Sixty species were found to have stable abundance levels, whilst the populations of 80 others were found to be increasing. However, of particular concern, overall biodiversity on the 52 wreck sites was shown to have declined by 7.9 % since 1995. This corresponds with the trends identified in the State of Nature Wales Report published in 2023, which suggests that Welsh wildlife numbers have decreased on average by 20% since 1994 (State of Nature Partnership 2023).

The Marine Life Information Network (MarLIN) provides methodologies for assessing species sensitivity to various physical, chemical, and biological pressures (Tyler-Walters *et al.* 2023). Using these, and identifying the factors most relevant to climate change, 29 species present on the wrecks were identified with the potential to act as biomarkers for climate change impact – i.e., the geographical regions they were previously known to inhabit are changing (Table 1).

Table 1: Species with the potential to be used as climate change biomarkers selected from the 478 species present on the 52 underwater sites

Southern or warmer waters species whose abundance is likely to increase and whose range will expand further into Welsh waters with warming seas	Northern or colder water species whose abundance is likely to decrease and whose range is likely to retreat northwards towards the polar region
Amathia citrina	Urticina felina
Aplidium glabrum	Henricia sanguinolenta
Axinella dissimilis	
Balistes carolinesis	
Callionymus reticulatus	
Crisualria plumosa	
Drachiella heterocarpa	
Entelurus aequoreus	
Gymnangium montagui	
Haliclona simulans	
Halopteris filicina	
Halyphysema tumanowiczii	
Homaxinella subdola	
Jassa falcata	
Kallymenia reinformis	
Macropodia deflexa	
Raja microcellata	
Palinurus elephas	
Parazoanthus axinellae	
Perophora listeri	
Phorbas fictitius	
Stolonica socialis	
Taonia atomaria	
Thecacera pennigera	
Zeus faber	

For example, the first UK sightings of the *Raja microocellata* (small-eyed ray) was in 2007. It was seen near the wreck of a small World War I submarine (HMSE39) at the mouth of Milford Haven. The numbers caught off the southwest coast of the UK and Ireland during recreational fishing or by commercial fishing has increased in the last two decades. According to research available on FishBase (Frose and Pauly 2024), it is believed that this species will continue to expand its range northwards and into the North Sea.

The same assessment methodology was applied to 21 species recorded for the intertidal wrecks. Seaweed species being impacted by rising temperatures include *Fucus spiralis* (Spiral Wrack), *Pelvetia canaliculata* (Channel Wrack), and *Ascophyllum nodosum* (Egg Wrack). Of the barnacle species, *Semibalanus balanoides* is recognized as preferring colder waters (i.e., it is likely to retreat northwards from Welsh waters in response to future predictions of warming seas and rising air temperatures).

Re-analysis of the intertidal and underwater ecological surveys has proven extremely insightful for understanding changes in shipwreck ecology. However, these surveys pose some limitations. First, the vast majority of underwater sites are in nearshore depths of less than 30m. There is no comparative data for sites in the deeper parts of Welsh waters (i.e., Celtic Deep, St George's Channel and the Irish Sea). Moreover, the species recorded are 'macro' flora and fauna. They do not include microbiological species, such as the marine fungi and bacteria, which are known to play a key part in shipwreck degradation. In particular, marine wood-boring species, such as gribble and shipworm, are known to play a major role in weakening and breaking down wooden shipwrecks. However, our knowledge of present range and where they might expand in numbers as a result of climate change is extremely poor. Even though it is known that invasive gribble, *Limnoria tripunctata*, which favours sea temperatures of 14˚C and warmer, was first observed near Newport in 1951 and at Swansea in 1959 (Jones 1963). There is only one other confirmed sighting for the UK for this gribble, from Portsmouth in October 2024 (National Biodiversity Atlas). This lack of sighting is not likely to reflect a lack expansion by shipworm and gribble species, with the highest sustained UK summer sea temperatures exceeding 21˚C in August 2022 (Pinnegar 2024).

Conclusion

This research has shown that the life of a ship is not over when it sinks or runs aground. Shipwreck sites affect the structure, chemistry, and biological makeup of marine ecosystems long after their loss. They are equally impacted by changes taking place in their surrounding environment because of climate change.

The practitioner's survey carried out as part of this project has confirmed that there are many areas of uncertainty which deserve future interdisciplinary research and worldwide collaboration. For example, the preferred preservation *in-situ* option of underwater cultural heritage assets requires radical review in the face of our climate emergency, since various changes to marine environmental parameters are already putting submerged and intertidal archaeological sites at risk.

In Wales, monitoring programmes have already begun to shed light on the changes taking place. The ecological surveys are shedding light on changes to shipwreck ecology. Photogrammetric surveys of intertidal wrecks in their winter and summer profiles have demonstrated significant potential for gathering environmental and heritage data quickly and efficiently. The interdisciplinary approach adopted (marine science and archaeology) has assisted in the analysis of a wide range of spatial and environmental information. The GIS products generated have enabled climate change risk assessments to be undertaken with more confidence.

The absence of data for the abundance of shipworm and gribble around the Welsh coast requires urgent further attention. The methodologies developed for exploring the impact of climate change on commercial fish stocks might be applied to the full range of species living on underwater archaeological sites with the assistance of marine biologists.

Overall, as this study highlights, the key to fully understanding the impacts of climate change on shipwreck sites is the encouragement of international cross-disciplinary studies combined with stakeholder collaboration. The objective - to create a sound science basis to inform decisions for safeguarding our common cultural heritage into the future.

Declarations

Author Contribution

This article is the result of 4 years independent research towards a Doctorate, the text and illustrations are of the author's own generations as per the regulations of post-graduate regulations of Bangor University.

Acknowledgement

I would to thank my PhD supervisors, Professors Katrien van Landeghem and Peter Robins, at Bangor University, and external examiner Professor Fraser Sturt, University of Southampton. Dr Trevor Winton of Flinders University kindly contributed the idea of creating matrixes to tease out the impacts of climate change across the physical, chemical and biological processes of underwater archaeological site formation. Dr Mark Coughlan, University College Dublin, also allowed the Sediment Mobilisation Index model to be adapted for assist in this research.

Data Availability

The archive created during the research has been deposited with the Royal Commission on the Ancient and Historical Monuments of Wales to ensure that it remains in the public domain.

