ORIGINAL PAPER

Residual relief modelling: digital elevation enhancement for shipwreck site characterisation

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Abstract

Scour processes play a critical role in the preservation status of submerged historic shipwrecks. Erosion of sediment leads to enhanced exposure of archaeological sites to physical, chemical and biological processes. Current methods for identifying erosional and depositional features at wreck sites are based primarily on visual interpretation of data, which is labour-intensive and entirely subjective. The increasing availability of high-resolution multibeam echosounder–derived digital elevation models (DEMs) of historic wreck sites allows for an entirely new level of detailed interrogation and analyses of the geomorphological features associated with these. In this study, we present a residual relief modelling method for the semi-automated extraction of such depositional and erosional features at wreck sites. Relief modelling is supplemented with a breakpoint classification approach, with final separation supported by DEM visualisation enhancement techniques. We applied the method to three World War I shipwreck sites and evaluated it against traditional manual vectorisation techniques. The results suggest that the semi-automated modelling method is robust, time-effective and capable of quantifying the products of scour processes with increased objectivity. Our method holds great potential for the objective characterisation of erosional and depositional patterns and processes at wreck sites, which have important implications for site formation studies and in situ preservation of underwater cultural heritage.

Keywords Shipwreck archaeology · Scour · Residual relief modelling · Site formation processes · Bathymetry · GIS

Introduction

The UNESCO Convention on the Protection of the Underwater Cultural Heritage states that in situ preservation of sites should be the first option (UNESCO 2002). In response, recent research has concentrated on better understanding and quantifying natural and anthropogenic forces affecting preservation and degradation of submerged sites commonly referred to as site formation processes (Quinn et al. 2007;

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Ruuskanen et al. 2015; Bethencourt et al. 2018; Fernández-Montblanc et al. 2016; Fernández-Montblanc et al. 2018a, 2018b). Among them, linked hydrodynamic and sediment dynamic processes are understood to control other natural formation processes such as biological encrustation and chemical corrosion (Ward et al. 1999).

One of the key morphodynamic processes that dominate wreck site formation is seabed scour, which occurs when a shipwreck placed on the seabed perturbs the local hydrodynamic regime (Quinn 2006), resulting in complex erosional and depositional patterns commonly described as scour or wreck marks. These features act as indicators of local net sediment transport and provide valuable information about the magnitude and direction of ocean currents (Caston 1979; Quinn 2006; Garlan et al. 2015). In seabed engineering, scour development around submerged bridge and windfarm piles is recognised as highly detrimental to structural stability and often requires special mitigation measures (e.g. Sumer 2007). Similarly, scour processes at shipwreck sites can lead to burial and/or exposure, accelerating wreck disintegration, and in extreme cases, it can cause the complete collapse and

loss of structures (Quinn 2006). Furthermore, the pace of a shipwreck's physical degradation close to scour pits may be enhanced by hydro-abrasive action, as these areas are subject to increased water turbulence and shear stress (Smyth and Quinn 2014; Quinn and Smyth 2018). Erosional scour pits may also be filled with archaeological artefacts from a disintegrating wreck (Quinn et al. 1997), thus acting as depositional zones for archaeological material. Therefore, in order to fully assess the preservation state of wreck sites, and to inform in situ preservation, it is essential to map and quantify scour marks.

Previous studies investigated how shipwreck-related scour develop and progress, based on difference modelling of time-lapse bathymetric surveys (Quinn and Boland 2010; Bates et al. 2011; Astley 2016) and computational fluid dynamic (CFD) simulations (Smyth and Quinn 2014; Quinn and Smyth 2018; Fernández-Montblanc et al. 2018b). Nevertheless, no objective method has been developed for the detection and extraction of scour marks at wreck sites. In order to delineate these features, they need to be separated from the background geomorphology, enabling objective quantification of scour area, depth, shape, volume and other morphometric characteristics (Garlan et al. 2015; Melling 2015).

An ideal way to identify scour signatures around wrecks would be to compare two bathymetric datasets: one collected before the wrecking incident (over an undisturbed seabed) and one after it (with scour fully developed). However, as no original high-resolution bathymetric datasets are available for historic wreck sites, a proxy for the pre-disturbed seabed can be reconstructed to a very limited extent using GIS methods (e.g. Garlan et al. 2015; Astley 2016). Nevertheless, such reconstructions do not provide accurate solutions for the delineation of wreck marks, which exhibit complex patterns of erosion and deposition on the seabed (e.g. Caston 1979). Currently, the only available method for mapping a shipwreck site's geomorphology is the visual interpretation of bathymetric data accompanied by labour-intensive vectorisation. This traditional approach to the problem is highly subjective and time-consuming.

Digital elevation models (DEMs) derived from remotely sensed data portray geomorphological features at different length-scales. Fine-scale features or forms are usually superimposed onto broad-scale forms. Therefore, the problem of the separation and classification of local features characterised by various length-scales is present in multiple applications of DEM data, and numerous mapping solutions have been proposed to solve this issue. Guisan et al. (1999) and Weiss (2001) proposed the Topographic Position Index (TPI), which employs methods of classifying landform types for ecological predictions. The TPI method was subsequently adjusted for seabed applications and evolved into the Bathymetric Position Index (BPI) (Walbridge et al. 2018),

which is mainly used for the classification of benthic environments. An alternative approach is to use high-pass filtering techniques to remove regional landscape features from DEMs, leaving local, fine-scale morphology termed 'residual relief' (Wessel 1998, 2016; Hiller and Smith 2008). Hesse (2010) proposed an analogous 'local relief' technique for terrestrial archaeological prospection. Smith and Clark (2005) investigated the application of DEM visualisation methods for the mapping of local landform features. However, none of the aforementioned methods has been tested or adapted to map scour-related wreck marks.

In this paper, we present a new method to objectively extract and classify erosional and depositional features from high-definition DEMs derived from multibeam echosounder (MBES) surveys using a combination of fine-scale feature delineation methods. A residual relief modelling (RRM) technique comprising high-pass filtering, a conditional classification tool and DEM visualisation techniques is used to isolate scour signatures from regional geomorphology. The methodology is tested on three World War 1 shipwreck sites, and manual vectorisation is used to compare the results. This method will significantly improve in situ preservation planning of shipwreck sites with respect to dominant physical site formation processes. This issue of local morphological feature extraction is not only relevant in underwater archaeology but also has important applications in offshore engineering (e.g. Melling 2015). We believe that this study will add to the existing knowledge on the use of high-resolution MBES data for such applications and presents a step towards automated seabed morphology extraction and characterisation.

Materials and methods

Study area

The three World War 1 shipwrecks used in this study are located in the Irish Sea; two off Dublin and one off Belfast (Fig. 1). The steam collier *SS Polwell* was sunk by the German submarine *U-96* on 5 June 1918 (Brady et al. 2012). The 93-m long wreck is located at a depth of 30 to 36 m, 20 km northeast of Dublin. On 14 December 1917, *SS Hare* was torpedoed by the German *U-62* (Brady et al. 2012) 22 km east of Dublin. The 54-m passenger/cargo ship now rests in 53 to 60 m of water. The merchant vessel *SS Tiberia* was torpedoed on 26 February 1918, probably by the German *U-19* (Wilson 1979). The 125-m long wreck is located in 48 to 63 m of water at the northern entrance to Belfast Lough.

