Characterising the Anthropocene in Belfast Lough using multibeam echosounder data

[redacted]

[redacted]

School of Geography and Environmental Sciences, Ulster University

Abstract

The Anthropocene is a term widely used to describe the current epoch humans are living through on Earth. This is when the actions and activities of humans are having measurable and lasting impacts upon the Earth, notably the seabed. Belfast Lough has been influenced by the Anthropocene, with evidence of engineering, shipwrecks, and dumping throughout. Multibeam echosounder data is used in characterising the seabed of Belfast Lough, with the analysis of bathymetry, backscatter and seismic data in ArcGIS. The analysis and characterisation of digital elevation models, their derivatives, and the geomorphology of the area gives an understanding of what anthropogenic signatures exist and if they have the potential to be preserved in the geological record. It is estimated that 4.4% of the total seabed study area has anthropogenic signatures with 51% being dumping grounds and 47% affected by ship propellors or anchors. Many of the anthropogenic signatures in the inner lough area have great potential to be preserved in the geological record due to the low energy environment and high sedimentation rates. The outer lough area towards the North Channel contains mobile sediment which is constantly reworked; this environment has less capability to preserve features in the geological record.

1. Introduction

1.1. The Anthropocene

The term 'Anthropocene' is used to describe the newest geological time epoch (Sprovieri et al., 2020), recording humans' impact upon the planet and its spheres. The identification of humans' impacts upon the Earth first arose in 1864 with George Perkins Marsh, an American diplomat, publishing *Man and Nature* (Carruthers, 2019). The term Anthropocene was later coined in 1873 by an Italian palaeontologist and geologist, Antonio Stoppani (Crutzen and Stoermer, 2000). However, the term did not become widely known until 2000 after Paul Crutzen used the term during a meeting of the International Geosphere-Biosphere Programme. Although it is widely accepted, the Anthropocene has still not been officially confirmed as the new geological epoch humans are living in as there is insufficient agreement on what indicates this as a new epoch (Carruthers, 2019). Foley et al. (2013) suggested the use of 'Paleoanthropocene' as a new term describing the time between the first recognisable human-induced change to the industrial revolution when human activity increased dramatically.

Crutzen and Stoermer (2000) identified that the shift from Holocene to Anthropocene was defined through human activities outweighing natural processes and affecting the natural cycles of the planet. It has also been identified as human-induced alterations to the atmosphere which result in geological changes on the Earth (Lewis and Maslin, 2015). The shift from Holocene to Anthropocene is also suggested using the Niche Construction Theory. This considers cultural, temporal and environmental factors that influenced the human ability to change the world to suit them (Smith and Zeder, 2013).

It is proposed that the beginning of this new epoch is in the latter part of the 18th Century (Crutzen and Stoermer, 2000) due to human impacts on Earth becoming more apparent, for example, an increase in greenhouse gas emissions from the Industrial Revolution. However, it has also been argued that the beginning could be in the mid-20th Century. This is a time where human activity and the exploitation of the planet increased drastically (Corlett, 2015), changing 30% to 50% of Earth's terrestrial surface (Crutzen and Stoermer, 2000).

1.2. The Anthropocene and the seabed

The Anthropocene epoch has had effects on all of Earth's surfaces, including those found underwater. The seabed has been affected by human activities for thousands of years, for example, the oldest in-tact shipwreck known to man is dated to be more than 2,400 years old (BBC, 2018). Deep-sea mining is another human impact on the seabed, exploiting the area for its mineral deposits. This idea was first brought about in the 1960s and still occurs today, creating environmental impacts such as pollution and harm to benthic ecosystems. Foden et al. (2011) discussed four types of pressures put on the seabed from human activity: smothering, obstruction, abrasion, and extraction. Examples of these include dredging material, shipwrecks, scouring, and removal of seabed sediments. Anthropogenic activities can also impact the supply and transport of sediments to the seabed through artificial structures such as dams and the repositioning of rivers (Bosman et al., 2020).

Shipwrecks cause obstructions on the seafloor, creating scour marks from interrupting flow currents and sediment transport (Quinn, 2006). However, they can often act as safe habitats for benthic communities and fish; areas surrounding shipwrecks are generally avoided by bottom trawling fisheries due to the obstruction caused (Lengkeek et al., 2013). They are also archaeological sites which may have cultural and/or historical importance (Majcher et al., 2020), often used for diving exploration. Seabed sediments can build up around shipwrecks and bury them under suitable conditions. This can preserve the wrecks and their scour features in the geological record (Quinn, 2006).

The fishing industry can cause lasting effects on the seabed by disturbing marine life and ecosystems. Jensen et al. (2009) determined that trawling by fishing boats had created tracks along 90% of the seabed in the study area of Tromsø Bank and Ingøydjupet in the Southern Barents Sea. It is suggested that trawling activities by humans causes sediment loss through the erosion of the seabed and re-suspension of sediments (Coughlan et al., 2015). These trawling fisheries have negative effects on benthic organisms and communities that live on the seabed. Large ships can disturb the seabed, creating linear depressions in the seabed and abrasion through propellor and keel grooves (Madricardo et al., 2019).

Humans often use seas and oceans as a dumping ground. This marine litter causes pollution of the seas, putting ecosystems and marine life at risk. Marine macro-litter, such as tyres, obstruct the natural hydrodynamic processes of the area, creating scour features much like shipwrecks. Madricardo et al. (2019) conducted a survey, calculating an average of 7.5 items of macro-litter per km^2 on the seafloor of Venice Lagoon in Italy. Depending on the conditions, this litter on the seabed can be buried and recorded in the geological record. Anthropogenic marine litter is usually not biodegradable and can last hundreds of years. For example, macro-litter in Venice Lagoon is dated the 1950s and earlier (Madricardo et al., 2019). Marine micro-litter is also a growing issue for the environment, such as microplastics. These particles accumulate within seabed sediments and are used for dating stages of the Anthropocene epoch through the geological record (Zalasiewicz et al., 2016).

The human engineering on the seabed are very common anthropogenic features affecting the seabed, such as cables and pipelines. In 2020, Fu et al. (2020) stated that 99% of all internet telecommunications travel through submarine cables. These cables are disruptive to the seafloor during installation and if they are not installed deep enough or in appropriate areas, they can become re-exposed (Whitehouse et al., 2000). They can also become re-exposed and broken through natural processes such as liquefaction during an earthquake (Fu et al., 2020). Material dug from the seabed in order to engineer these structures is often dumped on the seafloor and causes smothering to benthic habitats. Sediment extraction of sand from the seabed occurs to aid human actions such as beach nourishment, which strips the seabed of its sediments and changes the dynamic of the environment. Artificial structures on the seabed such as dock piles, force posts into the seabed to support structures above. These can cause scouring which can potentially put the structures at risk of being unsupported.

Multibeam echosounder data (MBES) will be used to analyse seabed data through the ArcGIS programme. This data will be interpreted and compared to existing literature to understand what effects humans have made upon the seabed. The aim of this research is to identify and characterise impacts of the Anthropocene epoch upon the seabed in Belfast Lough. A further aim is to understand if the signatures found have the potential to be recorded in geological history.

The aim is met through the following objectives:

1. To use MBES bathymetry data to create digital elevation models (DEMs) and analyse derivatives (roughness and local relief models) to highlight, identify and characterise areas of anthropogenic signatures.
2. To use MBES backscatter data and sediment samples to create a substrate map in order to correlate the anthropogenic signatures with the seabed type.
3. To integrate the results from the MBES bathymetric and backscatter analysis to classify bedforms and identify areas of mobile seabed in the study area.
4. To integrate results from relief models and substrate map with seismic and sedimentation rate data to highlight where anthropogenic signatures may be preserved in the geological record.

2. Materials and Methods

2.1. Study site and materials

Belfast Lough is a shallow embayment that is situated on the East coast of Northern Ireland (Fig.1a), with the main city of Belfast at its head. The lough is approximately 21km long, beginning at the mouth of the River Lagan, and 11km wide leading into the North Channel of the Irish Sea (Abascal et al., 2017). The study area averages at -13.5m deep before rapidly deepening to an average -63m towards its mouth and reaching a maximum depth of -98m (Fig. 1c).

The main hydrodynamic processes acting upon the study area are tidal currents and streams. There are semidiurnal tides in Belfast Lough with the mean spring tide measured at 3.1m and the mean neap tide at 1.9m (Abascal et al., 2017). In the northern region of the outer lough, tidal streams can be up to 2.5 to 3 m/s whereas in the open water of the lough they rarely exceed 0.5 m/s (Barne et al., 1997). These tidal ranges can be altered by adverse weather, with barometric pressure and wind direction affecting them (Barne et al., 1997). There are energetic waves in the outer region of the lough due to winds from the East and West, with the inner lough being sheltered from these due to the lough’s North-East orientation.