References

1. Bricheno, L. M. and J. Wolf. (2018) Future Wave Conditions of Europe, in Response to High-End Climate Change Scenarios. *Journal of Geophysical Research: Oceans* 123.12: 8762–8791. <https://doi.org/10.1029/2018JC013866>
2. Brown, J. M., A. J. Souza and J. Wolf (2010) An investigation of recent decadal-scale storm events in the eastern Irish sea. *Journal of Geophysical Research: Oceans* 115.5: 1–12. <https://doi.org/10.1029/2009JC005662>
3. Coflein, online database for the National Monuments Record of Wales (NMRW), Royal Commission on the Ancient and Historical Monuments of Wales (RCAHMW), viewed 15 March 2025, <https://coflein.gov.uk/en/>.
4. Coughlan, M. et al. (2021). A new seabed mobility index for the Irish Sea: Modelling seabed shear stress and classifying sediment mobilisation to help predict erosion, deposition, and sediment distribution. *Continental Shelf Research* 229(August), p. 104574. < https://www.sciencedirect.com/science/article/pii/S0278434321002302 >
5. Couple Model Intercomparison Project 5 (CMIP 5), viewed 15 March 2025, <https://wcrp-cmip.org/cmip5/>.
6. Dunkley, M. (2015) "Climate is what we expect, weather is what we get": managing the potential effects of oceanic climate change on underwater cultural heritage, in W. J. H. Willems and H. P. Van Schaik (eds) *Water and heritage: material, conceptual, and spiritual connections*: 217–230. Amsterdam: UNESCO.
7. Dye, S.R. et al. (2020) Climate change and salinity of the coastal and marine environment around the UK. < http://www.mccip.org.uk/media/2007/04_salinity.pdf >
8. Froese, R. and D. Pauly (2024) FishBase, viewed 15 March 2025, <www.fishbase.org>.
9. Gearheart, R., D. Jones, A. Borgens, S. Laurence, T. DeMunda, J. Shipp (2011)*. Impacts of Recent Hurricane Activity on Historic Shipwrecks in the Gulf of Mexico Outer Continental Shelf*. New Orleans: U.S. Department of the Interior - Bureau of Ocean Energy Management, Regulation and Enforcement Gulf of Mexico OCS Region.
10. Gjelstrup Bjordal, C., D. Gregory and A. Trakadas. (2011) *Wreck Protect: Decay and protection of archaeological wooden shipwrecks*. Oxford: Archaeopress.
11. Hiscock, K. (1996) *Marine Nature Conservation Review: Rationale and methods. Coasts and seas of the United Kingdom*. Peterborough: Joint Nature Conservation Committee.
12. Horsburgh, K., Rennie, A. and M. Palmer (2020) Impacts of climate change on sea-level rise relevant to the coastal and marine environment around the UK. MCCIP Science Review 2020, 116–131. <doi: 10.14465/2020.arc06.slr, https://nora.nerc.ac.uk/id/eprint/527112/1/07_storms_waves_2020.pdf >
13. Howarth, M. J. (2005) *Hydrography of the Irish Sea: SEA6 Technical Report*. London: British Geological Survey and UK Department of Trade and Industry's offshore energy Strategic Environmental Assessment programme.

14. Humphreys, M. P., Artioli, Y., Bakker, D.C.E, Hartman, S. E., León, P., Wakelin, S., Walsham, P. and P. Williamson (2020) Air – sea CO_2 exchange and ocean acidification in UK seas and adjacent waters. *Marine Climate Change Impacts Partnership Science Review*: 54–75. <https://doi.org/10.14465/2020.arc03.oac>
15. ICOMOS (International Council on Monuments and Sites) (1997) The ICOMOS Charter on the Protection and Management of Underwater Cultural Heritage. *Conservation and Management of Archaeological Sites* 2.1: 35–38. <https://doi.org/10.1179/135050397793138925>
16. Jarvis, C., M. P. Ermida and O. Varmer (2023) Threats to Underwater Cultural Heritage from Existing and Future Human Activities*. Blue Papers* 2.1: 76–83. <https://doi.org/10.58981/bluepapers.2023.1.08>
17. Jarvis, C. (2024) *Threats to Our Ocean Heritage: Bottom Trawling*. Cham: Springer. <https://doi.org/10.1007/978-3-031-57953-0>
18. Jones, L. T. (1963) The geographical and vertical distribution of British Limnoria [Crustacea: Isopoda]. *Journal of the Marine Biological Association of the United Kingdom* 43.3: 589–603. <https://doi.org/10.1017/S0025315400025546>
19. Kintisch, E. (2016) Arctic shipworm discovery alarms archaeologists. *Science* 359.6276: 901. doi: 0.1126/science.351.6276.901. <https://doi.org/10.1126/science.351.6276.901>
20. Lesgidi, P. (2020) Interpreting the Significance of Underwater Archaeological Photogrammetry*. Maritime Archaeology Graduate Symposium 2019*. London: Honor Frost Foundation. <https://doi.org/10.33583/mags2019.07>
21. Manders, M. (2008) In Situ Preservation: “the preferred option”. *Museum International* 60.4: 31–41.
22. Marine Life Information Network (MarLIN), viewed 15 March 2025, < https://marlin.ac.uk/evidence). >.
23. McCarthy, J. (2014) Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement. *Journal of Archaeological Science* 43.1: 175–185. <https://doi.org/10.1016/j.jas.2014.01.010>
24. McCarthy, J., J. Benjamin, T. Winton and W. Van Duivenvoorde (2019) The Rise of 3D in Maritime Archaeology, in J. McCarthy, J. Benjamin, T. Winton and W. Van Duivenvoorde (eds) *3D Recording and Interpretation for Maritime Archaeology*. Cham: Springer. <https://doi.org/10.1007/978-3-030-03635-5_1>
25. Murphy, P., C. Pater and M. Dunkley (2008) Out to Sea: climate change and the maritime historic environment. *Conservation Bulletin* 57 Spring: 17–19.
26. Murphy, P., D. Thackray and E. Wilson (2009) Coastal Heritage and Climate Change in England: Assessing Threats and Priorities. *Conservation and Management of Archaeological Sites* 11.1: 9–15. <https://doi.org/10.1179/135050309X12508566208281>
27. Mustow, S. E. (2021) Marine Invasive Non-native Species in the UK: Scale of the Problem and Progress of the Response*. CIEEM in practice* 112: 21–25.
28. National Biodiversity Atlas viewed 15 March 2025, <https://nbnatlas.org/>.