All three wrecks lie on non-cohesive sandy sediments (Brady et al. 2012; Bond 2014). Considering the depths of the shipwrecks and their location in the western part of the semi-enclosed Irish Sea, the wave influence at the sites is minimal, and processes acting on the sites are dominated by
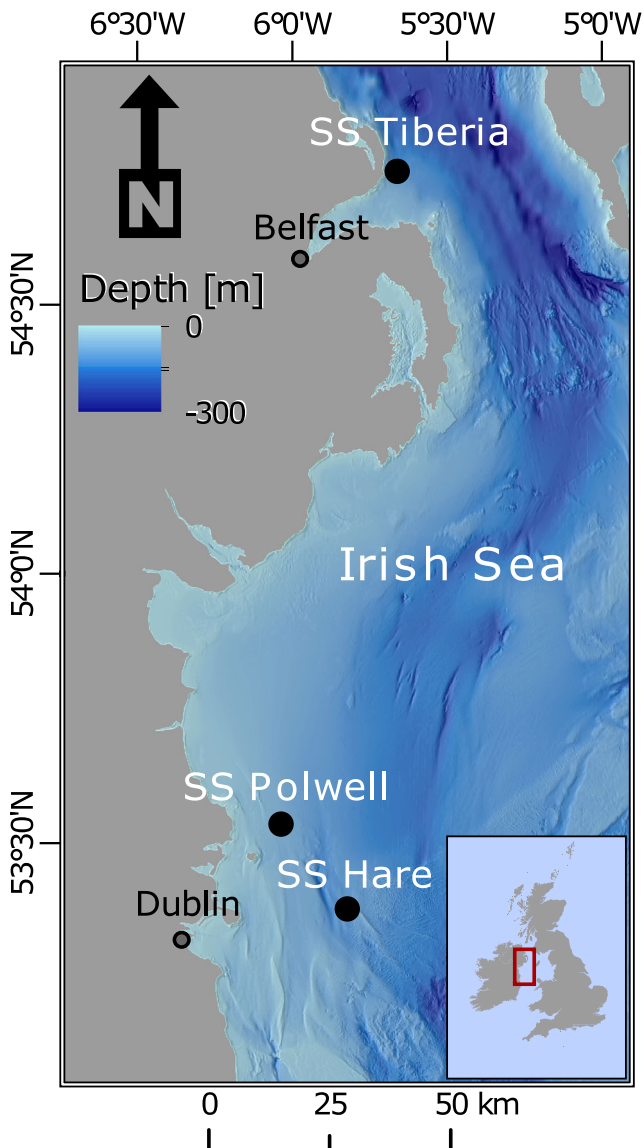
Fig. 1 Locations of the sites chosen for the study in the Irish Sea (backdrop bathymetry obtained from EMODnet Bathymetry Consortium 2018)

bi-directional tidal currents. Around *SS Tiberia*, depth-averaged tidal currents reach up to 0.5 m/s during spring tides (Atkins 1997). In the more open Irish Sea, *SS Polwell* and *SS Hare* are influenced by stronger currents, with velocities up to 1.0 m/s (Howarth 2001).

Bathymetric data from shipwreck sites

MBES surveys over the three shipwreck sites were conducted between 4 and 10 September 2016 onboard *RV Celtic Voyager* using a Kongsberg dual-head EM2040 operating at 400 kHz. Position fixing was provided by an Integrated GNSS/L-Band receiver CNAV 3050 (horizontal/vertical accuracies of ± 5 cm/10 cm). Motion referencing, secondary positioning, and accurate timing

were provided by a Seatex Seapath 330+. Water column sound velocity control used a Valeport Midas SVP and a real-time AML surface sound velocity sensor. Data were logged onboard using the Kongsberg's Seafloor Information System (SIS) v. 3.8.3 acquisition software. Raw and processed data are currently archived at the Marine Institute of Ireland under the Integrated Mapping for the Sustainable Development of Ireland's Marine Resource (INFOMAR) programme. DEMs of the wreck sites were derived from tidally corrected and cleaned MBES data at 0.5-m resolution using Caris HIPS and SIPS v. 8.1.
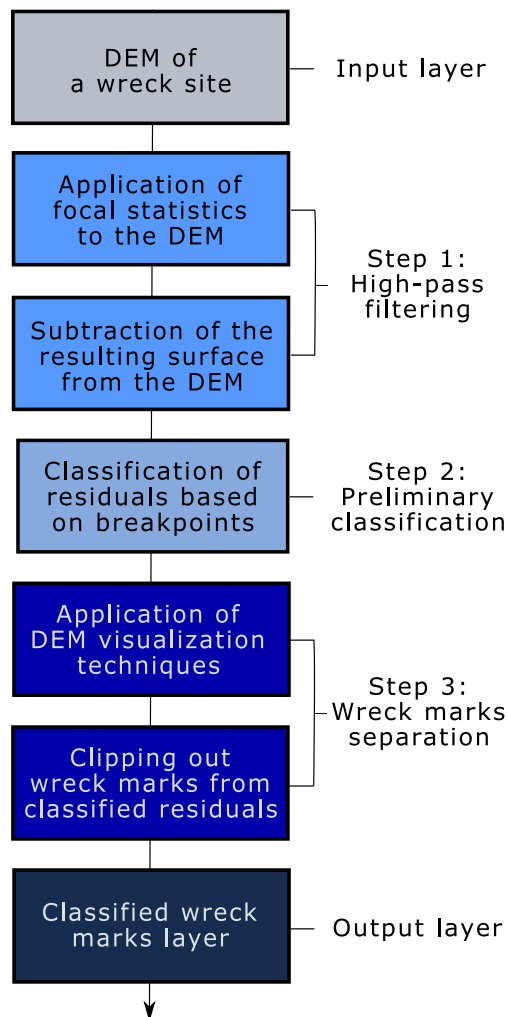
Objective separation of erosional and depositional wreck marks

The RRM method employed for the objective separation of scour marks was designed and performed using ESRI ArcMap v. 10.6.1 and consists of three steps (Fig. 2): (1) application of a high-pass filter on the DEM data, (2) preliminary classification of a local, residual morphology on the resulting layer and (3) a final separation of scour-related wreck marks with the support of DEM visualisation techniques. A detailed, step-by-step GIS workflow is given in the Online Resource. To compare and test the method, the wreck marks were also separated manually.