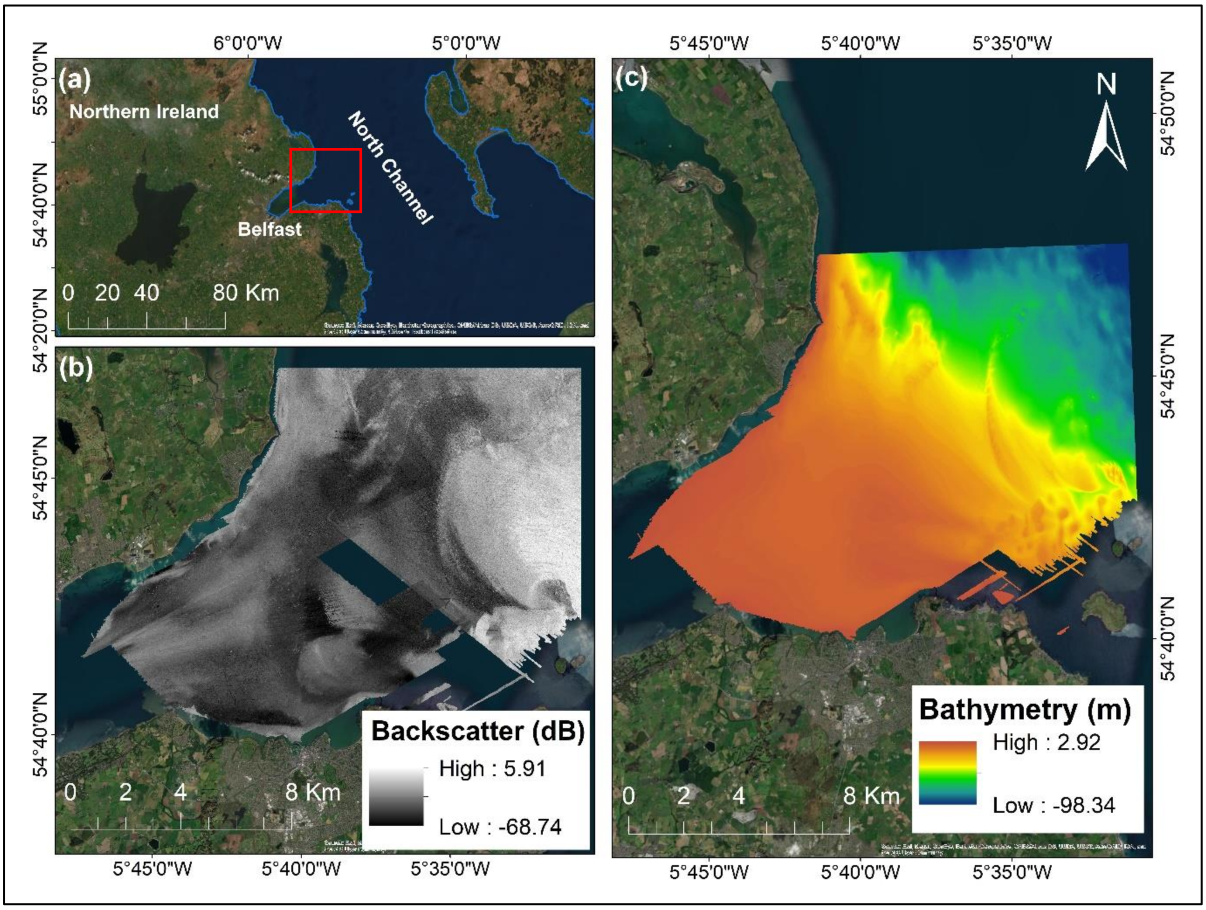

Figure 1: (a) Location map of Belfast Lough on the east coast of Northern Ireland, (b) MBES backscatter data of the study area, (c) MBES bathymetry data of the study area in Belfast Lough.

Sharples and Holligan (2004) concluded that the bottom sediments in Belfast Lough and North Channel are mainly rock or glacial till, with areas covered in thin gravel. This glacial till sediment is derived from glacier deposits (Plets et al., 2019) and bedrock material ranges from the Palaeozoic to the Tertiary ages (Kelley et al., 2006; Geological Survey of Northern Ireland, 1997). According to Barne et al. (1997), the inner lough is mainly composed of sandy mud, as highlighted by the areas of low backscatter to the south-west (Fig. 1b). These finer sediments could be derived from the River Lagan (Cooper, 2006). Beyond the mouth into the North Channel, the main sediment found was gravelly sand which is shown as the mid to low backscatter signatures found in the northern region (Fig.1b). The area towards the east shows very high scatter signatures which indicates there is very coarse sediments in the area such as rocks.

The study involves the use of multibeam echosounder and seismic Pinger line data (secondary data) gathered by the Royal Navy and the Agri-Food and Biosciences Institute in 2009 using the Kongsberg Simrad EM1002 and EM3002 systems. The data was processed at a 2-metre resolution in reference to the Lowest Astronomical Tide and is licensed under the Open Government License v3.0. Access to this data is provided by the Ministry of Defence and the

UK Hydrographic Office as it is public sector information. Data will be processed using ESRI ArcMap 10.5.1 with maps at a resolution of 300 dpi.

2.2. Digital Elevation Models

A Digital Elevation Model (DEM) of the study area was created using MBES bathymetry data through adding a hillshade (315º azimuth, 45º altitude). This acts as an artificial illumination to visualise the seabed's elevation and any unusual occurrences.

The Benthic Terrain Modeller (BTM) using bathymetric data was used for seafloor classification and understanding seafloor terrain, in other words its roughness. This was calculated using the Vector Ruggedness Measure (VRM), which combines the aspect and slope in a single measure (Hobson, 1972), using 3D dispersion of vectors which are orthogonal to the surface (Sappington et al., 2007). The result of this is then subtracted from 1 to gain a VRM result between 0 and 1, which is low/no variation to high/complete variation respectively (Walbridge et al., 2018). The data used was at 2-metre resolution; therefore, roughness was calculated over a 10-metre window. Areas of anthropogenic impact such as shipwrecks will show as high complexity through this roughness layer. This type of analysis on the seafloor is used in de Oliveira et al. (2020) and Madricardo et al. (2020) to understand the seabed ruggedness of the study area.

A Local Relief Model (LRM) was created for the study area using Focal Statistics. This is in order to differentiate anthropogenic features on the seabed through showing positive/neutral/negative relief values. A low pass filter was applied to the DEM with a 10x10 kernel which operated at approximately 20 metre length scale. The LRM was then created through subtracting the low pass filter from the DEM. These DEMs were used to detect anthropogenic features on the seabed such as shipwrecks. These shipwrecks were identified and measured on the seabed using profile graphs, similar to methods used in Majcher et al. (2020) and recorded in a table.

2.3. Seabed substrates, bedform characterisation and seismic stratigraphy

Sediment samples provided were related to backscatter data in order to form a characterisation of sediments in the study area (Fig. 2). For example, rocks and boulders have high backscatter while mud has low backscatter. A study from de Oliveira et al. (2020) used the same method of classification using substrate samples and backscatter data to understand the seabed sediments of the study area. A classification was carried out using seven training sites for sediments (1) Sandy mud, (2) Muddy sand, (3) Gravel, (4) Sand, (5) Mud, (6) Mixed sediment, and (7) Rocks and boulders. An interactive supervised classification was carried out and appropriately coloured to indicate the sediment types.

These DEMs allowed for the characterisation of the bedforms that exist in Belfast Lough. Using sediment wave examples from Van Landeghem et al. (2009) and the Bedform-Velocity Matrix (Stow et al., 2009), a map was created with arrows highlighting direction of flow, similar to those presented in Bøe et al. (2009). The potential for anthropogenic features to be recorded in geology was then investigated through sediment movement and position of features.

In order to understand the sedimentation rates throughout the lough, seismic stratigraphy data was used. Firstly, seismic sequence analysis was carried out, marking multiples and identifying units and their boundaries. Secondly, seismic facies analysis was performed in which units were characterised through their configurations and reflection attributes. This same seismic analysis was performed in Plets et al. (2019).

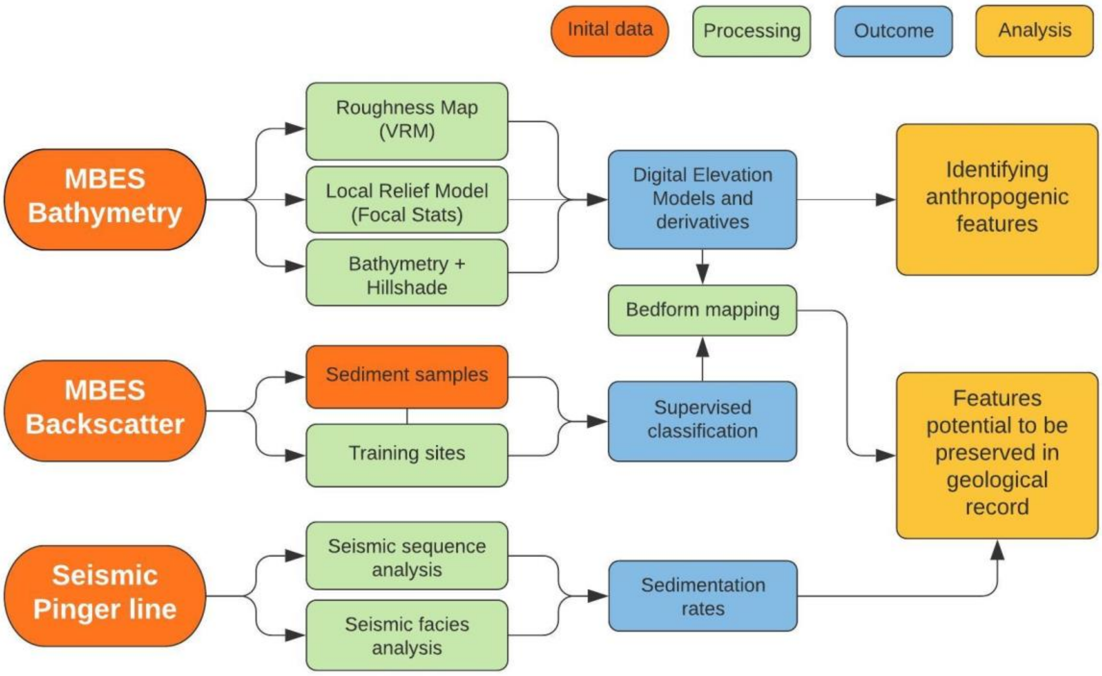

Figure 2: Flowchart highlighting the main components of the methods.