29. Paxton, A. B., C. Mcgonigle, M. Damour, G. Holly, A. Caporaso, P. B. Campbell, K. S. Meyer-Kaiser, L. J. Hamdan, C. H. Mires, and C. Taylor (2024) Shipwreck ecology: Understanding the function and processes from microbes to megafauna. *BioScience* 74.1: 12-24. <https://doi.org/10.1093/biosci/biad084>
30. Perez-Alvaro, E. (2016) Climate change and underwater cultural heritage: Impacts and challenges. *Journal of Cultural Heritage* 21: 842–848. <https://doi.org/10.1016/j.culher.2016.03.006>
31. Picton, B. E. and C. C. Morrow (2023) Encyclopedia of Marine Life of Britain and Ireland – Habitas, viewed 15 March 2025, <https://www.habitas.org.uk/marinelife/>.
32. Pinnegar, J. (2024) Turning up the heat: Advancing UK science to better predict and respond to marine heatwaves, Centre for Environment, Fisheries and Aquaculture Science (CEFAS) < https://marinescience.blog.gov.uk/2024/09/26/turning-up-the-heat-advancing-uk-science-to-better-predict-and-respond-to-marine-heatwaves >
33. Seasearch, Marine Conservation Society, viewed 15 March 2025, <https://www.seasearch.org.uk/>.
34. Sharples, J., J. Holt and S. Wakelin (2020) Impacts of climate change on shelf-sea stratification, relevant to the coastal and marine environment around the UK. *Marine Climate Change Impacts Partnership Science Review*: 103-115. <http://dx.doi.org/10.14465/2020.arc05.str>
35. State of Nature Partnership (2023) State of Nature Wales, viewed 15 March 2025, < https://stateofnature.org.uk/wp-content/uploads/2023/09/TP26053-SoN-Wales-summary-report-v10.pdff>.
36. Stieglitz, T. C. and P. Waterson (2013) Impact of Cyclone Yasi on the wreck of the SS Yongala documented by comparative multibeam bathymetry analysis. *Queensland Archaeological Research* 16: 33–43. <https://doi.org/10.25120/qar.16.2013.222>
37. Tinker, J. and E. L. Howes (2020) The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK. *Marine Climate Change Impacts Partnership Science Review*: 1-30. <https://doi.org/10.14465/2020.arc01.tem>
38. Tyler-Walters, H., H. M. Tillin, E. A.S. d'Avack, F. Perry, and T. Stamp. 2023. Marine Evidence–based Sensitivity Assessment (MarESA) - Guidance Manual. *Marine Life Information Network (MarLIN)*. Plymouth: Marine Biological Association of the UK. <https://www.marlin.ac.uk/publications>
39. UNESCO, 2001, Convention on the Protection of Underwater Cultural Heritage, viewed 14 April 2024, <https://unesdoc.unesco.org/ark:/48223/pf0000126065>.
40. Wavenet, Cefas, viewed 15 March 2025, <https://wavenet.cefas.co.uk/map>.
41. Welsh Coastal Monitoring Centre, viewed 15 March 2025, <https://www.wcmc.wales/>.
42. Welsh Government (2019) Welsh National Marine Plan <https://www.gov.wales/sites/default/files/publications/2019-11/welsh-national-marine-plan-document_0.pdf >
43. Whitehead, H. W. (2019) Lost at Sea: Utilizing Photogrammetry to monitor two submerged F8F Bearcats. University of West Florida. Unpublished MA Dissertation, University of West Florida.

44. Wolf, J., Woolf, D. and L. Bricheno (2020) Impacts of climate change on storms and waves relevant to the coastal and marine environment around the UK. MCCIP Science Review 2020, 132–157. <doi: 10.14465/2020.arc07.saw, https://nora.nerc.ac.uk/id/eprint/527112/1/07_storms_waves_2020.pdf >
45. Young, E. F. and J. T. Holt (2007) Prediction and analysis of long-term variability of temperature and salinity in the Irish Sea. *Journal of Geophysical Research: Oceans* 112.1. <https://doi.org/10.1029/2005JC003386>

Footnotes

1. Sediment Flux Models resolve the seabed sediment into particular chemical environments relating to the depth at which processes consume molecular oxygen, including dissolved sulphide and methane.
2. ‘Significant Wave Height’ is a well-defined, statistical standard to characterise waves in any sea state, whether they area created by winds or swell. It is defined as the mean wave height (tough to crest) of the highest third of waves.
3. The term ‘Wave Base’ is used to describe the depth beneath the sea surface at which a passing wave begins to agitate sediment and set sediment transport in motion.
4. When wave energy is high, such as during winter storms, sediment is drawn offshore to change the slope to the best profile which best absorbs high levels of wave energy. As a result, the slope of the beach reduces and elongates. Archaeological sites in the intertidal are often exposed by this removal of beach sediment offshore. When calmer weather prevails, most often through the summer months, sediment is brought back onto to the beach by the asymmetry in sediment transport between by waves running up and then returning in backwash. The results is that beaches rebuild to a steeper profile, with sites reburied once more.
5. The four low-cost waterproof cameras tested were as follows: Olympus Tg-6 Tough (still resolution 12 MP); GoPro Hero 9 (still resolution 20 MP); Panasonic Lumix DMC-FT30EB-D Tough (still resolution 16.1 MP); and Cannon EOS 2000D DSLR (still resolution 16MP).

Figures

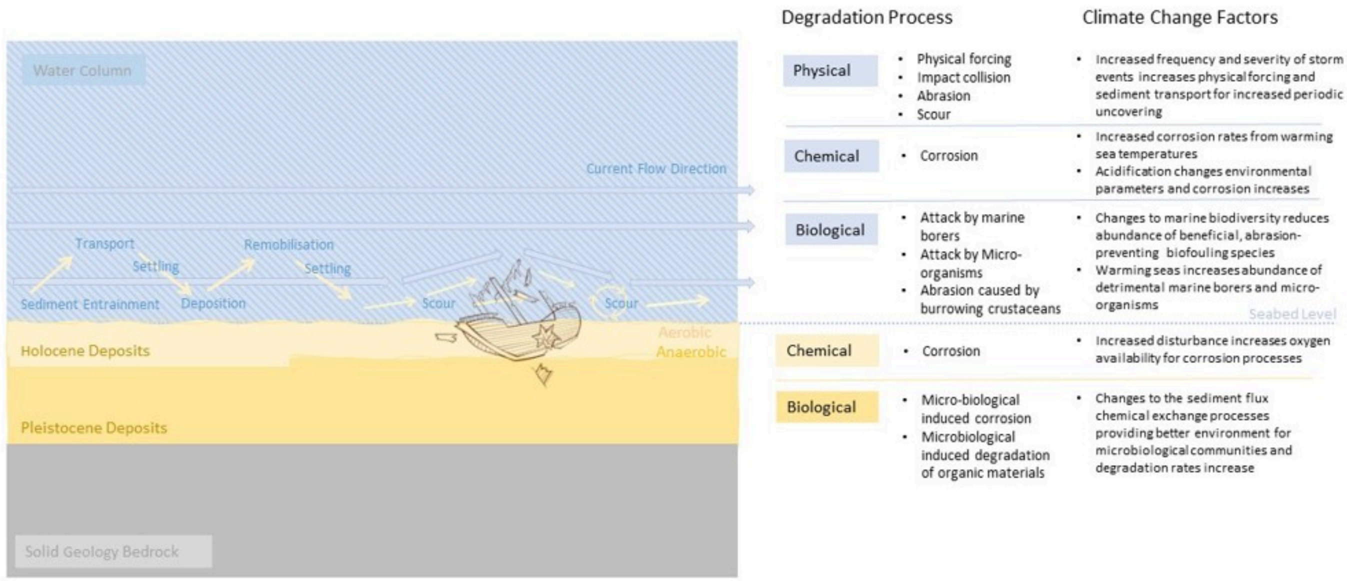

Figure 1

Processes of degradation and where they take place in relation to the water column and seabed. Illustration developed from the concept of site formation processes published in Gjelstrup Bjordal, Gregory and Trakadas 2011: 109. Copyright: Deanna Groom.