High-pass filtering of the DEM

Focal statistics were calculated for each DEM, with the resultant raster values representing a function of the input cell within a specified neighbourhood around it. In this study, a moving mean function was used, calculated for a circular kernel or window for all the DEMs. The radius of the kernel was based on a visual estimation of the length-scales (i.e. widths) of the scour marks. The general rule is that the moving kernel needs to be wide enough to capture more cells from the outside of a scour mark than from the inside. The radii defined in this study were 50 m for *SS Tiberia*, 100 m for *SS Polwell* and 200 m for *SS Hare*.

Application of the focal function can be termed as low-pass filtering, as it smooths local morphology, leaving only regional characteristics (Wessel 1998). A high-pass filter, on the other hand, extracts local, residual morphology, with positive and negative cells respectively representing areas which are higher or lower than the average (regional) height of the surrounding seabed. The high-pass filtered layer (HP) was obtained by a subtraction of the focal mean raster (low-pass filtered data, LP) from the original DEM (1), hence measuring the difference between a central cell and the mean elevation in

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┌─────────────────────┐
│      DEM of         │ ── Input layer
│    a wreck site     │
└─────────────────────┘
          │
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│   Application of    │ ┐
│   focal statistics  │ │
│     to the DEM      │ │
└─────────────────────┘ │  Step 1:
          │             │  High-pass
┌─────────────────────┐ │  filtering
│  Subtraction of the │ │
│  resulting surface  │ │
│    from the DEM     │ ┘
└─────────────────────┘
          │
┌─────────────────────┐
│  Classification of  │ ── Step 2:
│  residuals based    │    Preliminary
│   on breakpoints    │    classification
└─────────────────────┘
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┌─────────────────────┐
│   Application of    │ ┐
│  DEM visualization  │ │
│     techniques      │ │  Step 3:
└─────────────────────┘ │  Wreck marks
          │             │  separation
┌─────────────────────┐ │
│   Clipping out      │ │
│  wreck marks from   │ │
│ classified residuals│ ┘
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│  Classified wreck   │ ── Output layer
│    marks layer      │
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Fig. 2 Schematic representation of the workflow for the proposed RRM method

the kernel (Wilson and Gallant 2000):

$$HP = DEM-LP \qquad (1)$$

High-pass–filtered data is scale-dependant, i.e. when the kernel size increases, so does the range of values. Therefore, to establish a robust classification tool for residual reliefs, which can be applied for sites with various geomorphological settings, the resulting HP layers need to be normalised. This standardisation was performed by the subtraction of the layer's global mean and dividing it by its standard deviation (std) (2).

$$HP_{stdd} = (HP-mean)/std \qquad (2)$$

By standardising the layer, the resulting raster's standard deviation has a value approximating 1 and a mean value of 0. This process should be performed only if the original HP layer's global mean is also reasonably close to zero. This standardisation is an inherent step for methodologies dealing with datasets containing multiple variables such as for principal component analysis (PCA) or neural networks. It is also used in

the TPI (Weiss 2001) and BPI (Walbridge et al. 2018) workflows, where different kernel sizes are used to separate both broad-scale and fine-scale morphology. However, in the latter two methods, the values are converted to integers. In the case of the detection of wreck marks with submetric variations in sizes, centimetric accuracy is required. Therefore, in the RRM technique proposed here, the numbers are always stored as floating-point type, thus preserving decimals. After the standardisation of values representing residual reliefs, their classification using breakpoint values was performed.

Preliminary classification of residuals

The standard score values derived from the HP layer were classified into three groups of residuals: positive (class 1), negative (class 2) and highly positive (class 3). Positive and negative classes consisted of cell values which were higher or lower than + 0.5 and − 0.5 standard deviations respectively, and were designed to store values corresponding to depositional and erosional wreck marks. A highly positive class (more than 5 standard deviations) separates the actual wreck structure from the DEM. The remaining values (between − 0.5 std and + 0.5 std) are defined as a featureless seabed (class 0). At this stage, the residuals were classified in such a way that significant deviations in local bathymetry were captured into classes. In the final step, the wreck marks were separated from classified residuals which were more likely to represent natural morphological features.

Separating wreck marks with support of DEM visualisation techniques

The preliminary classification of residuals separated the local morphology from its regional background. An additional step involving the application of visualisation techniques on the original bathymetric DEMs was designed to distinguish wreck marks from other local geomorphic features. The traditional shaded relief technique tends to introduce directional bias (Smith and Clark 2005). Therefore, in this study, a multidirectional hillshade function was applied to the original DEM using multiple illumination angles. With transparency set to 50%, it was used as an occluding layer for the original DEM with an increased contrast. As scour features are associated with flow regimes affected by the presence of a wreck, they often exhibit directional characteristics, especially in the far-field. Closer to a wreck (i.e. in the near-field), scour marks are usually associated with steep slopes (Quinn 2006). Such characteristics can be exposed by calculating bathymetric derivatives like aspect and slope to distinguish the scour marks from other residuals. Here, the aspect function was used to show the direction of slope, which was also calculated with a 3 × 3 pixel rectangular window to differentiate areas with steep slopes. Additionally, Sobel horizontal and vertical edge detection

filters were applied on the DEMs to emphasise edges in both horizontal and vertical directions. Finally, a focal standard deviation filter was applied as another measure to expose areas with significant changes in values. With the given resolution of the DEMs, the filtering window for focal standard deviations was circular with a 2-m radius to expose local variations in relief (Wilson and Gallant 2000).

All these techniques support the final classification step. Areas assigned as either positive or negative residuals, which were not related to the presence of a shipwreck but were assigned by a breakpoint classifier, were manually clipped. The filters were designed to increase objectivity of this step, by visually exposing morphological characteristics of the seabed surrounding a shipwreck. The wreck marks were assumed to possess at least one of the following essential attributes during the final separation (Quinn 2006):

- Continuity from the area in proximity to the wreck structure
- Steep slopes in proximity to the wreck structure
- Distribution along some predominant direction associated with the bottom current regime
- Heights/depths decreasing with distance from the shipwreck

Residuals extending away from a wreck were separated up to the point where the amplitude difference with the surrounding seabed was less than 10 cm, as this was within the vertical positioning error of the survey platform.

Manual vectorisation of wreck marks as a validation method

In an attempt to validate the RRM, the extent of the wreck marks on the DEMs were picked manually and vectorised as polygons by visual examination and 3D bathymetric profiling. The assumptions guiding the fully manual separation were the same as those used for the final extraction using DEM visualisation techniques in the RRM method.

The vectorised polygons were divided into two classes corresponding to positive (depositional) and negative (erosional) wreck marks. Areas and extents of the wreck marks picked by the RRM and manual vectorisation methods were then compared. The effectiveness of the residual relief method was examined, focusing on areas where wreck marks were classified by their presence or absence.