3. Results

3.1. Digital Elevation Models and derivatives

The bathymetry map of the study area (Fig. 3a) highlights a very clear linear progression from the shallow inner lough to the deeper outer areas. The inner lough towards the south-west is relatively shallow and flat, with the main channel ranging from -6m to -13m ranging, reaching a minimum depth of 2.92m. In contrast, the outer lough region to the north-east deepens rapidly towards the North Channel from -20m to a maximum of -98m within the study area.

The roughness map (Fig. 3b) showed a theme of generally low roughness throughout the inner lough. Further eastwards towards the outer lough, Figure 3b shows major areas of roughness as sandwaves, shipwrecks, rocks and boulders. The local relief model (Fig. 3c) showed neutral relief mainly everywhere except from high and low relief around anthropogenic features, areas of sandwaves, rocks/boulders and depressions in the seabed.

3.2. Seabed substrates, bedform characterisation and seismic stratigraphy

3.2.1. Seabed substrates

The substrate map (Fig. 3d) highlights the main sediment types in Belfast Lough. The inner lough is mainly comprised of sandy mud, sand and gravel, with individual pockets to the southern area of mud and muddy sand. The outer lough region to the East is mainly comprised of mixed sediment and rocks and boulders. The bedform features to the east of the study area occur where the mixed sediment changes to sand, gravel and mainly sandy mud in the outer lough.

3.2.2. Bedform characterisation

The main bedform features in Belfast Lough can be seen (Fig. 3a-d) in the outer lough area through high ruggedness values and areas of significant positive/negative relief. These waves form in a curved pattern with a NW-SE orientation (Fig. 4) (Parker, 1982). The main compound waves form this ridge up the centre, up to 5m in amplitude and 75m in wavelength. The surrounding smaller 3D waves run from 12-80m in length and up to 1.3m in amplitude. The isolated trochoidal waves are the longest in the study area, up to 160m with amplitudes up to 12.5m. Surrounding these waves are in assemblage trochoidal waves and straight-line ripples. These in assemblage waves have a mean wavelength of 48m and an amplitude of 1.45m. The straight-line/undulatory ripples have wavelengths up to 140m and amplitudes up to 3.5m. The sharp crests towards the north-east of the study area are furthest into the north channel, reaching up to 14m in amplitude and 150m in wavelength.

3.2.3. Seismic stratigraphy

There are five units recognized in the seismic analysis (Fig. 5), with unit 1 (U1) being the deepest with its upper boundary at -36m. This unit is discontinuous with a chaotic configuration and medium amplitude. Unit 2 (U2) overlies U1 from the middle of the study area towards the outer lough. It is also discontinuous, but with low amplitude and a disrupted configuration. Unit 3 (U3) mostly overlies U1 towards the inner lough and U2 towards the centre, between -17m and -37m. It then overlies both towards the outer lough. This unit has medium-high amplitude with continuity towards the inner lough and discontinuity towards the outer lough. U2 and U3

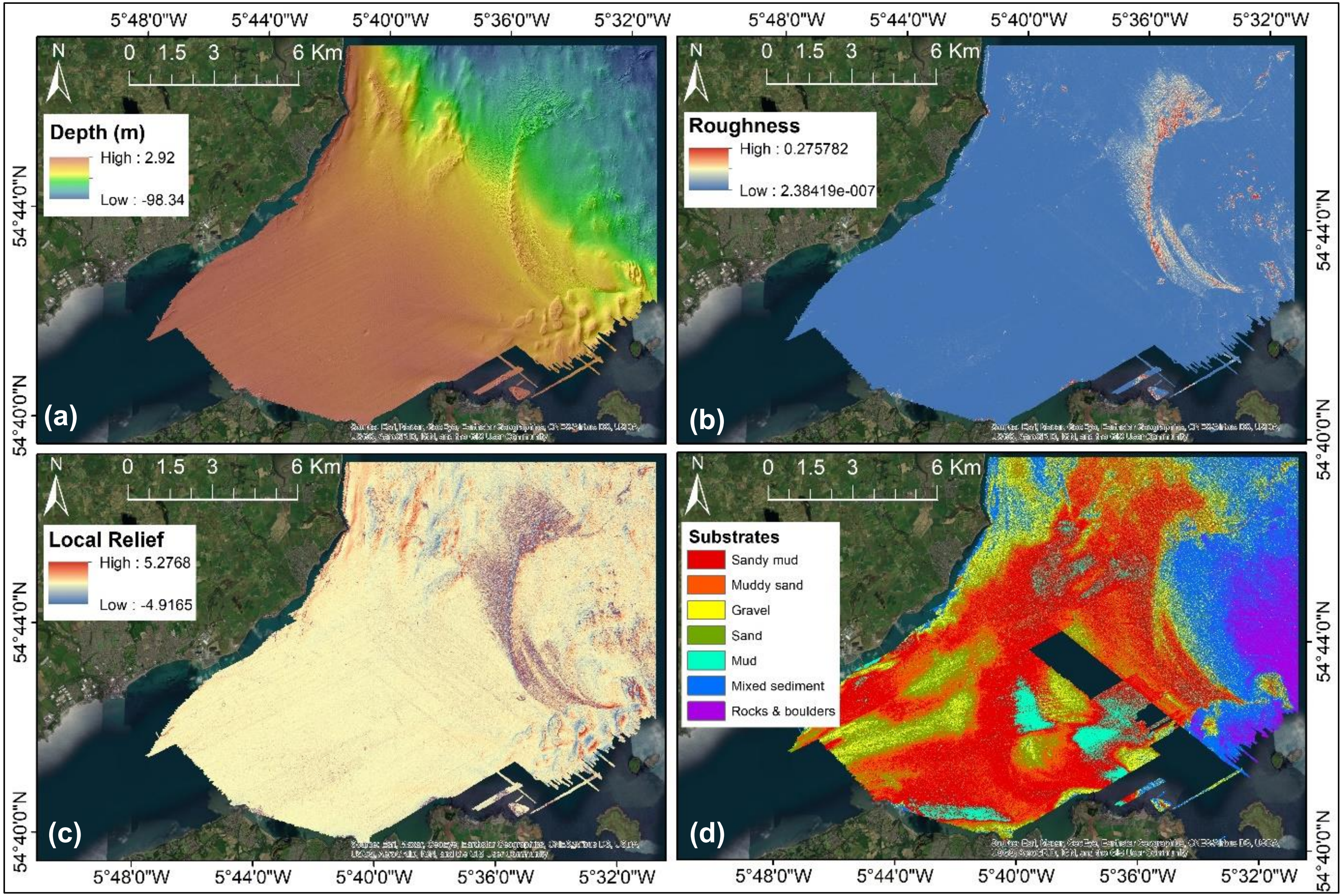

Figure 3: DEMs and derivatives of Belfast Lough study area, (a) Bathymetry data in metres, (b) Roughness map, (c) Local Relief Model, (d) Classified substrate map.

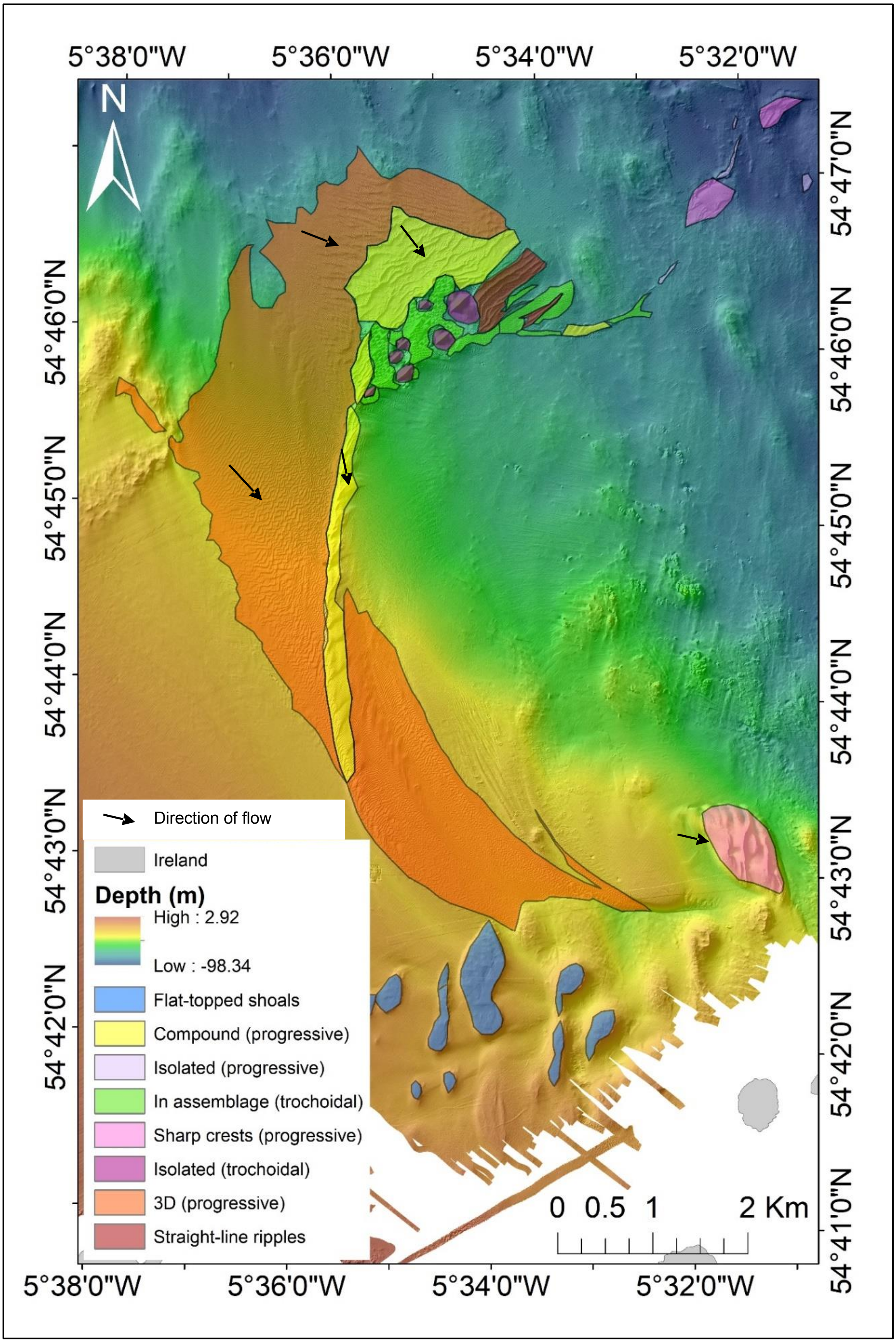

Figure 4: Classified bedform map of the main features in Belfast Lough, with bathymetry data and direction of flow labelled.