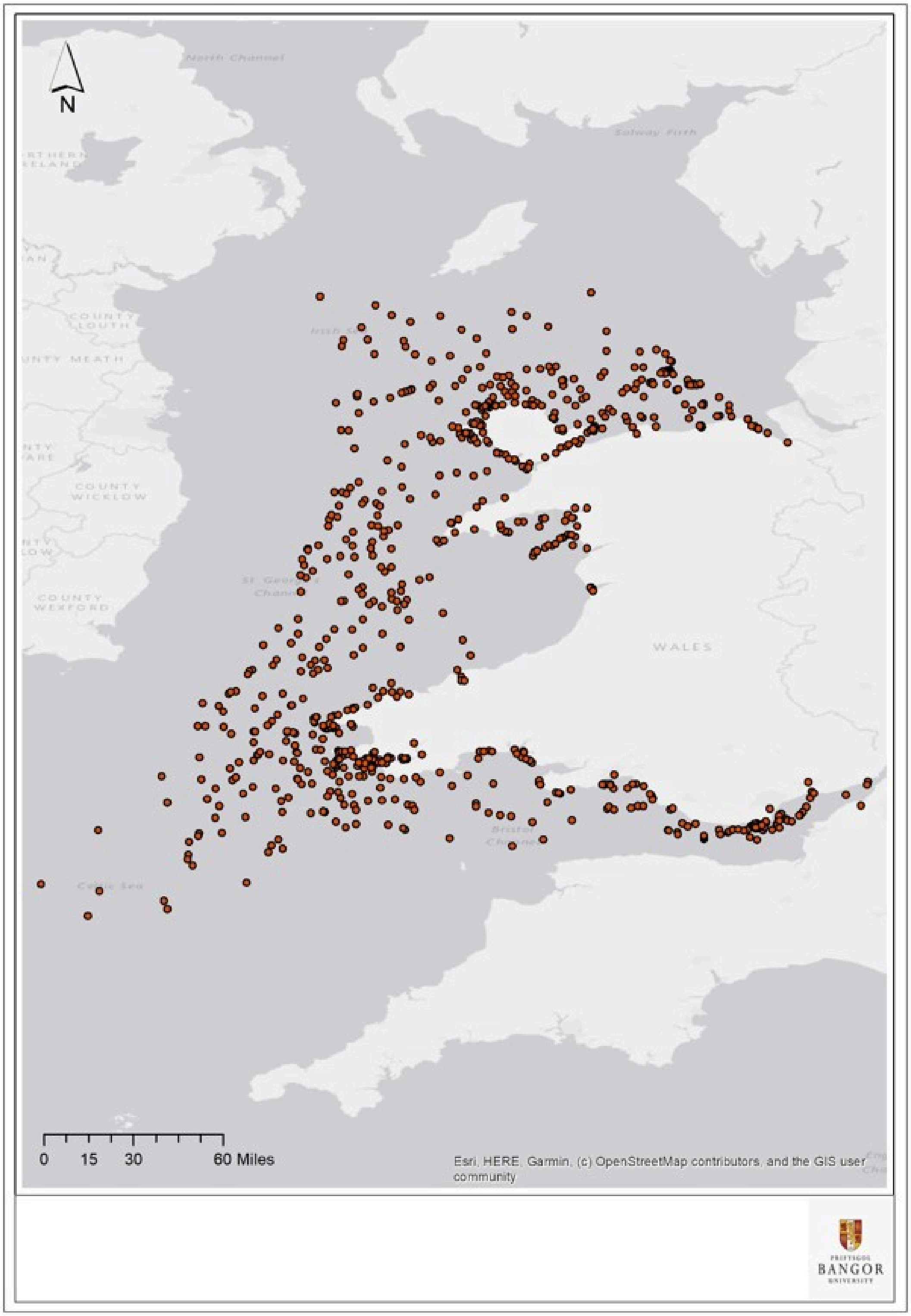

Figure 2

Study Area encompassing 32,000km^2 of seabed and 2100km of coastline as defined by the responsibility given to Welsh Government for marine planning (https://www.gov.wales/welsh-national-marine-plan). Data Copyright: CBHC/RCAHMW Open Government Licence.

Figure 3

Locations from which practitioners responded to the questionnaire. Copyright: Deanna Groom.