Results

Digital elevation models

DEMs of the three wreck sites are presented in Fig. 3. These were chosen because they each have a different background geomorphology, allowing the methodology to be tested on different regional settings. On the SS Polwell site, a pipeline to the north of the shipwreck (Fig. 3a) intersects the extensive longitudinal erosional and depositional wreck marks. Ridge-shaped features of a similar length-scale as the scour marks are present to the south of the wreck structure. SS Tiberia (Fig. 3b) rests on a sloping seabed, which deepens to the east. Two distinct scour pits are imaged around the wreck, with more subtle far-field depositional and erosional marks to the north and south. SS Hare lies semi-buried within a deep and extensive scour pit, with dunes developed across the entire site (Fig. 3c). The regional bathymetry deepens to the south, with the trend being disrupted by the scour pit.

Residual relief modelling

The results of the residual relief modelling are shown in Fig. 4. On the SS Polwell site, the relief modelling distinguishes extensive, longitudinal positive and negative relief features clearly related to the presence of the wreck (Fig. 4c). On a preliminarily classified layer (Fig. 4b), the amount of positive and negative residuals is significantly higher than on the final output layer obtained after the final separation (Fig. 4c), as many of the local morphological features are of the same scale as the wreck marks and needed to be removed during the third step. This operation was supported by visual examination of the enhanced contrast DEM, occluded with the multidirectional hillshade and the Sobel vertical functions (Fig. 5a, d). Both visualisation techniques allowed for the clear distinction of the longitudinal far-field scour mark boundaries, which were less clear on the original DEM. The wreck marks extend beyond the pipeline to the north of the site (Fig. 3a), which in turn gives rise to its own depositional marks (Fig. 4c). The high-pass filtering step identified negative reliefs near the pipeline, which were removed during the final separation, after being interpreted as natural bathymetric variation rather than effects of the seabed scour (Fig. 4b, c). The scour marks caused by the shipwreck extend 1200 m north/north-west of the wreck and 300–400 m to the south, with areas of 64,392 m^2 for the depositional marks and 12,4681 m^2 for the erosional marks (Table 1).

On the SS Tiberia site (Fig. 4d), the more homogenous local morphology surrounding the wreck results in fewer residuals unrelated to scouring (Fig. 4e). During the third step of the relief modelling, the aspect function was used to support the final separation based on the variable directivity of the steepest sides of the scour marks (Fig. 5c). Additionally, the focal standard deviation function, highlighting local variations in values, exposed the boundaries of the main near-field pits and the marks extending to the far-field (Fig. 5f). The separated
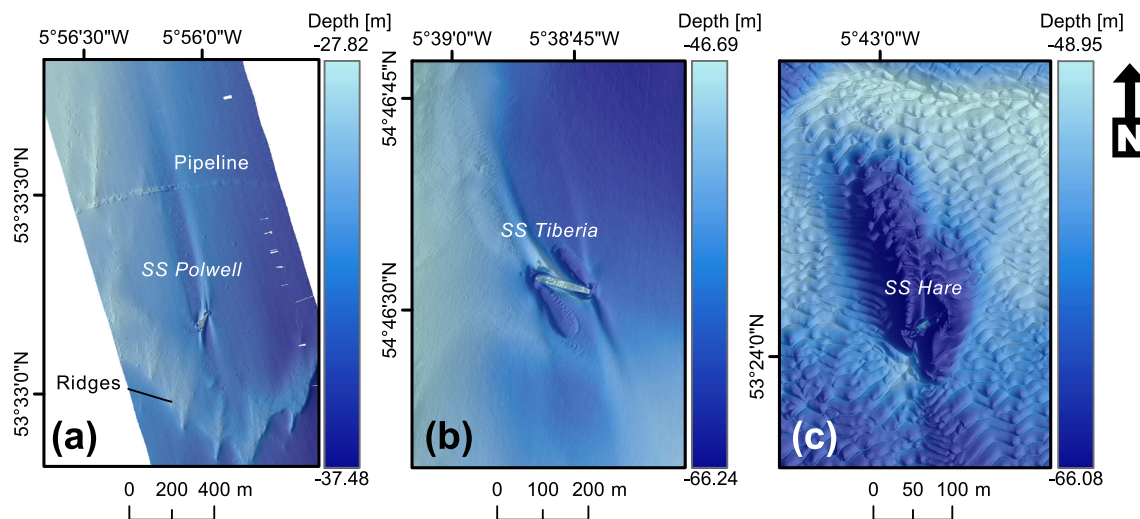
Fig. 3 DEMs representing (a) SS Polwell, (b) SS Tiberia and (c) SS Hare sites. The rasters were occluded with a hillshade layer set to 70% transparency

wreck marks on the RRM output layer (Fig. 4f) show nice symmetry, reaching lengths of 250 m to the southeast and 270 m to the north-west of the wreck. The depositional and erosional marks have similar areas of 29,115 m² and 27,094 m² respectively (Table 1).

Only negative residuals were picked by the relief modelling on the SS Hare site, delineating the scour pit observable on the high-pass filtered layer (Fig. 4g). A positive relief surrounding the pit was initially captured with the breakpoint classification (Fig. 4h); however, it was clipped out during the last step of the modelling, as this is clearly not associated with scouring. Slope function exposed the extent of the pit, which has steep sides, especially in proximity to the shipwreck (Fig. 5b). Sobel horizontal filtering significantly enhanced the visibility of the dunes imaged on the site (Fig. 5e). The separated erosional residual encompassing the pit (Fig. 4i) has an area of 32,535 m² (Table 1).

The highly positive residuals were classified successfully as shipwrecks on the SS Polwell (Fig. 4c) and SS Tiberia (Fig. 4f) sites. The wreck structure of SS Hare was not separated successfully, as it was masked by the length-scale of the extensive scour pit. Only a small part of the wreck structure was initially classified as a positive residual after the high-pass filtering (Fig. 4h).

Manual vectorisation of wreck marks as a validation method

The manual vectorisation supported by the 3D bathymetric profiles allowed for the separation of prevailing scour patterns (Fig. 7) and calculation of their areas; these in turn were compared with the areas of wreck marks separated by the RRM method (Table 1).

The greatest differences between the two methods occur where more subtle wreck marks, embedded in the regional bathymetry, are present. They were not straightforward to vectorise, even when supported with the 3D profiles. As an example, Fig. 6 represents the SS Polwell DEM with the 3D profiles used to support the manual vectorisation process. Whilst the wreck marks were clearly distinguishable on the near-field profile B-B′, the far-field profile C-C′ did not provide enough information to ascertain the width of the scour. Similarly, the A-A′ profile drawn over the wreck showed two erosional lows, but the depositional mark which intersects the profile and extends to the south of the wreck (as seen on Fig. 7) was barely discernible from the featureless seabed. These uncertainties, which arose during the manual separation, caused differences compared with the RRM in the proximity of the shipwreck and to the south of it. With respect to the areal calculation, this resulted in the underestimation of erosional features using the manual method (Table 1).

On the SS Tiberia site, relief modelling also resulted in the detection of more extensive erosional and depositional features than the manual vectorisation approach (Table 1). The erosional pits proximal to the wreck (Fig. 7b) were recognised by both methods, but the relief modelling indicates the pits extending farther than when picked manually (Fig. 7b). In addition, a depositional mark southwest of the wreck, which was successfully separated by relief modelling, was missed in the manual vectorisation process.