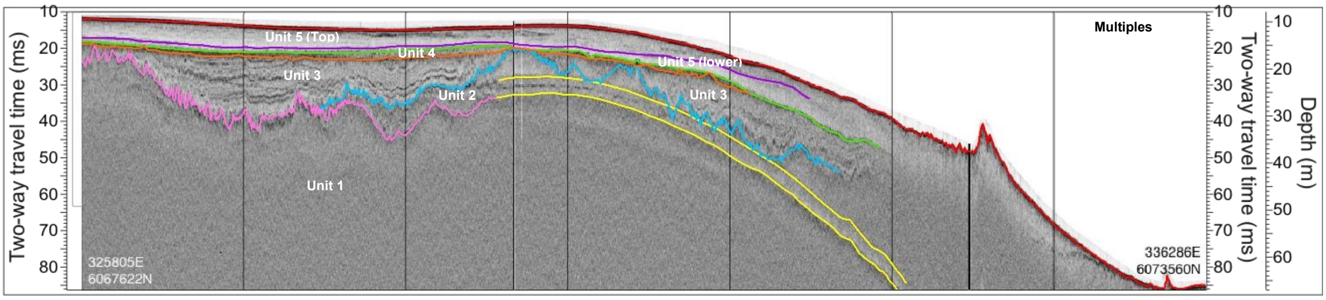

Figure 5: Interpreted seismic Pinger line section of Belfast lough, from inner to outer lough.

both highlight the slope downwards towards the outer lough to the east. Plets et al. (2019) highlight the thickness of these layers, with the main depositional area in U3 towards the inner lough, up to 20m deep compared to the east which is less than 10m deep. Unit 4 (U4) is very thin, with the deepest area seen towards the west (inner lough), between -15m and -18m. It is discontinuous with high amplitude and a slightly chaotic configuration. Unit 5 (U5) has been split into two facies with the lower facies having low amplitude and a subparallel configuration. The top facies of U5 has medium amplitude and subparallel configuration, with the deepest area towards the outer lough. Two multiple lines are shown in Figure 5, but these are ignored.

3.3. Shipwrecks

There are 13 shipwrecks identified in in the lough ranging from debris to almost fully intact ships. Two of these ships exact locations are unknown and three cannot be detected in the DEM. Scour features are visible on four of the most prominent shipwrecks in the lough as seen in Table 1. Two of the most well-known shipwrecks, S.S. *Tiberia* and the S.S. *Chirripo* are characterised in Figures 6-7.

Table 1: Characteristics of shipwrecks in Belfast Lough and their related scour features.

Name	***Location***	***Length (m)***	***Depth underwater (m)***	***Scour features***
S.S. *Tiberia*	54°46'39"N, 5°38'50"W	125	44-61	2 scour pits 4m deep, NW: 330-370m, SE: 130-230m
S.S *Chirripo*	54°45'55"N, 5°40'44"W	105	18-28	2 scour lines, N: 870-940m, S: 400m
H.M.T. *Rose II*	54°44'15"N, 5°38'49"W	33-36	18-20	2 scour lines, N: 60m, S: 46m
S.S. *Azure*	54°46'2"N, 5°39'0"W	25	44-56	2 scour lines, N: 65m, S: 27m
S.S. *Troutpool*	54°41'45"N, 5°40'21"W	110	8-9	None seen, dispersed as a hazard
S.S. *Annagher*	54°41'0"N, 5°37'49"W	54	8-9	None seen, dispersed by explosives
S.S. *Lagan*	54°42'58"N, 5°35'20"W	51	23-29	None seen
M.V. *Karanan*	54°42'52"N, 5°31'43"W	50	30-40	None seen
S.S. *Eveleen*	54°41'0"N, 5°44'42"W	Unknown	-	-
Eureka VI	54°43'2"N, 5°45'5"W	Unknown	-	-
M.V. *Sea empress*	54°44'14"N, 5°36'29"W	Unknown	-	None seen, ship as debris

The S.S. *Tiberia* is the deepest ship identified, between 44 and 61m deep (Table 1). This depth ranges due to the ship lying on a sloping area of seabed which deepens eastwards. The wreck site has two distinct scour pits (Fig. 6a-b) running 330m-370m north-west and 130m-230m south-east. There is significant relief seen at this shipwreck, with very high relief at the shipwreck itself and low relief in the scour spits at and around the shipwreck (Fig. 6b). The backscatter on the wreck reads -28.9dB and the surrounding of the wreck is -34.2dB (Fig. 6c). The wreck lies on an area mainly composed of sandy mud, with mixed sediment and gravel in the scour pits and lines (Fig. 6d).

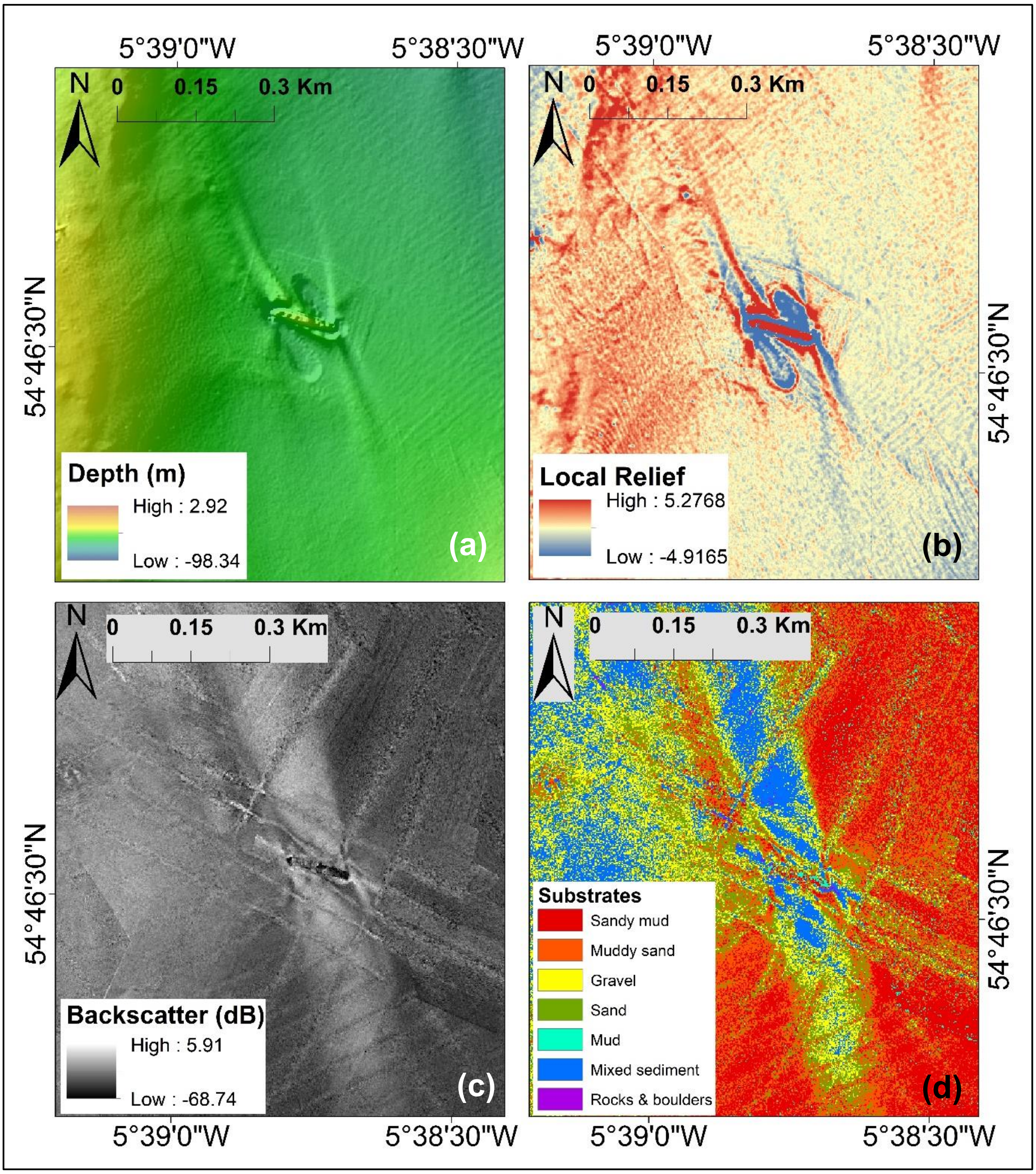

Figure 6: DEMs and derivatives of *SS Tiberia* in Belfast Lough, (a) Bathymetry data in metres, (b) Local Relief Model, (c) Backscatter map, (d) Classified substrate map.