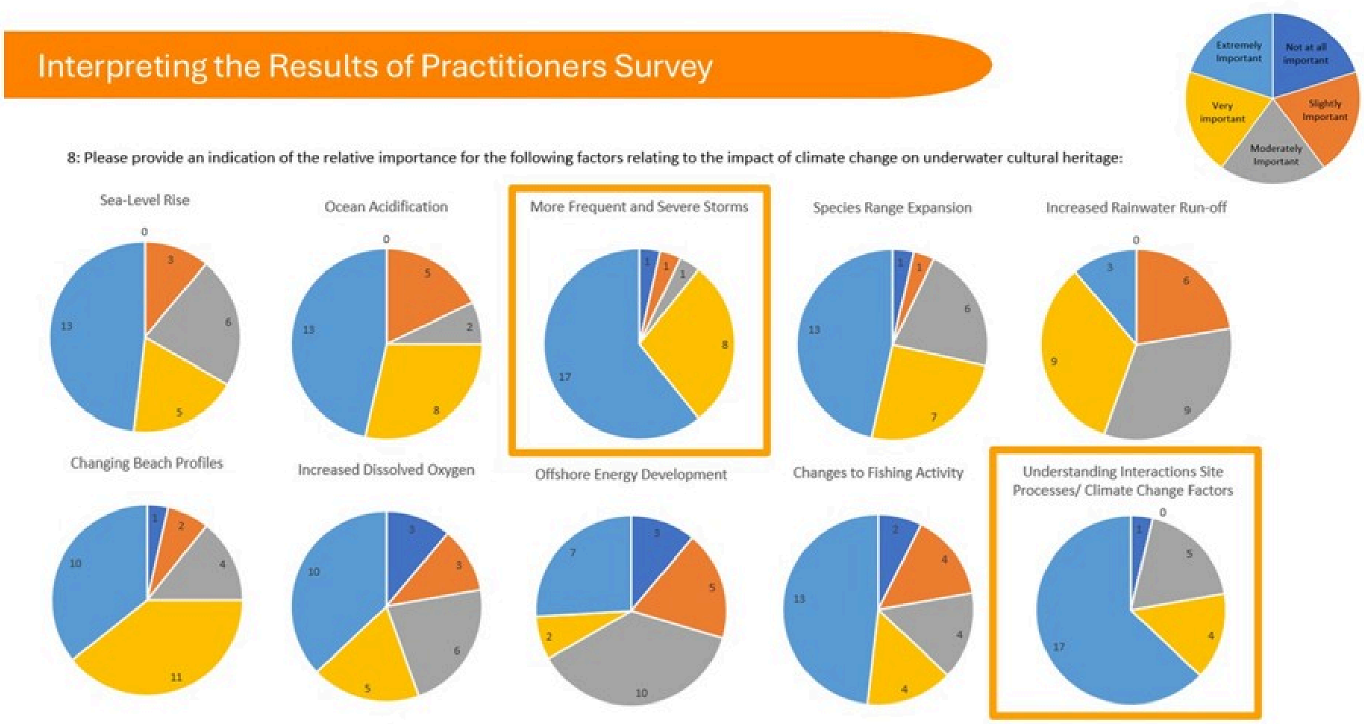

Figure 4

Analysis of responses to Question 8 of the survey. A 5-point Likert scale was used to identify the levels of agreement with statements (i.e. scale of responses ranging from ‘extremely important’ to ‘not important at all’). Copyright: Deanna Groom.

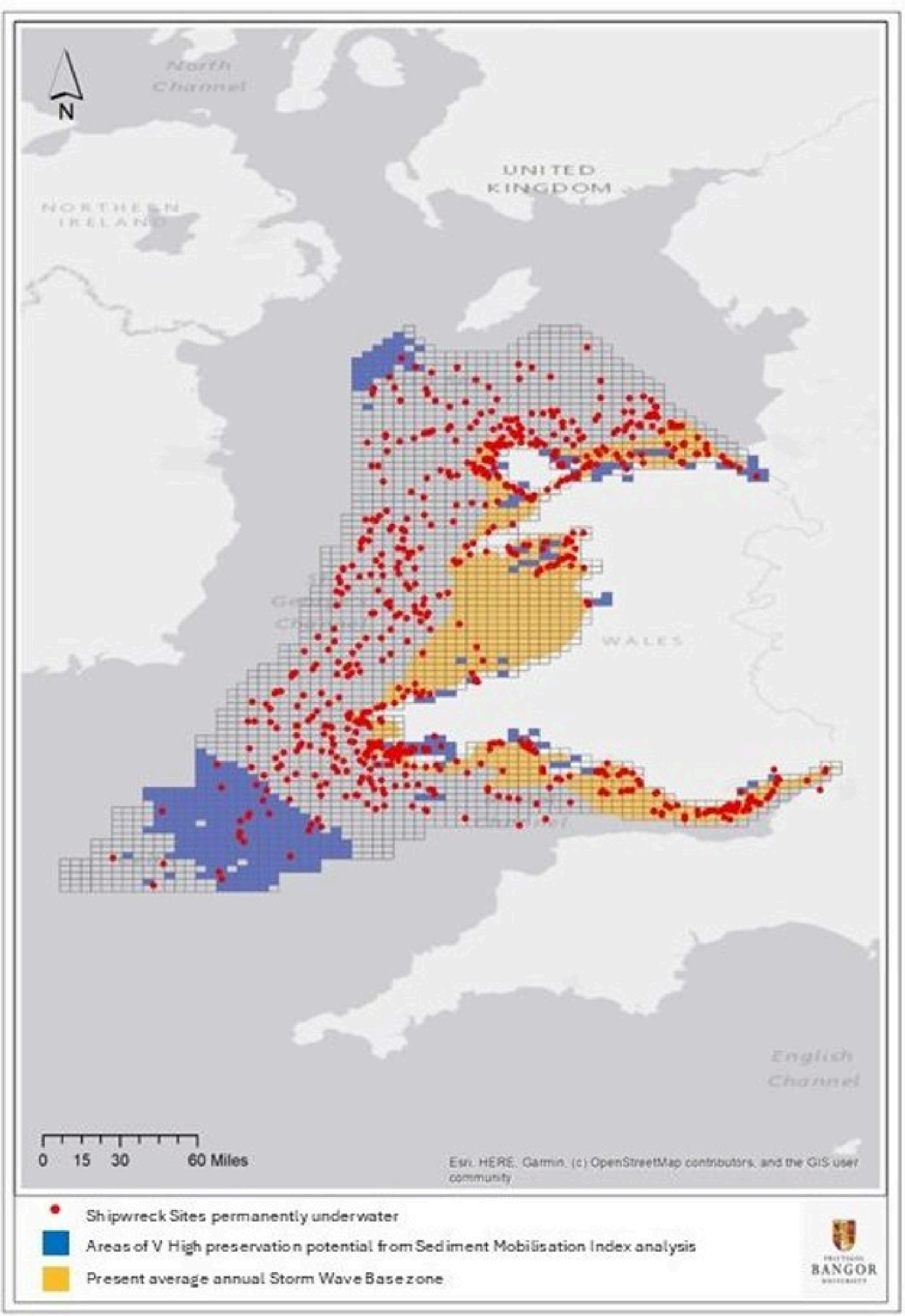

Figure 5

Data sampling grid used in combination with Sediment Mobilisation Index and polygons defining the areas of seabed most frequently set in motion during storm events (based analysis of 5th percentile of highest significant wave heights). Shipwreck Site Data Copyright: CBHC/RCAHMW Open Government Licence. Map Copyright Deanna Groom.