Differences between the techniques applied on the SS Hare site are negligible, with the scour pit defined by relief modelling reaching only slightly farther than that interpreted in the manual vectorisation process (Fig. 7c; Table 1).
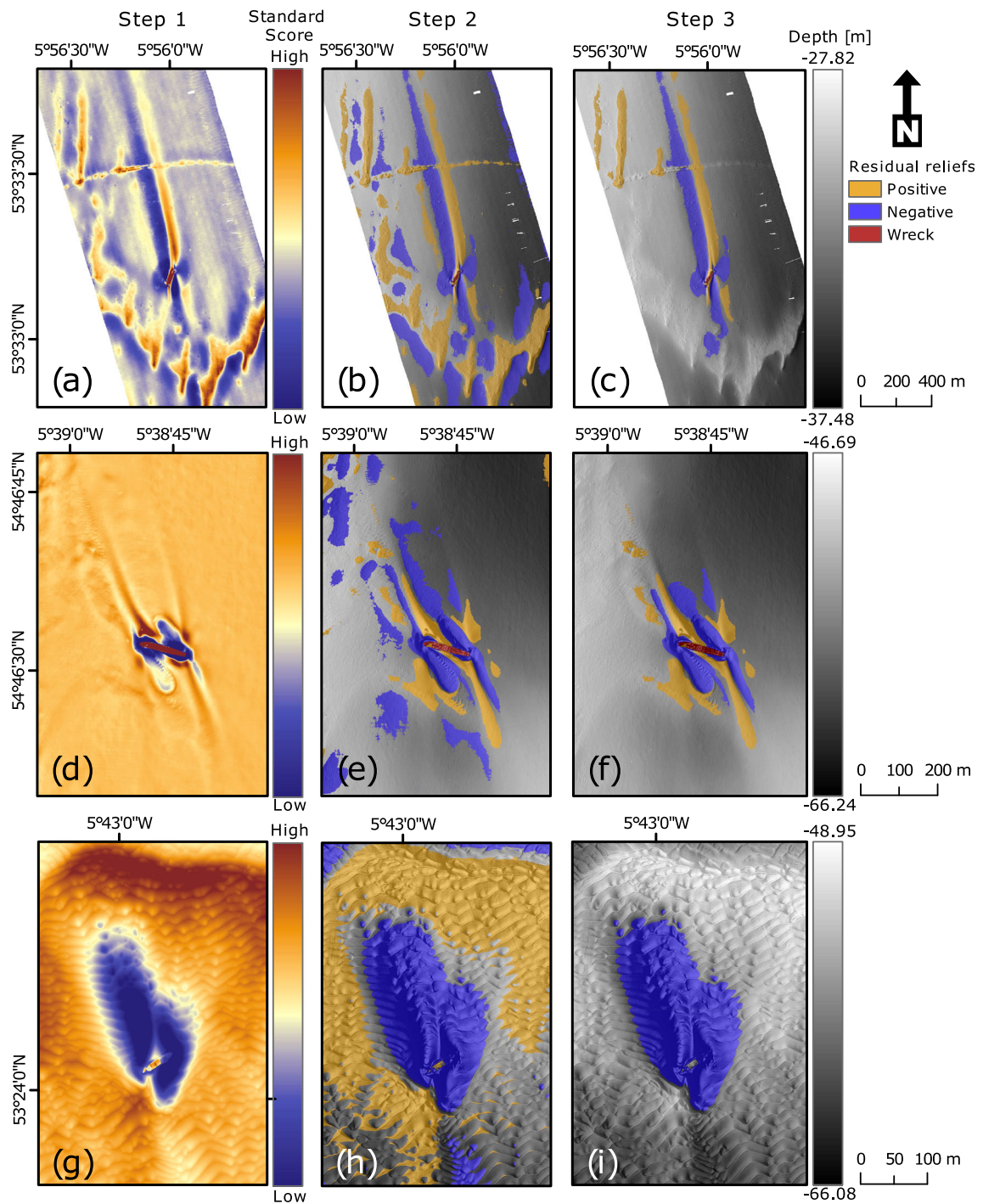
Fig. 4 RRM's step 1 (high-pass filtering), step 2 (preliminary classification) and step 3 (separation of wreck marks) are shown respectively in the first column (left), second column (middle) and third column (right). SS Polwell is shown in (**a**), (**b**), (**c**); SS Hare in (**d**), (**e**), (**f**) and SS Tiberia in (**g**), (**h**), (**i**)

Discussion

Objective separation of erosional and depositional wreck marks

In this study, we aimed to develop a method for objective extraction and classification of erosional and depositional scour marks from high-definition bathymetric DEMs of shipwreck sites. We successfully used a combination of residual relief modelling and DEM visualisation techniques, building on previous work in several fields of study which required the separation of morphological features of various length-scales (e.g. Wessel 1998; Smith and Clark 2005; Walbridge et al. 2018).
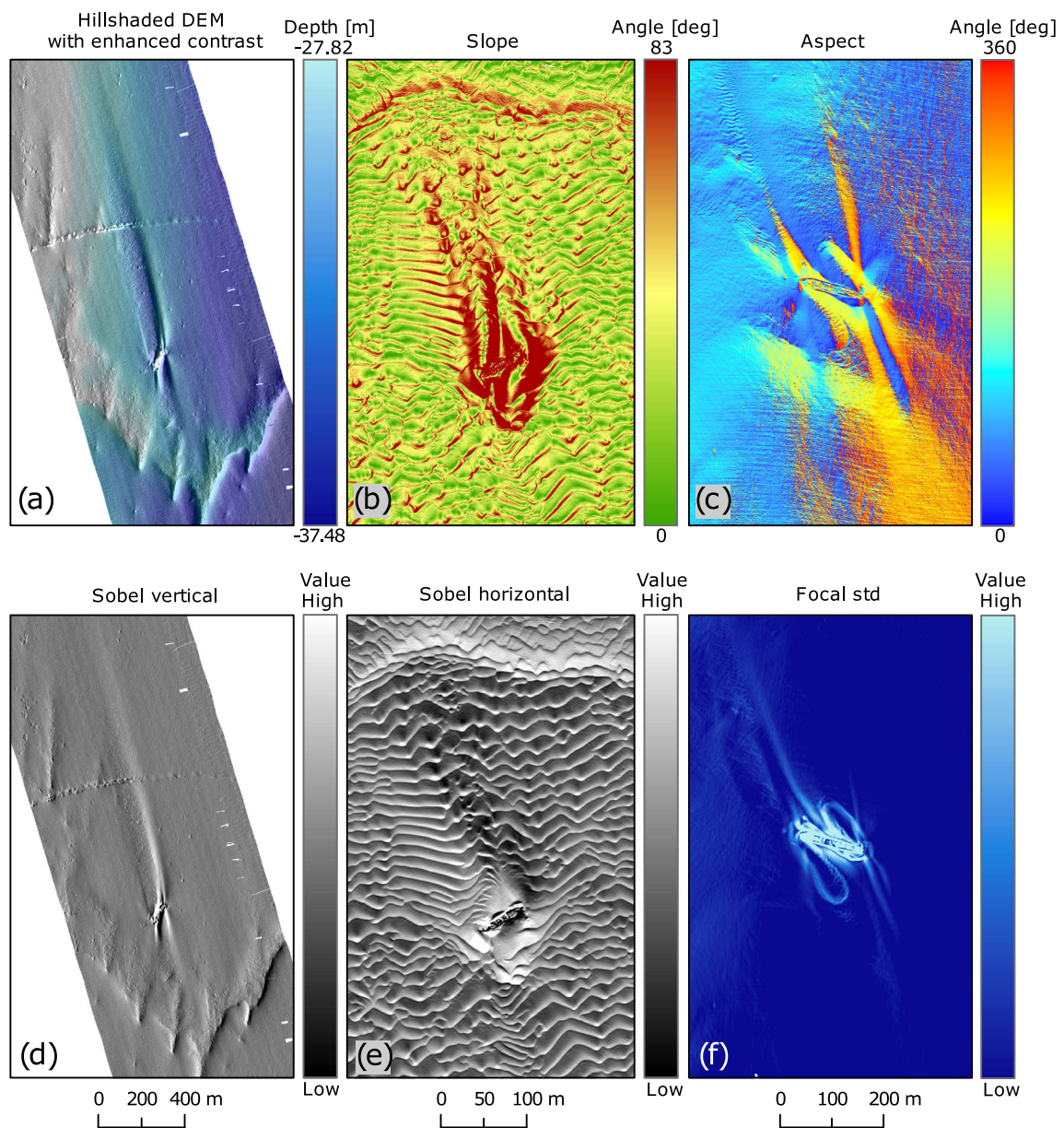
Fig. 5 DEM visualisation techniques applied to the sites. (**a**) Increased contrast DEM with the multidirectional hillshade occlusion on SS Polwell, (**b**) slope on SS Hare, (**c**) aspect on SS Tiberia, (**d**) Sobel vertical on SS Polwell, (**e**) Sobel horizontal on SS Hare, (**f**) focal standard deviation on SS Hare