Another major shipwreck is the S.S. *Chirripo*, located 560m from the tip of the coast at Blackhead Lighthouse (Fig. 7a-d) in shallower waters between 18m and 28m. It is 105m long and has two scour lines towards the north and south at 870m-940m and 400m respectively. The backscatter of the wreck is -26dB and the immediate surrounding is -44.7dB (Fig. 7c). The wreck has a high positive relief, with a negative relief surrounding the wreck. There are also circular features of low relief around the north and west sides of the wreck (Fig. 7b). The S.S. *Chirripo* is lying on mixed sediment and gravel, with the scourlines surrounded with mixed sediment.

Two other ships, H.M.T. *Rose II* and S.S. *Azure,* have visible scour lines but these are much smaller with the northern lines at 60m and 65m, and the south lines at 46m and 27m respectively. The shipwrecks found at the shallowest waters between 8-9m in the inner lough area were Troutpool and Annagher, which had little to no scour features as they are scattered debris.

3.4. Engineering and shipping transport

The engineered Cloghan point oil terminal is shown in Figure 5, situated off the south-west coast of Whitehead. The terminal extends 1,210m from the coastline and is 373m wide at the end of the jetty, ranging from depths of 5m towards the coast to 12m depth at the end of the jetty (Fig. 8a). There are areas of low and high relief around the dock piles in the seabed and some sandwaves behind the end of the jetty towards the north (Fig. 8b). The backscatter signature for the oil terminal area averages at -24.8dB (Fig. 8c). The area around the terminal and behind the end of it is mostly comprised of gravel, sand and mixed sediments. The area beyond the end of the terminal towards the inner lough areas, the substrate changes to sandy mud and muddy sand (Fig. 8d). There is another small area of engineering seen towards the middle of the inner lough (Fig. 10) and these are the anchorage points for a tidal stream panel.

Grooves are seen in the seabed (Fig. 6) and these could be anchorage marks or propellor/keel grooves. The relief of the grooves is low and the area surrounding them is slightly higher. The grooves are mainly seen in sediments of sandy mud and muddy sand.

3.5. Dumped material

Signs of dumping can be seen in Belfast Lough in multiple areas: off the coast at Whitehead (Fig. 9a-d) and north of the Copeland Islands (Fig. 10). These signatures are seen in the form of circles, as impact craters of dumping material onto the seabed. These areas were identified through comparisons of the data with online admiralty charts (i-Boating, 2021).

The sediment in the raised area off the coast of Whitehead contains circular impact features

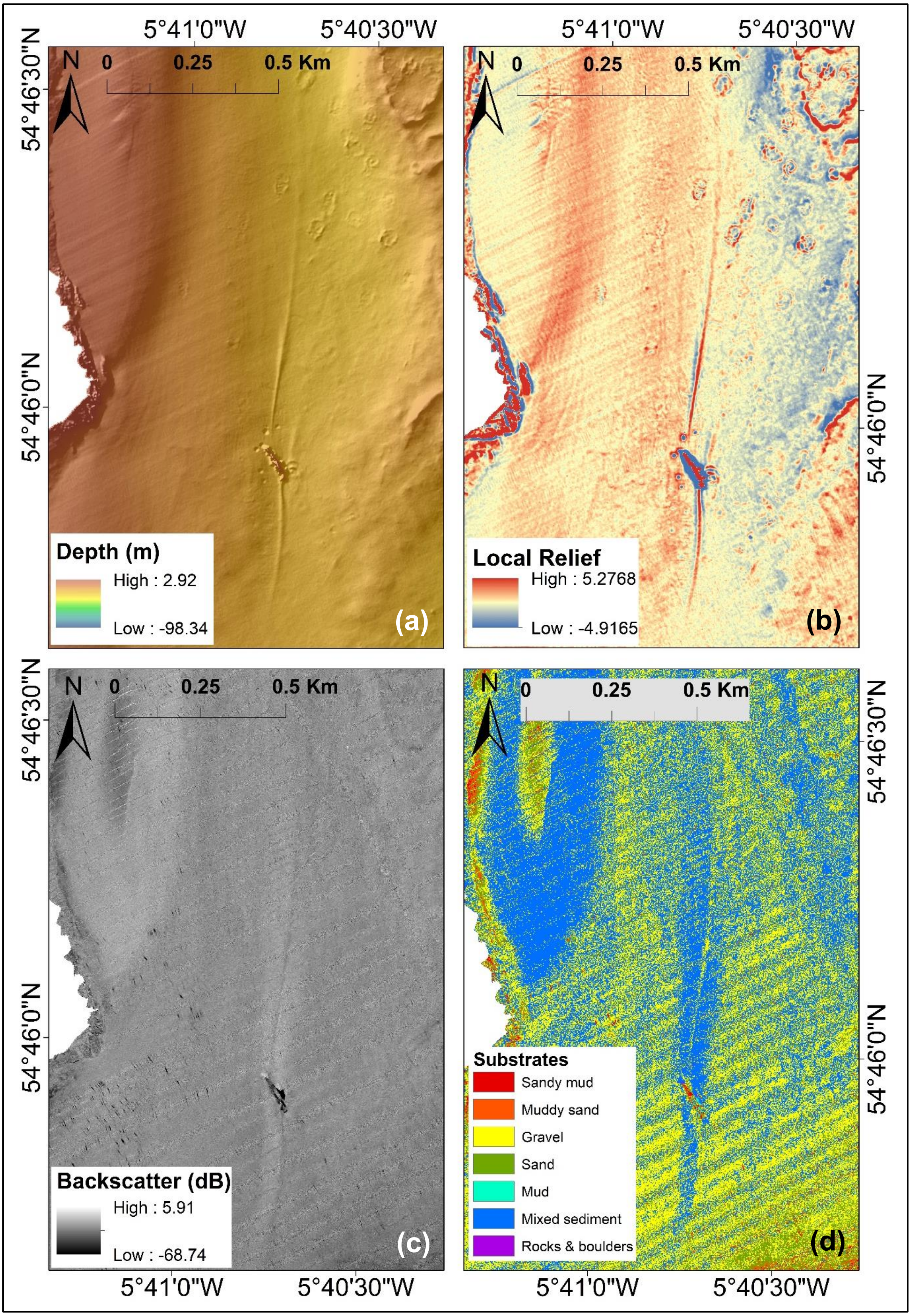

Figure 7: DEMs and derivatives of *SS Chirripo* in Belfast Lough, (a) Bathymetry data in metres, (b) Local Relief Model, (c) Backscatter map, (d) Classified substrate map.

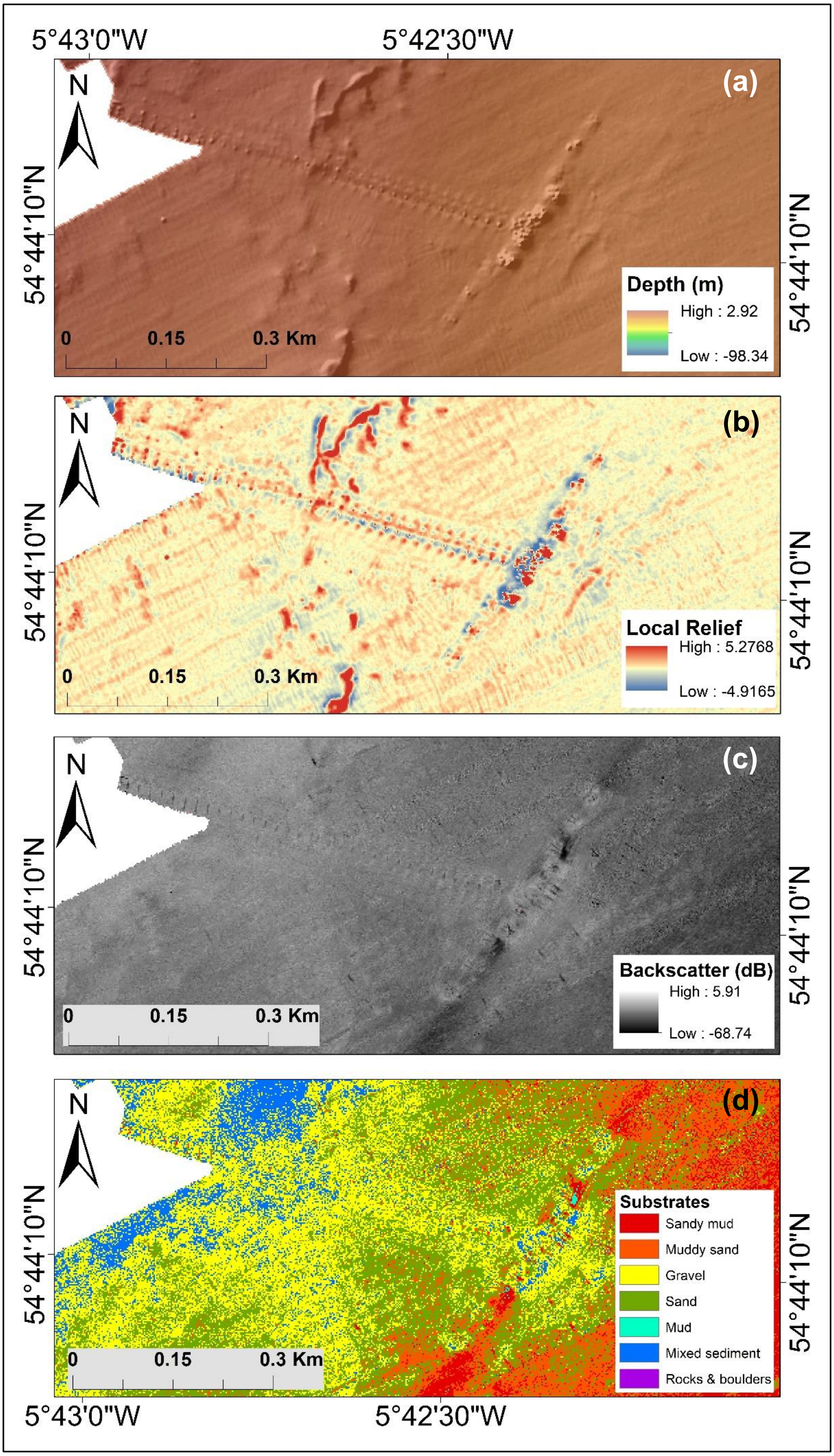

Figure 8: DEMs and derivatives of Cloghan point oil terminal in Belfast Lough, (a) Bathymetry data in metres, (b) Local Relief Model, (c) Backscatter map, (d) Classified substrate map.

which are highlighted through areas of low relief with a ring of higher relief around them (Fig. 9b). They are found between depths of 17m and 40m (Fig. 9a). The area consists mainly of mixed sediments and gravel with a small area of sandy mud (Fig. 9d). The roughness map (Fig. 9c) also highlights these circular signatures and an area of high roughness where the sandy mud exists. The material seen northwards of the Copeland Islands is similar to that seen off the coast of Whitehead, with the circular impact signatures of high and low relief. These are found at depths of 40m and exist in an area of mixed sediment and gravel.