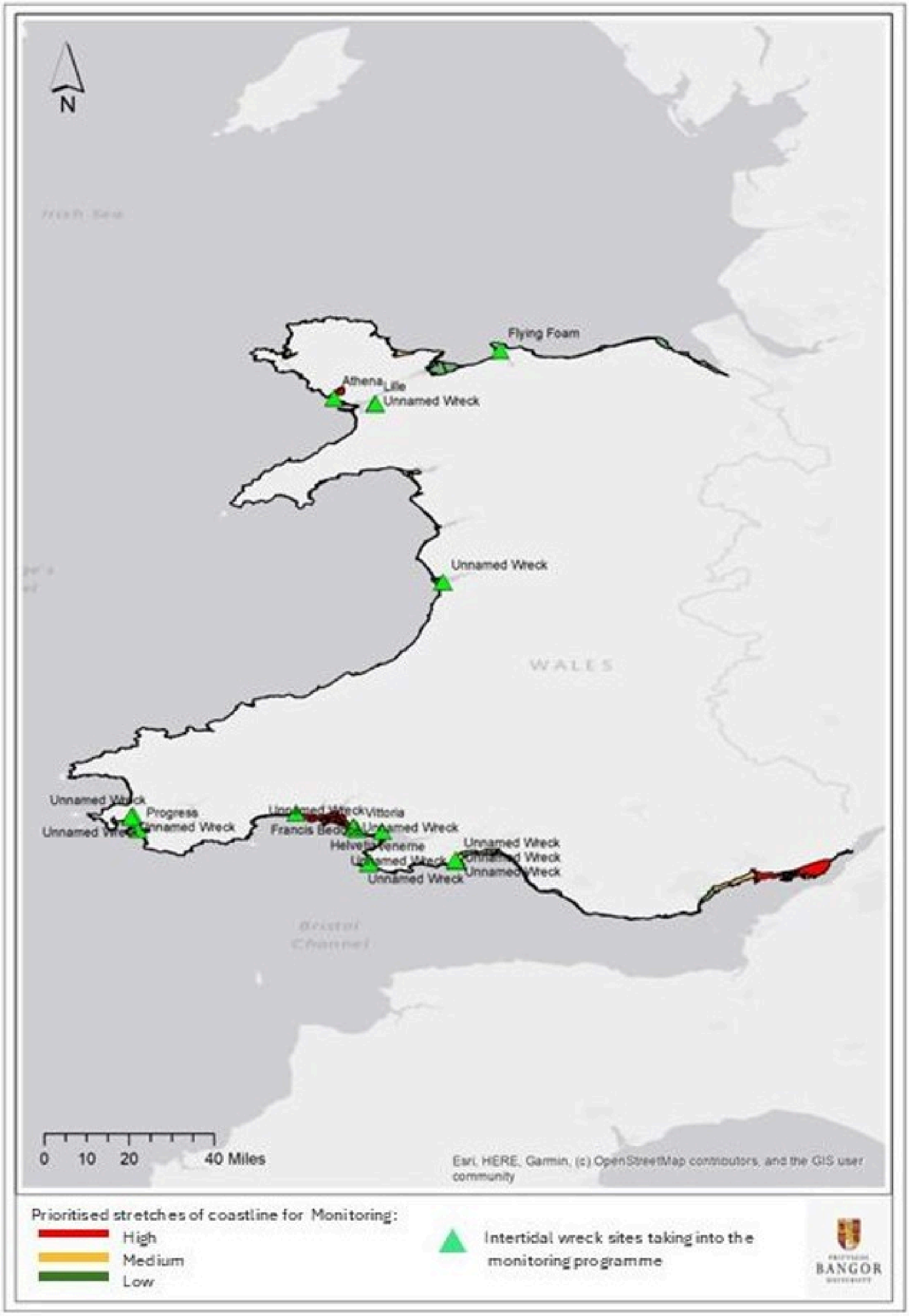

Figure 6

Coastal vulnerability analysis created a series of polygons where attributes captured information about beach conditions. The analysis helped identify where photogrammetric monitoring of sites at risk should be conducted. Shipwreck Site Data Copyright: CBHC/RCAHMW Open Government Licence. Map Copyright: Deanna Groom.

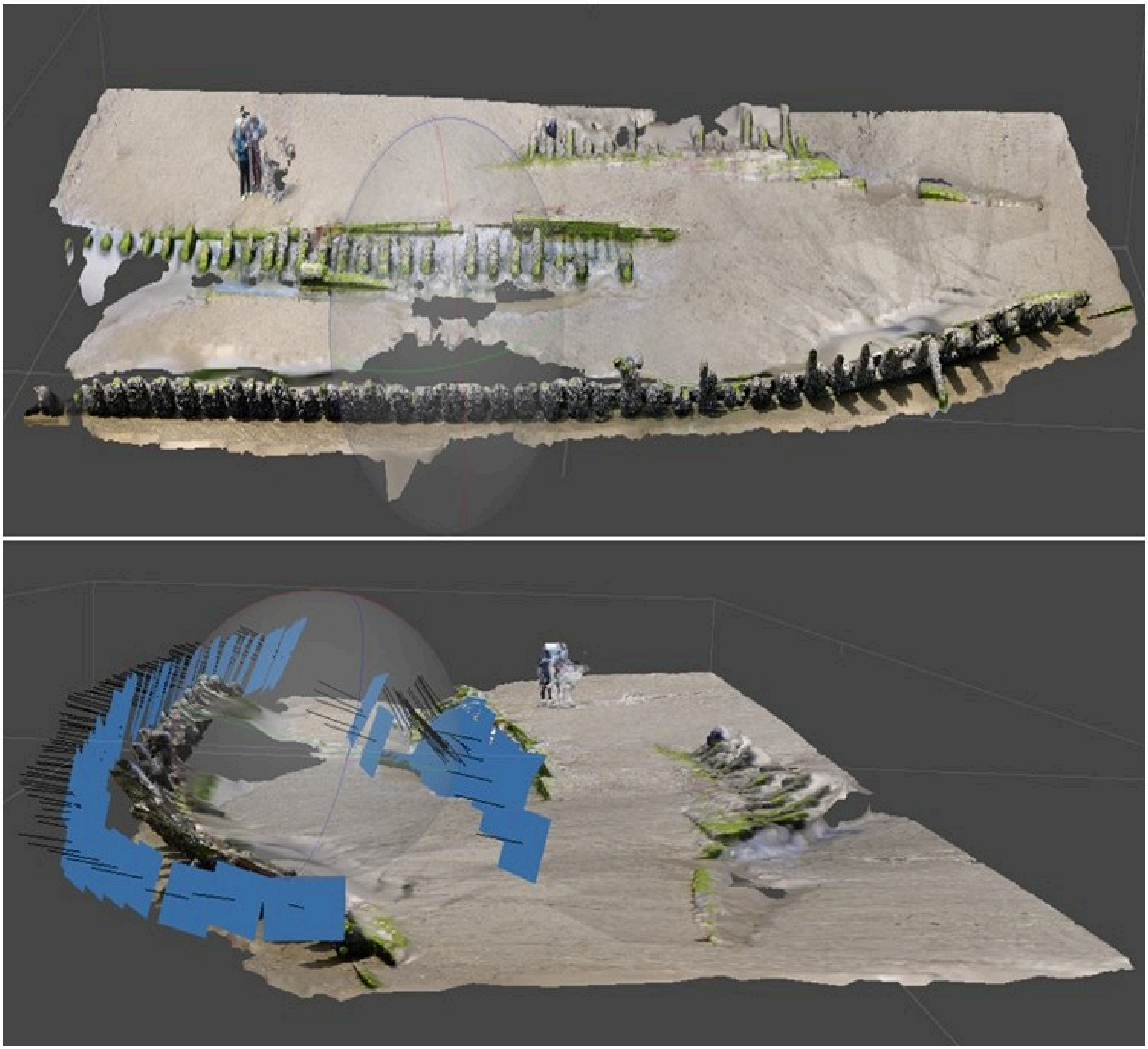

Figure 7

Above – beach walkers attracted to view a large timber wreck at Cefn Sidan, Carmarthen Bay, whilst it was being surveyed in June 2022. Below – the 'Show Cameras' function of Agisoft Metashape reveals where photographs were taken. Copyright: Deanna Groom.