Although separation of wreck marks can be performed by manual vectorisation in GIS, this naturally introduces user-bias due to the subjective nature of the process. In our study, the residual relief modelling method was compared with a

Table 1 Areas of depositional and erosional wreck marks extracted by the manual vectorisation and the RRM method

Wreck	Manual vectorisation		Residual relief modelling			
	Deposition (m²)	Erosion (m²)	Deposition (m²)	Δ%	Erosion (m²)	Δ%
SS Polwell	67,193	98,197	64392	− 4.16	124,681	+ 26.97
SS Tiberia	17,292	17,208	29115	+ 68.37	27,094	+ 57.45
SS Hare	-	35,482	-		32,535	− 8.31
Total area (m²)	*235,373*		*277,818*			*+ 18.03*

Δ% represents a percent difference between the areas delineated by the two methods
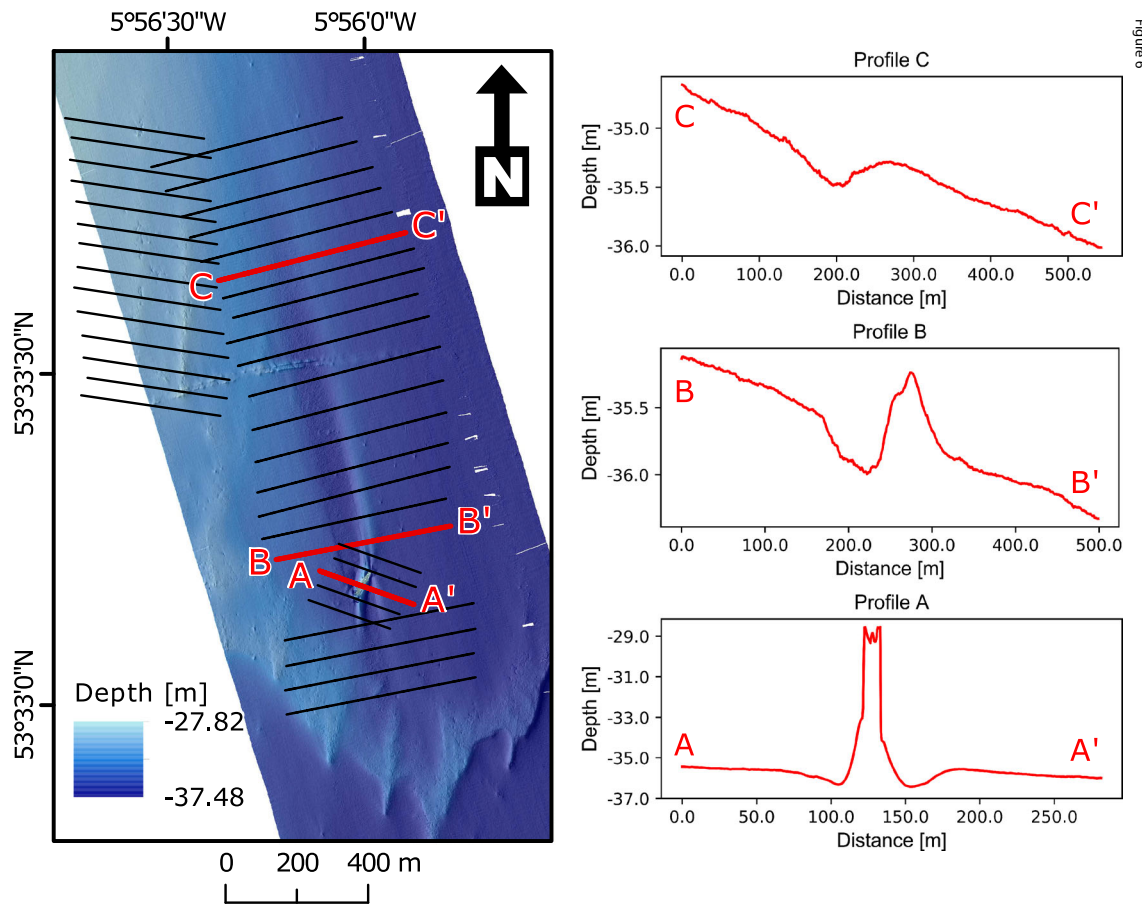
Fig. 6 Depth profiles created for the manual vectorisation of wreck marks on the SS Polwell DEM. Profile graphs A, B and C are shown representatively