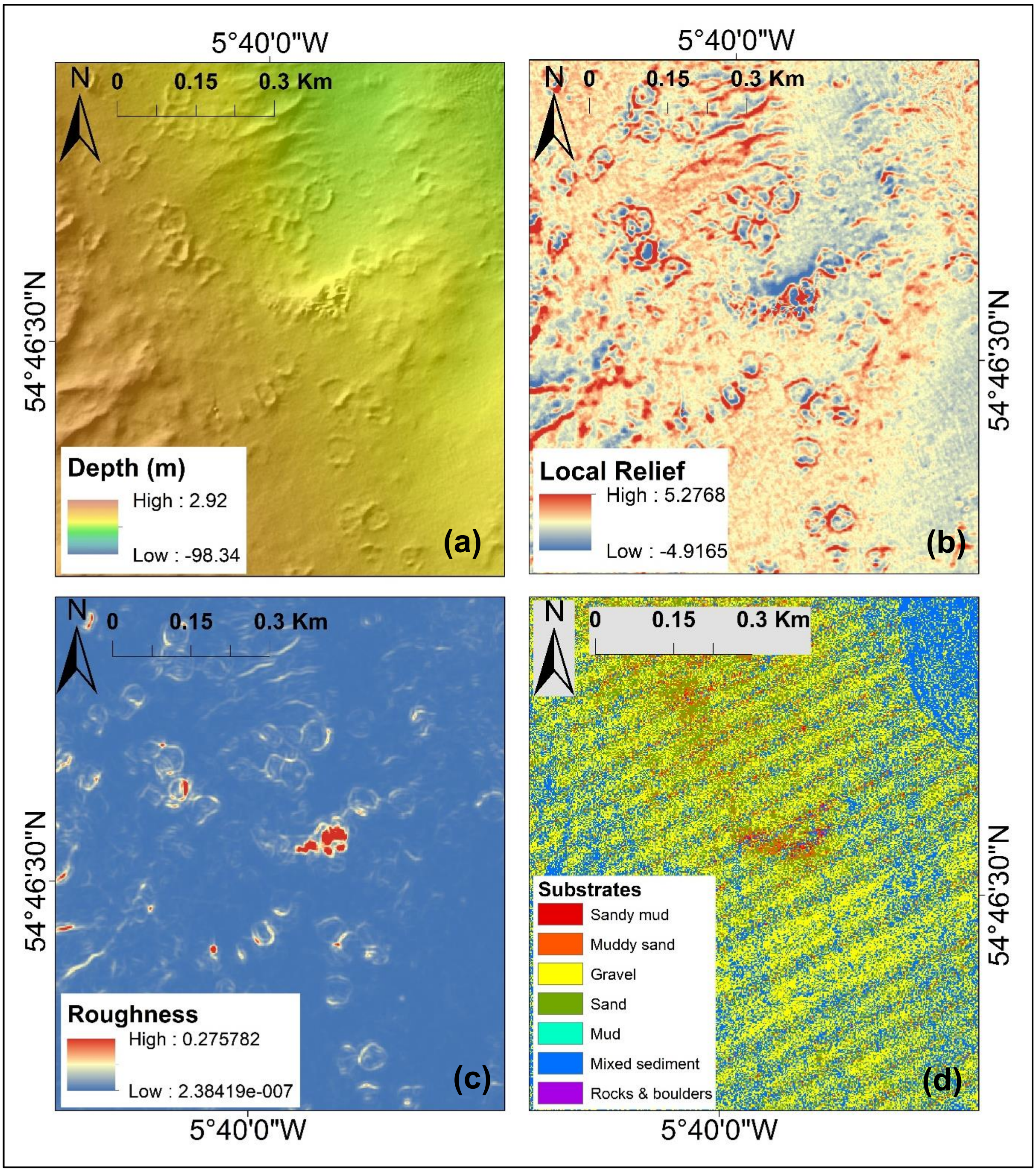

Figure 9: DEMs and derivatives of an designated dumping area in Belfast Lough, near Whitehead. (a) Bathymetry data in metres, (b) Local Relief Model, (c) Roughness map, (d) Classified substrate map.

3.6. Overall results

There has been 7.22km^2 of the study area (164km^2) affected by anthropogenic features. This is 4.4% of the total area (Table 1). From this 4.4%, the highest culprit for anthropogenic signatures is dumping craters, at 51.1% and shipping impacts at 46.7% (Fig. 10). The lowest area of impacts are shipwrecks, their scour signatures, and engineering structures at 0.2%, 0.7% and 1.3% respectively (Table 1). The shipwrecks, scourlines and dumping signatures in the outer lough region have less chance of preservation in the geological record in comparison to the shipwrecks, scourlines, shipping impacts and engineering features (Table 1).

Shipwrecks are found throughout the study area (Fig. 10) with the dumping signatures mainly found towards the outer lough. The evidence of shipping impacts such as propeller/keel grooves and anchor marks are mainly found in the inner lough regions, especially towards the south. Engineering on the seabed has occurred in the inner lough with the Cloghan point oil terminal and the anchored tidal stream panel.

4. Discussion

4.1. Shipwrecks

There are over 20 shipwrecks in Belfast Lough, with 13 highlighted in the study area. These shipwrecks have historical and cultural value, attracting divers to explore the historic wrecks, for example, the S.S. *Tiberia* and the S.S. *Rose II* are wrecks from World War I (Majcher et al., 2020). The S.S. *Rose* has unexploded mortars around it, making the surrounding of the wreck dangerous. The wrecks S.S. *Troutpool* and S.S. *Annagher* were safely dispersed for this reason, as they contained explosives and were hazardous.

These shipwrecks act as obstacles on the seafloor and change the hydrodynamics of the water around them, changing the intensity of turbulence and increasing the flow velocity (Quinn, 2006). These changes help to create scour features such as lines and pits. Scour features are dependent on the geology, bathymetry, and hydrodynamic regimes at the site and are controlled by the wreck orientation (Quinn, 2006). Under extreme conditions of high tidal currents and waves, shipwrecks can be destroyed and scattered, further changing scour features and destroying the wrecks. Scour features can be preserved in the geological record under suitable conditions of initial erosive environments that create the scour features and then high sedimentation rates to preserve the features. An example of these features being preserved are the scour features of King Henry VIII's ship, *Mary Rose*, wrecked in 1545 (Quinn et al., 1997).

Shipwrecks towards the inner lough, such as H.M.T. *Rose II* and S.S. *Lagan*, have a larger potential for survival than wrecks towards the outer lough. This is due to the relatively sheltered

Table 2: Characterised anthropogenic signatures from Belfast Lough seabed, by area and potential for preservation in the geological record.

Anthropogenic signature		***Area (m²)***	***Area as % of total study area***	***Area as % of total area of signatures***	***Potential for preservation (Low/Medium/High)***
Shipwrecks	*Tiberia*	2,997	0.002	0.04	Low
	Chirripo	1,412	0.0009	0.02	Medium
	Rose II	385	0.0002	0.005	High
	Azure	372	0.0002	0.005	Medium
	Troutpool	4,065	0.003	0.06	High
	Annagher	657	0.0004	0.009	High
	Lagan	715	0.0004	0.01	Medium
	Karanan	713	0.0004	0.01	Low
	Total	**11,316**	**0.008**	**0.16**	
Shipwreck scour lines	*Tiberia*	26,825	0.02	0.37	Low
	Chirripo	25,202	0.02	0.35	Medium
	Rose II	793	0.0005	0.01	High
	Azure	494	0.0003	0.007	Medium
	Total	**53,314**	**0.04**	**0.74**	
Engineering (artificial structures)	Oil terminal	40,721	0.03	0.56	High
	Tidal stream panel	1,926	0.001	0.03	High
	Other	49,037	0.03	0.68	High
	Total	**91,684**	**0.06**	**1.27**	
Propeller/Keel grooves and anchor marks	**Total**	**3,695,267**	**2.25**	**51.1**	**High**
Dumped material	Whitehead (east)	3,269,570	1.99	45.3	Low/Medium
	Copeland Islands (north)	104,932	0.06	1.45	Low
	Total	**3,374,502**	**2.05**	**46.7**	
	Overall total	7,226,083	4.4		