Figure 8

Comparison of photogrammetry surveys undertaken after a succession of storms in March 2022 (above) and at the end of the relative calm of summer months in October 2020 (below). The upper model was generated by images captured by the Olympus Tg-6 camera. The model below from images taken by a GoPro9. The Olympus produced a crisper and more detailed 3D digital model. Copyright: Deanna Groom.

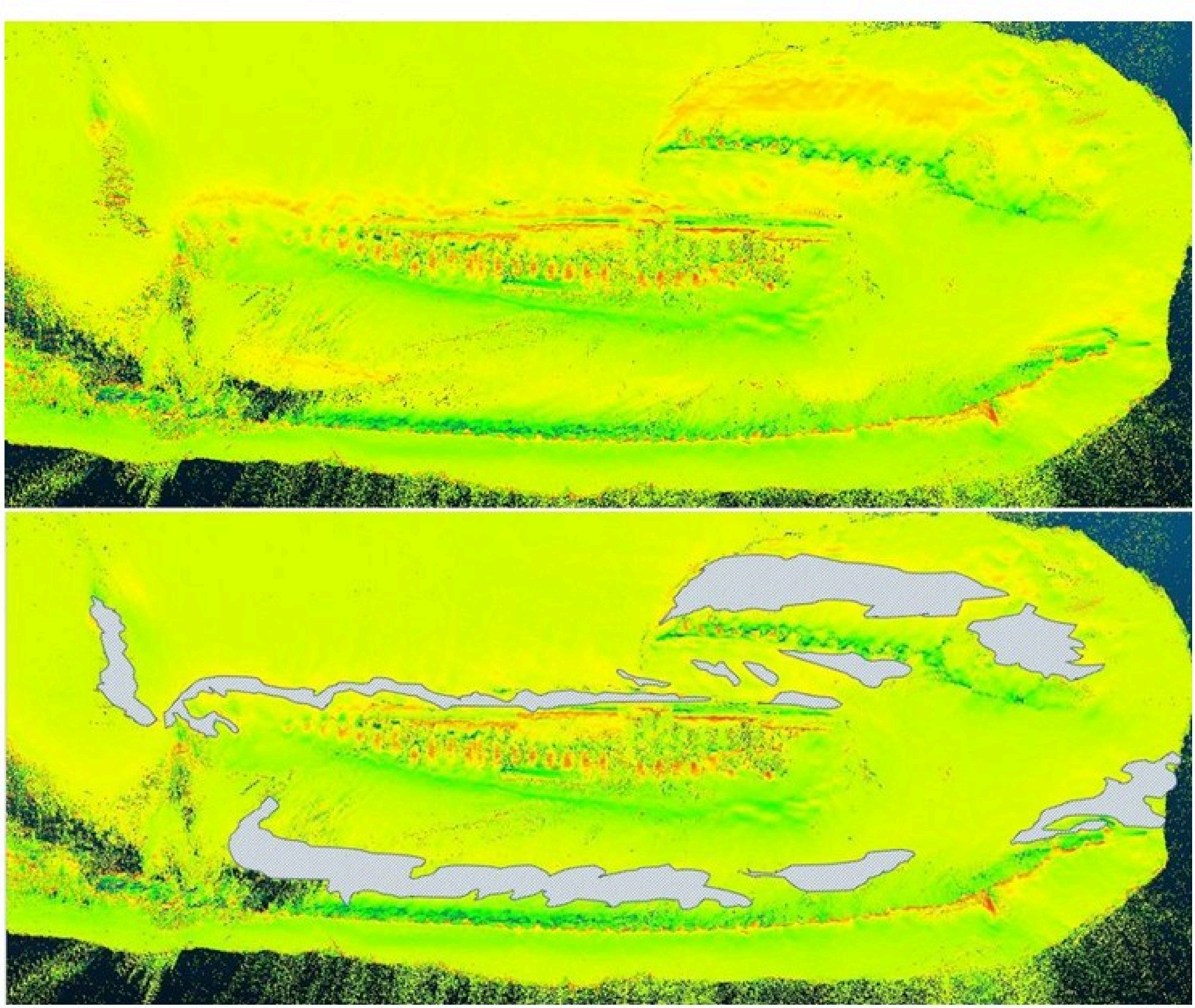

Figure 9

The point clouds created by Agisoft Metashape were brought into Cloud Compare. Alignment of the two surveys reveals sediment height differences - where erosion (green) and accretion (yellow-orange) have taken place. The areas of accretion are highlighted in grey above. Copyright: Deanna Groom.