manual separation supported by 3D profiles derived from the DEMs. Both methods were successful in identifying the main scour marks on all of the wreck sites. However, differences in the extents and shapes of the picked areas were observed (Fig. 7, Table 1). Relief modelling outperformed manual vectorisation with respect to the total defined erosion/deposition areas by 18% (Table 1). The greatest differences were noted in places with subtle scour marks, which are difficult to define visually and vectorise using the manual approach. The results indicate that manual vectorisation alone cannot be used as a benchmarking validation method, and that scour signature separation should always be accompanied by
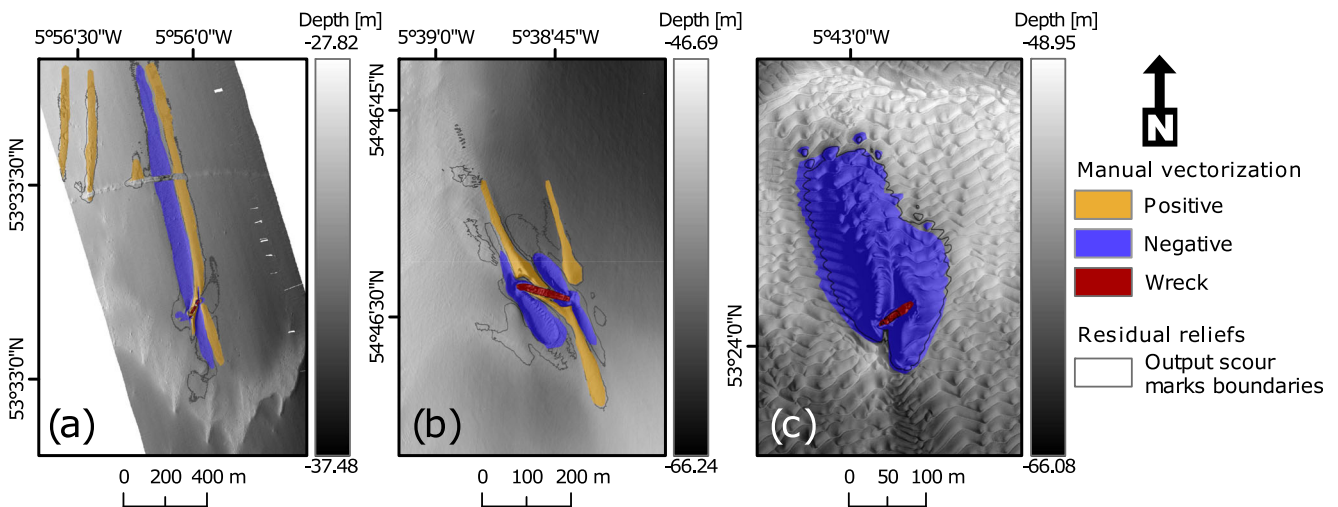
Fig. 7 Results of the manual vectorisation for (**a**) SS Polwell, (**b**) SS Tiberia and (**c**) SS Hare with the scour areas separated by the RRM highlighted with a grey line in the background for a comparison

statistical analysis. The fact that the residual relief modelling method is semi-automated and based on statistical differences between elevation values (Wilson and Gallant 2000) makes it a more effective tool compared with manual vectorisation.

Methodological considerations for residual relief modelling

There are some important methodological points to consider when using residual relief modelling for wreck mark separation. For example, the residuals initially classified during the second step as erosional features extending from the pipeline at the *SS Polwell* site (Fig. 4b) are in fact the result of natural bathymetric variation rather than scour. So care must be taken when reviewing the outputs. High-pass filtering, the first step of the relief modelling method, can also create artificial positive and negative relief features. Mean values assigned to cells corresponding to a featureless seabed on the original DEM can be influenced by proximal positive and negative values. As a result, non-existing residuals may occur and later be classified. The morphology of the wreck structure and the presence of other additional high elevation differences inside a kernel are the significant factors that can introduce these types of errors during the first and second steps of the process.

Wessel (1998) demonstrated that the application of median filters for high-pass filtering avoids the bias of extreme observations and enables the effective separation of residual morphologies. However, empirical observations indicate that computation times to calculate focal medians as opposed to means is an order of magnitude higher, dependent on kernel size and raster size/resolution. Additionally, focal statistics window shape can be adjusted. For example, in the TPI (Weiss 2001) and BPI approaches (Walbridge et al. 2018), an annulus (donut)-shaped kernel is used when separating topographic features of various length-scales. Empirical testing indicated that a circular moving window is the most universal and time-effective solution, whereas pilot results obtained with an annulus kernel did not indicate significant improvement in the wreck mark separation for the test sites.

Another consideration is the choice of the moving mean's window size in the first step, which is determined by specific characteristics of the scour marks and other geomorphological features developed at each site. In general, the more complex the local geomorphology, the harder it becomes to estimate a filter radius. For example, a filtering window with a radius of 200 m was applied on the *SS Hare* site to separate the large and deep scour pits (Fig. 8). A smaller radius allowed separation of the wreck structure and the positive feature located inside the pit, but did not fully separate the scour pit itself. As shown in Fig. 8, at point (S) which was picked near the side of the scour pit, a 50-m radius window would capture a similar amount of negative and positive cells, and thus, the calculated average would be close to the value of a central cell.

Therefore, this part of the scour pit would not be captured as an erosional wreck mark during the classification process. A 100-m radius window would potentially separate the wreck structure, the positive feature and the negative scour pit, but only partially (Fig. 8). Hence, when dealing with scour marks, wrecks and geomorphological features at various length-scales, multiple window sizes need to be applied iteratively.

Whilst the size of a kernel defines the accuracy of separation related to length-scales, the choice of breakpoints during the classification controls the tolerance of values inside the classes. For example, in this study, minus and plus 0.5 standard score were used as the main breakpoints for each of the sites. If they were to be moved closer to zero (e.g. plus and minus 0.2), anything in between these breakpoints would be classified as featureless, and more values would be classified as depositional and erosional scour marks (i.e. outside the plus and minus 0.2 range). However, this would also increase the number of irrelevant, natural morphological features inside the classes. Empirical refinement indicated that +/− 0.5 standard deviation breakpoints are the most robust.

In the residual relief method developed in this study, the additional validating step supported by the DEM visualisation techniques was added in order to eliminate erroneous classifications and separate scour marks from other local geomorphological features. The techniques reveal some characteristics which are inherent to scour marks and difficult or impossible to spot solely by visual examination of the original DEM and bathymetric profiles. The enhanced visual techniques employed in this study not only serve for the separation of wreck marks but are also useful for the archaeological and geomorphological interpretation of wreck sites (e.g. for detection purposes or for drawing site plans).

Archaeological implications

Although the residual relief method was tested on three WW1 wreck sites, it is an important step towards the standardisation of the quantification of erosional and depositional zones on all underwater archaeological sites. As this method is semi-automated, it generates metrics for the delineation of local morphologies which are based on statistical comparisons, rather than on purely manual user interpretation. The method can be applied to any underwater site type, from individual artefacts, to single wrecks, to submerged landscapes with varying characteristic length-scales. In this paper, we specifically tested it to separate scour signatures, as their quantification is fundamental to the understanding of wreck site formation processes.