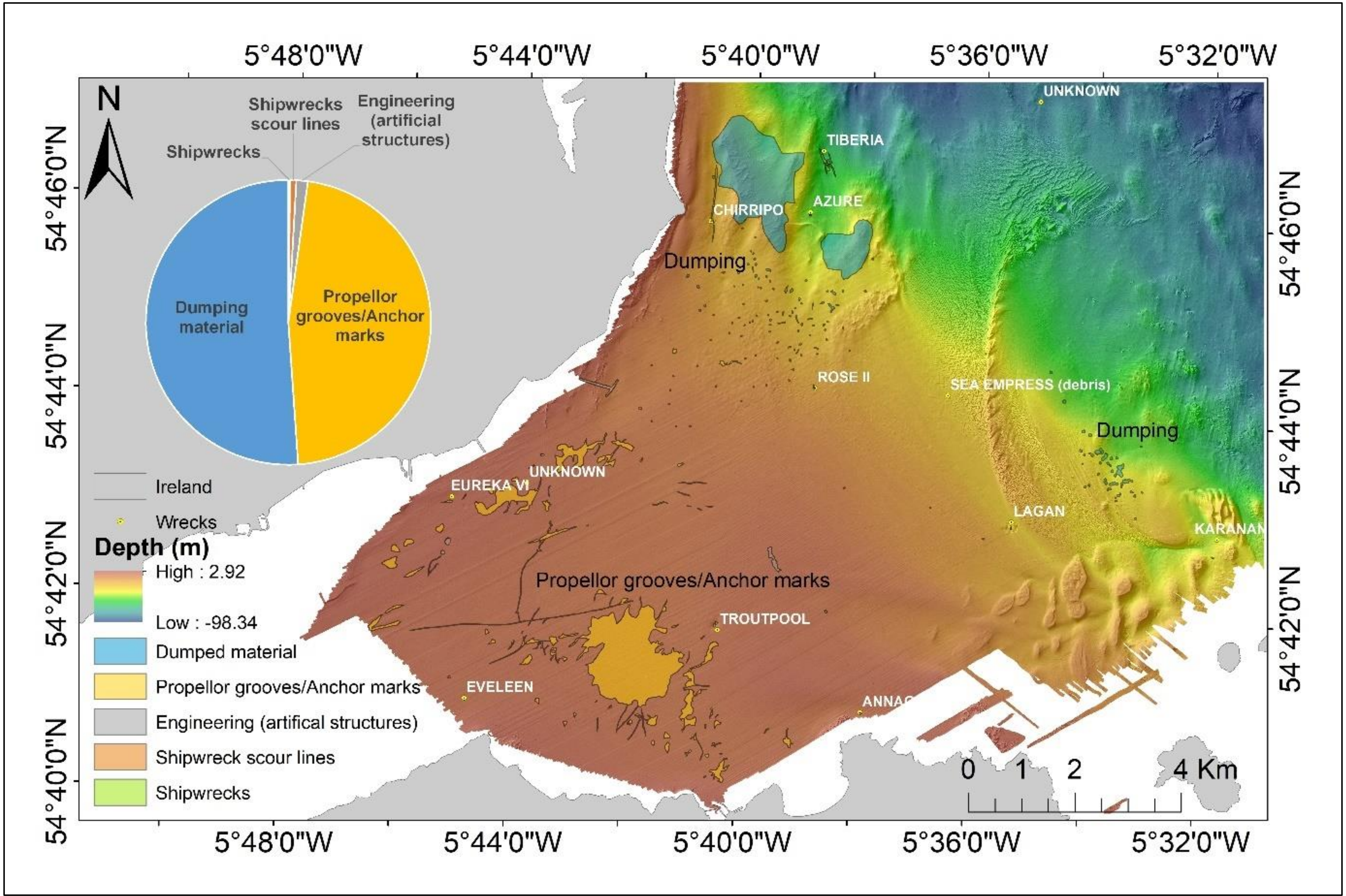

Figure 10: Anthropogenic features characterised on a bathymetry map of Belfast Lough, with a pie chart insert showing the signatures as percentages of the entire area of features identified.

environment and high sedimentation rates, free from large sediment movement from strong currents. There is a relatively slow tidal stream of 0.5 m/s (Barne et al., 1997) which does not have major effects destroying shipwrecks and other anthropogenic features through sediment transport. Instead, the higher sedimentation rate and lower seabed current allows sediment to build around the features, preserving them in the geological record. In contrast, the open waters at the mouth of the lough, tidal streams increase up to 3 m/s and flow velocities increase around structures on the seabed. The seabed currents become stronger further into the outer lough, creating the bedform features seen in Figure 4. In the outer lough, this mobile sediment does not create a suitable environment for signatures to be preserved in the geological record because the seabed is constantly being reworked.

The S.S. *Tiberia* wreck site contains complex erosional and depositional features of the scour pits and depositional ridges. This is due to a higher peak seabed current of 0.53m/s (Majcher et al., 2021) and the wreck orientated at an angle to these currents. The sediments in the area are more mobile as there is more sandy mud, muddy sand, and sand. These mobile sediments and higher currents are not suitable conditions for the wreck and its scour features to be preserved in the geological record as the sediment is constantly being moved.

The S.S. *Chirripo* is orientated at an angle to the seabed currents; this is why elongated scour features exist in the area. The peak seabed currents in the area are 0.28m/s (Majcher et al., 2021) with the surrounding seabed being mainly mixed sediments and gravel. There are no significant erosional features at this site due to the slow seabed currents, although there are two depositional ridges to the north and south. Pockmark-like features have formed in the around the north and west of S.S. *Chirripo* wreck in the softer sandy sediments. These formations are large circular depressions in the seabed which could possibly indicate the release of gas due to pressure on the seabed from the wreck (Majcher et al., 2021). However, it is still unconfirmed why these formations occurred. This wreck is likely to be preserved in the geological record due to the lack of erosion and higher sedimentation with the depositional features seen the site. Although, Majcher et al. (2021) indicated that the wreck site is stable and has a lack of sediment supply, suggesting that it may remain stable for years.

4.2. Engineering and Shipping transport

Artificial anthropogenic structures occur all over the world's seabeds, in the form of cables, pipelines, dock piles, oil terminals, among others. These structures on the seabed are at risk of erosion as they are not naturally occurring and often create obstacles, changing hydrodynamic regimes. They can create scour features from constricting and changing hydrodynamic regimes in areas, and under extreme conditions structures can be undermined and collapse onto the seabed (Quinn, 2006).

Engineering on the seabed has not been a major impact of the Anthropocene in Belfast Lough, although it still has its impacts, such as the creation of the Cloghan point oil terminal. This terminal was initially completed construction in 1979 as a storage facility to supply power stations in Kilroot and Ballylumford, although it became almost inessential in 2008. This huge structure extends out over a kilometre from the coastline, held up by poles driven into the seabed. There are depressions on the seabed where there was an anchored tidal stream panel in the centre of the inner lough (Fig. 10). These artificial structures have potential to be preserved in the inner lough region as they are not built in an extreme environment with mobile sediment and high seabed currents which would erode and undermine features.

Belfast Lough seabed has undergone constructions in the past to install submarine cables and pipes. These are not exposed on the seabed; however, their installation disrupts the seabed and can create signatures from machinery or dumping excess material. They also can damage benthic habitats and communities, but these can recover. The lough has intense history of shipping and transport, with huge ships and ferries entering the relatively shallow channel daily. Ships can often leave grooves in the seabed from anchors and propellors, as seen in the Venice Lagoon in Italy (Madricardo et al., 2019). These propellor grooves and anchor marks covered 2.26% of the study area which was over half of the entire anthropogenic signatures characterised, indicating that shipping has had a huge impact upon the seabed. These grooves in the inner area of Belfast Lough maintain a potential for preservation in the geological record due to the high sedimentation rates in the area and the lack of mobile sediments.

4.3. Marine litter

Belfast Lough has been subject to both legal and illegal dumping, with designated areas decided by government bodies such as the Department of Agriculture, Environment and Rural Affairs. It is estimated that there were between 5-30 items of waste/litter per km^2 on the seafloor in Belfast Lough in 2011 (Maes et al., 2018).

The designated disposal site off the coast of Whitehead was used for sewage sludge disposal (Barne et al., 1997), creating the circular impact craters in the seabed in the area (Fig. 9). Another designated area is north of the Copeland Islands, near the bedform features in the outer lough. This area was designated for the disposal of dredged material in 2016 from Belfast Harbour (Marine and Fisheries Division, 2016). This area was also licensed for 152,600 tonnes of waste disposal allowance in 1994 (Barne et al., 1997). The dumping site near Whitehead has a chance of preservation in the geological record as it is still within an area of relatively low seabed currents, however the sediment may be more mobile, so this is undecided. The dumping zone north of the Copeland Islands has very little change of preservation due to the nature of the environment it is in. The sediments around the site are mobile and the seabed currents are high, ensuring that the seabed is always changing. It is unknown the total volume of landfill dumped in the study area but any plastics that lie on the seafloor have high potential to be preserved in the geological record (Zalasiewicz et al., 2016).

4.4. Limitations

The secondary MBES data used in this study was collected in 2009. This could limit the study as the geomorphology of the area may have changed since the data was collected and it may have been further altered by humans through engineering and shipping. The MBES data also does not reach the coastlines and there are gaps in the backscatter data which limits the signatures that can be found. It is high resolution; however, small details cannot be identified. Lastly, human errors could limit this study. There are features on the seabed that could not be identified or could be identified wrongly through human error.

4.5. Conclusions

To conclude, dumping and shipping impacts (through propeller/keel grooves) are the biggest anthropogenic signatures recorded on the seabed in Belfast Lough. Shipwrecks and scour features are present throughout the study area and many have the potential to be preserved. It is concluded that anthropogenic features towards the inner lough have higher potential for preservation in the geological record. This is due to high sedimentation rates, low peak seabed currents and lack of mobile sediment. On the other hand, features found towards the outer lough have less potential for preservation due to lower sedimentation rates, higher peak seabed currents and mobile sediment, meaning the seabed is constantly changing in this area.