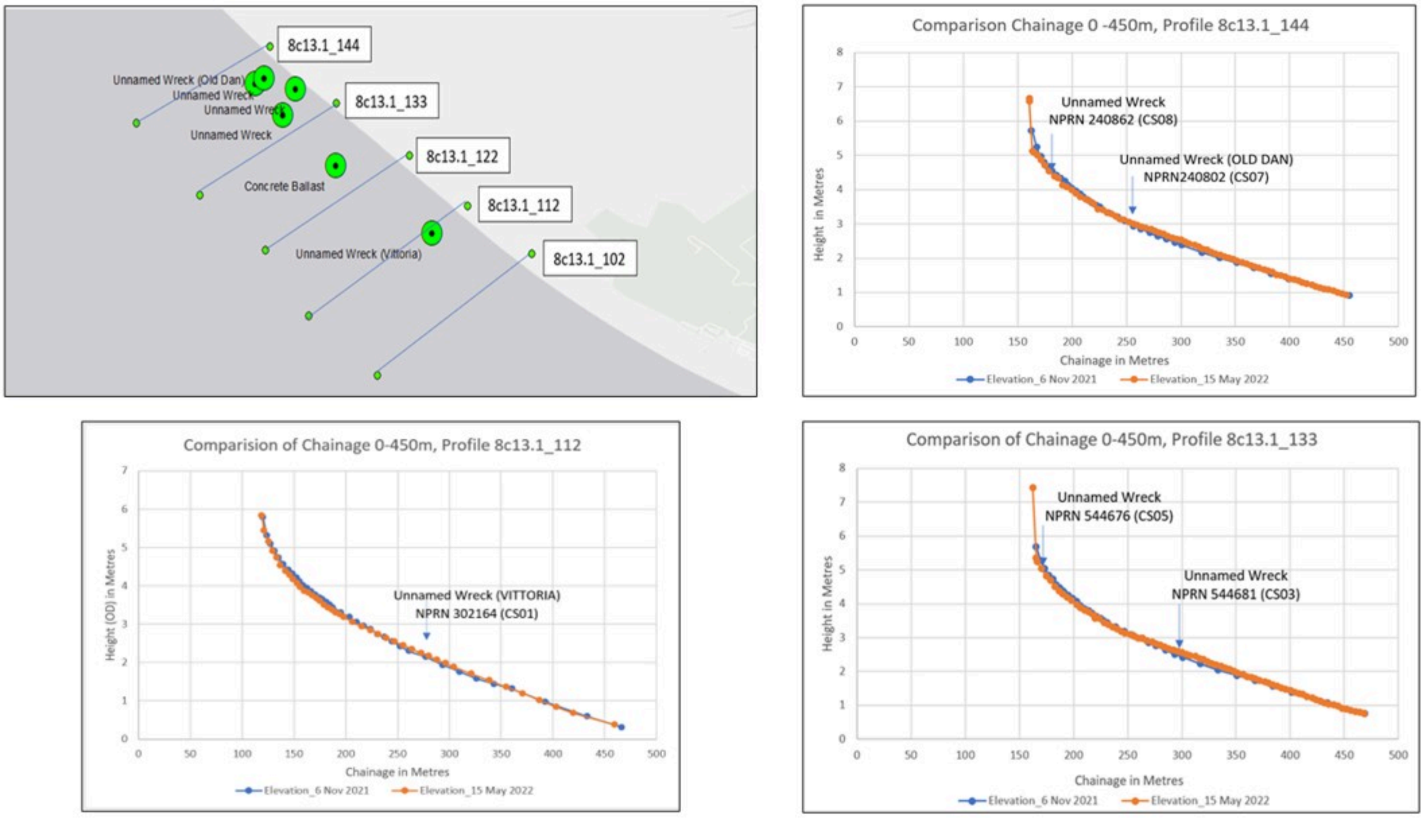

Figure 10

A national programme of beach profile gathering was able to provide data in the close vicinity to the wrecks in the foreshore of Cefn Sidan. Locating the wrecks along the profile provided confirmation that all are situated within foreshore that is draw down and rebuilds in response to differing wave climates. Data sourced from the Welsh Coastal Monitoring Centre (https://www.wcmc.wales/).

Figure 11

Distribution plots of present (2006-2025) and future (2050-2070) significant wave heights kindly supplied by National Oceanographic Centre, Liverpool, for three locations around the Welsh coast. Data Copyright: British Oceanographic Data Centre on behalf of the Natural Environment Research Council (NERC).

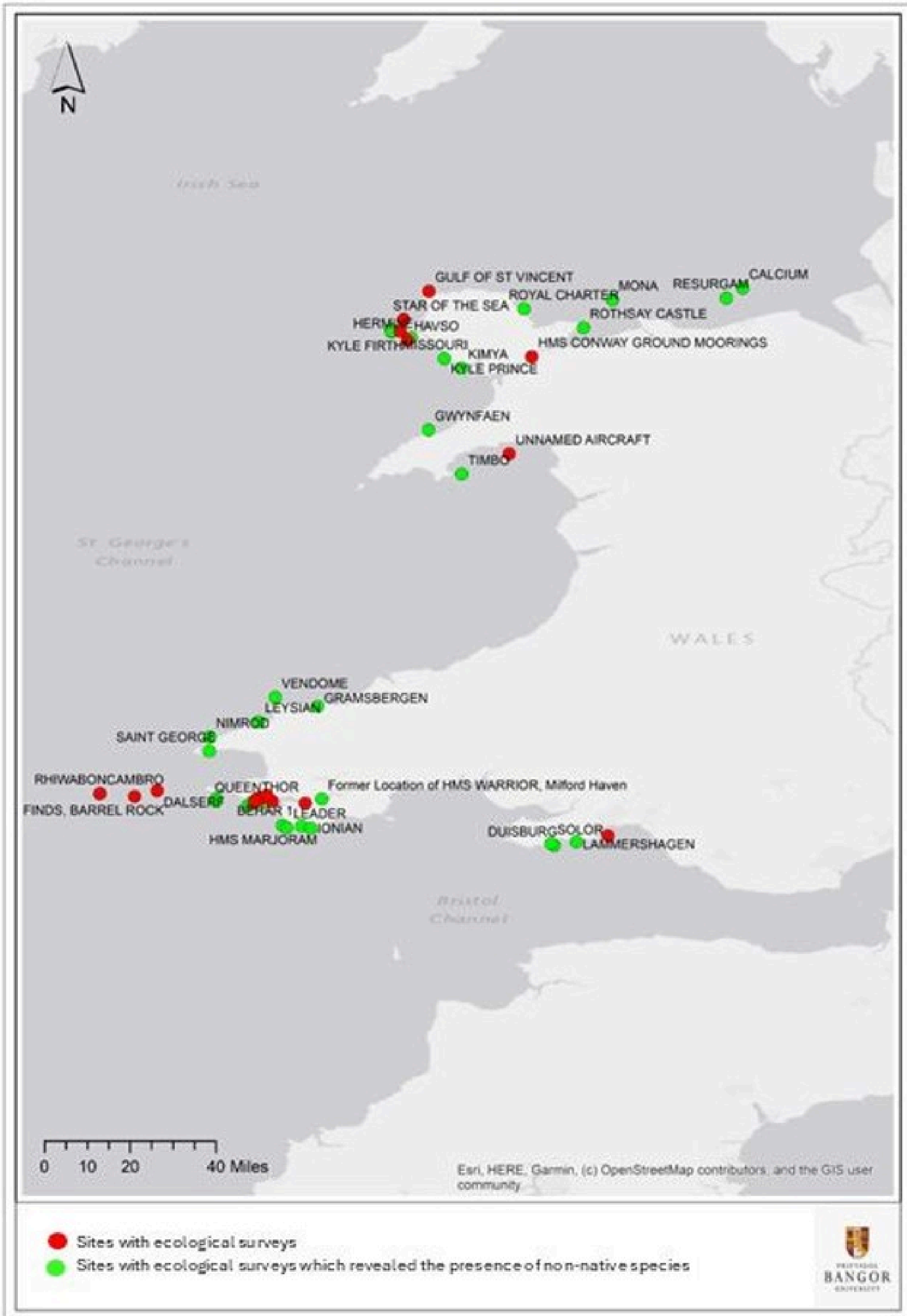

Figure 12

Wreck sites with ecological surveys in the data by the Marine Conservation Society. These include a statutorily protected wreck - the early submarine Resurgam which foundered on 24 February 1880 off the northeast coast of Wales. Data Copyright: CBHC/RCAHMW Open Government Licence and the Marine Conservation Society.