Firstly, scour and associated sediment fluxes can trigger the burial of archaeological material within the sediments or can lead to the exposure of material into an oxygenated water column. This in turn influences processes like corrosion or biological encrustation (Ward et al. 1999). On the *SS Hare* site for example, scour processes cause the shipwreck to sink

Fig. 8 A-A′ depth profile drawn on SS Hare site to show the range of various filtering window sizes inside the scour pit. Filter ranges for circular window radiuses of 200 (used for the site in this study), 100 and 50 m are marked on profile graph A
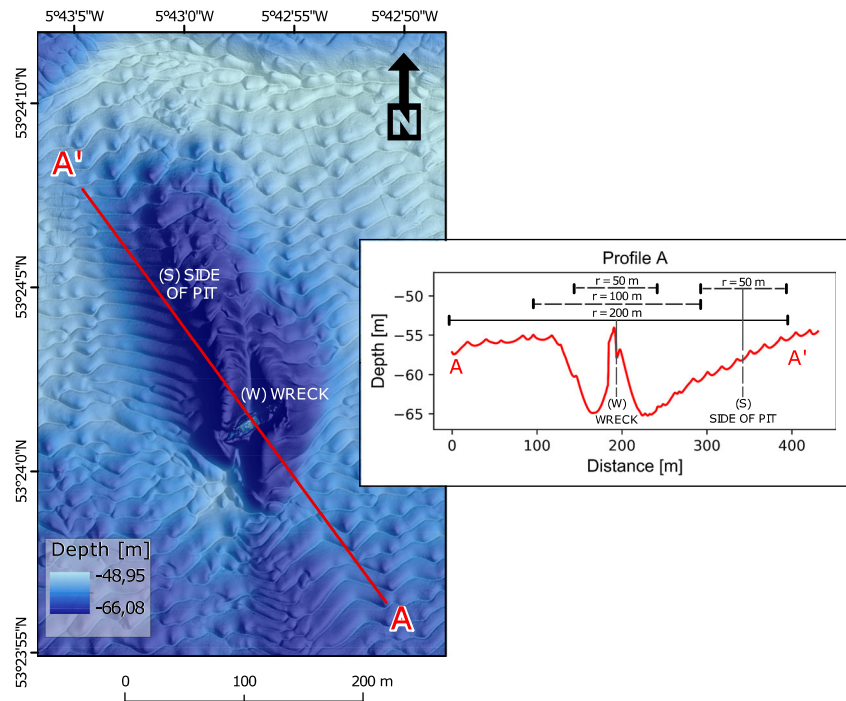
below the elevation of the regional seabed (Fig. 8). Similar scour mechanisms are described by Voropayev et al. (2003) and Jenkins et al. (2007) for small objects, where subsequent sinking of scour nuclei leads to their partial or complete burial. Similar processes happening on shipwreck sites influence the rate of their structural degradation (Ward et al. 1999).

Furthermore, changes in sediment budget caused by scouring in a dynamic marine environment may also influence the distribution of high- and low-pressure zones on a hull structure, potentially leading to the partial or complete collapse of the wreck (Quinn 2006). Erosional scour pits are also associated with increased local flow vorticity and turbulence (Quinn and Smyth 2018), and as a result, wreck elements in these areas are subject to increased fluid forcing. Thus, the objective separation of zones of erosion and accumulation helps to categorise a shipwreck site into regions characterised by different grades of preservation potential.

Zones undergoing erosional processes threaten the integrity of a submerged archaeological site, and therefore emphasis should be put on their monitoring. On the other hand, areas influenced by depositional processes generally represent the more stable component of the site, where the accumulated sediment aids preservation. Accurate characterisation and delineation of these zones can help site managers to target specific places to deploy monitoring equipment and undertake site protection measures involving, for example, the arrangement of sand bags and geotextiles. The residual relief modelling method provides an effective and objective method for the extraction of these features and therefore has great potential to enhance effective in situ preservation planning, as encouraged by UNESCO (2002).

From an oceanographic point of view, the distribution of scour marks provides information about directions and magnitudes of dominant bottom currents and the local net sediment transport (Caston 1979). The three shipwrecks chosen for this study are all located in similar bi-directional flow regimes in the Irish Sea, on non-cohesive beds. However, the results of the RRM show that the complex patterns of wreck marks vary significantly across individual sites and between different shipwreck sites (Fig. 4). Although all three shipwreck sites are characterised by scour marks extending in opposite directions as a result of bi-directional tidal flow, only on the *SS Tiberia* site are the scour marks aligned symmetrically. Asymmetrical distribution of scour marks indicates two possibilities: either that ebb and flow current magnitudes are distributed unequally or that local variations in seabed morphology and/or composition can limit the extent of scour development. The RRM method successfully captured the zones of scour marks, which act as proxies allowing for the analysis of local sediment mobility.

The separation method reported here can also be applied to offshore engineering. For example, on the *SS Polwell* site, the wreck-related scour clearly extends beyond the pipeline located 600 m north of the wreck (Fig. 4c; Fig 3a). The location of the wreck therefore influences the integrity of the seabed engineering, indicating that wreck marks should be mapped rigorously to estimate buffer zones, within which no offshore development should take place. Such an approach would potentially minimise detrimental effects caused by shipwreck-induced scour impacting offshore engineering, and vice versa. This factor is becoming increasingly important at a time when coastal and marine landscapes are being transformed as a

result of coastal engineering initiatives to support developing urban centres.

Conclusions

In this study, we present a GIS-based residual relief modelling method for the semi-automated extraction of depositional and erosional features at wreck sites. We applied the method to three World War I shipwreck sites and evaluated it against traditional manual vectorisation techniques. The results suggest that the semi-automated modelling method is robust, time-effective and capable of quantifying the products of scour processes with increased objectivity. Our method holds great potential for the objective characterisation of erosional and depositional patterns and processes at wreck sites, which have important implications for site formation studies and in situ preservation of underwater cultural heritage.

High-resolution multibeam echosounder surveys of wreck sites are now routinely used for archaeological prospection and assessment as they provide detailed, wide and time-effective coverage (Manders 2009; Plets et al. 2011; Astley et al. 2014). The increasing availability of high-definition multibeam-derived digital elevation models of historic wreck sites (Westley et al. 2019) allows for an entirely new level of detailed interrogation and analyses of the geomorphological features developed around them. Multibeam surveys are however still financially expensive and resource-demanding. Therefore, their products should be used comprehensively to provide as much information as possible. The residual relief modelling coupled with the application of the DEM visualisation techniques adds another layer to the use of the bathymetric surfaces.

Accurately delineated zones of erosion and accumulation allow us to quantify seabed change by deriving areas, volumes and other metrics for the displaced sediments. The method presented in this paper helps to define the local geomorphology, which is a prerequisite for other established methods investigating the influence of fluid dynamics on the local seabed (Smyth and Quinn 2014; Quinn and Smyth 2018; Fernández-Montblanc et al. 2018b) and assessing how it changes with time (Quinn and Boland 2010; Bates et al. 2011; Astley 2016).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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