References

Abascal, A., Castanedo, S., Núñez, P., Mellor, A., Clements, A., Pérez, B., Cárdenas, M., Chiri, H. and Medina, R. (2017) A high-resolution operational forecast system for oil spill response in Belfast Lough. *Marine Pollution Bulletin*, 114(1), 302-314.

Bøe, R., Bellec, V., Dolan, M., Buhl-Mortensen, P., Buhl-Mortensen, L., Slagstad, D. and Rise, L. (2021) Giant sandwaves in the Hola glacial trough off Vesterålen, North Norway. *Marine Geology*, 267, 36-54.

Barne, J.H., Robson, C.F., Kaznowska, S.S., Doody, J.P., Davidson, N.C., & Buck, A.L., eds. (1997) *Coasts and seas of the United Kingdom. Region 17. Northern Ireland*. Peterborough, Joint Nature Conservation Committee.

BBC. (2018) ‘Shipwreck found in Black Sea is 'world's oldest intact'’, *BBC*, 23 October [Online]. Available at https://www.bbc.co.uk/news/world-europe-45951132 (Accessed 16 April 2021).

Bosman, A., Romagnoli, C., Madricardo, F., Correggiari, A., Remia, A., Zubalich, R., Fogarin, S., Kruss, A. and Trincardi, F. (2020) Short-term evolution of Po della Pila delta lobe from time lapse high-resolution multibeam bathymetry (2013–2016). *Estuarine, Coastal and Shelf Science*, 233, 106533.

Carruthers J. (2019) The Anthropocene. *South African Journal of Science*, 155(7/8), 1.

Cooper, J.A.G. (2006) Geomorphology of Irish Estuaries: Inherited and Dynamic Controls. *Journal of Coastal Research*, 1(39), 176-180.

Corlett, R.T. (2015) The Anthropocene concept in ecology and conservation. *Trends in Ecology & Evolution*, 30(1), 36-41.

Coughlan, M., Wheelers, A.J., Dorschel, B., Lordan, C., Boer, W., van Gaever, P., de Haas, H. and Mörz, T. (2015) Record of anthropogenic impact on the Western Irish Sea mud belt. *Anthropocene*, 9, 56-69.

Crutzen, P.J and Stoermer, E.F. (2000) The “Anthropocene”. *The International Geosphere-Biosphere Programme Newsletter*, May, 41,17-18.

Foden, J., Rogers, S. and Jones, A. (2011) Human pressures on UK seabed habitats: a cumulative impact assessment. *Marine Ecology Progress Series*, 428, 33-47.

Fishing-app.gpsnauticalcharts.com (2021) i-Boating : Free Marine Navigation Charts & Fishing Maps [Online]. Available at: http://fishing-app.gpsnauticalcharts.com/i-boating-fishing-web-app/fishing-marine-charts-navigation.html#12/54.7211/-5.6968 [Accessed 20 April 2021].

Foley, S., Gronenborn, D., Andreae, M., Kadereit, J., Esper, J., Scholz, D., Pöschl, U., Jacob, D., Schöne, B., Schreg, R., Vött, A., Jordan, D., Lelieveld, J., Weller, C., Alt, K., Gaudzinski-Windheuser, S., Bruhn, K., Tost, H., Sirocko, F. and Crutzen, P. (2013) The Palaeoanthropocene – The beginnings of anthropogenic environmental change. *Anthropocene*, 3, 83-88.

Fu, C., Qin, X. and Wang, Y. (2020) Effects of Parameter Uncertainties on Interaction between Submarine Telecommunication Cables and Lateral Seabed Movements. *Advances in Civil Engineering*, 2020, 1-13.

Geological Survey of Northern Ireland (1997). Geological Map of Northern Ireland. *Solid Geology*,1/250,000 map.

Hobson, R.D. (1972) *Surface roughness in topography: a quantitative approach*, London: Methuer, 221–245.

Jensen, H.K.B., Boitsov, S., Finne, T.E., Klungsøyr, J. and Knies, J. (2009) Physical and chemical traces of anthropogenic influence at the seabed and in the sediments in Ingøydjupet, Southern Barents Sea. *Norwegian Journal of Geology*, 89, 101-108.

Kelley, J.T. Cooper, J.A.W, Jackson, D.W.T., Belknap, D.F. and Quinn, R.J. (2006) Sea-level change and inner shelf stratigraphy off Northern Ireland. Marine Geology, 232, 1-15.

Lengkeek, W., Coolen, J., Gittenberger, A. and Schrieken, N. (2013) Ecological relevance of shipwrecks in the North Sea. *Nederlandse Faunistische Mededelingen*, 41, 49-57.

Lewis, S. and Maslin, M.A. (2015) Defining the Anthropocene. *Nature*, 519(7542), 171-180.

Madricardo, F., Foglini, F., Campiani, E., Grande, V., Catenacci, E., Petrizzo, A., Kruss, A., Toso, C. and Trincardi, F. (2019) Assessing the human footprint on the sea-floor of coastal systems: the case of the Venice Lagoon, Italy. *Scientific Reports*, 9(1), 1-13.

Maes, T., Barry, J., Leslie, H., Vethaak, A., Nicolaus, E., Law, R., Lyons, B., Martinez, R., Harley, B. and Thain, J. (2018) Below the surface: Twenty-five years of seafloor litter monitoring in coastal seas of North West Europe (1992–2017). *Science of The Total Environment*, 630, 790-798.

Majcher, J., Plets, R. and Quinn, R. (2020) Residual relief modelling: digital elevation enhancement for shipwreck site characterisation. *Archaeological and Anthropological Sciences*, 12(122), 1-13.

Majcher, J., Quinn, R., Plets, R., Coughlan, M., McGonigle, C., Sacchetti, F. and Westley, K. (2021) Spatial and temporal variability in geomorphic change at tidally influenced shipwreck sites: The use of time-lapse multibeam data for the assessment of site formation processes. *Geoarchaeology*, 36(3), 429-454.

Marine and Fisheries Division (2016) Conservation Objectives and potential Management Options for Outer Belfast Lough MCZ [eBook]. Belfast: Department of Agriculture, Environment and Rural Affairs, 28. Available at: https://niopa.qub.ac.uk/bitstream/NIOPA/5164/1/Conservation%20Objectives%20and%20Potential%20Management%20Options%20-%20Outer%20Belfast%20Lough%20MCZ_0.pdf [Accessed 23 April 2021].

de Oliveira, N., Bastos, A.C., da Silva Quaresma, V. and Vieira, F.V. (2020) The use of Benthic Terrain Modeler (BTM) in the characterization of continental shelf habitats. *Geo-Marine Letters*, 40, 1087-1097.

Parker, J.G. (1982) Grain-size characteristics of Recent sediments in Belfast Lough. *Marine Geology*, 50, 153.

Plets, R., Callard, L., Cooper, A., Kelley, J.T., Belknap, D., Edwards, R., Long, A., Quinn, R. and Jackson, D.W.T. (2019) Late Quaternary sea-level change and evolution of Belfast Lough, Northern Ireland: new offshore evidence and implications for sea-level reconstruction. *Journal of Quaternary Science*, 34(4-5), 285-298.

Quinn, R. (2006) The role of scour in shipwreck site formation processes and the preservation of wreck-associated scour signatures in the sedimentary record – evidence from seabed and sub-surface data. *Journal of Archaeological Science*, 33(10), 1419-1432.

Quinn, R., Bull, J.M. and Dix, J.K. (1997) Buried scour marks as indicators of palaeo-current direction at the *Mary Rose* wreck site. *Marine Geology*, 140(3-4), 405-413.

Sappington, J., Longshore, K. and Thompson, D. (2007) Quantifying Landscape Ruggedness for Animal Habitat Analysis: A Case Study Using Bighorn Sheep in the Mojave Desert. *Journal of Wildlife Management*, 71(5), 1419-1426.

Sharples, J. and Holligan, P.M. (2004) Interdisciplinary studies in the Celtic Seas (19, E). *In:* Robinson, A.R. and Brink, K.H. eds. *The Sea*. Cambridge: Harvard University Press, 1003-1031.

Smith, B.D. and Zeder, M.A. (2013) The onset of the Anthropocene. *Anthropocene*, 4, 8-13.

Sprovieri, M., Passaro, S., Ausili, A., Bergamin, L., Finoia, M.G.,Gherardi, S., Molisso, F., Quinci, E.M., Sacchi, M., Sesta, G., Trincardi, F. and Romano, E. (2020) Integrated approach of multiple environmental datasets for the assessment of sediment contamination in marine areas affected by long-lasting industrial activity: the case study of Bagnoli (southern Italy). *Journal of Soils and Sediments*, 20, 1692-1705.

Stow, D.A.V., Hernández-Molina, J., Llave, E., Sayago-Gil, M., Díaz del Río, V. and Branson, A. (2009) Bedform-velocity matrix: The estimation of bottom current velocity from bedform observations. Geology, 37(4), 327-330.

Van Landeghem, K.J.J., Wheeler, A.J., Mitchell, N.C. and Sutton, G. (2009) Variations in sediment wave dimensions across the tidally dominated Irish Sea, NW Europe. *Marine Geology*, 263, 108- 119.

Walbridge, S., Slocum, N., Pobuda, N. and Wright, D.J. (2018) Unified Geomorphological Analysis Workflows with Benthic Terrain Modeler. *Geosciences*, 8, 94.

Whitehouse, R.J.S., Damgaard, J.S. and Langhorne, D.N. (2000) Sandwaves and seabed engineering: the application to submarine cables. *Proceedings of the Marine Sandwave Dynamics*, 227-234.

Zalasiewicz, J., Waters, C.N., Ivar do Sul, J.A., Corcoran, P.L., Barnosky, A.D., Cearreta, A., Edgeworth, M., Gałuszka, A., Jeandel, C., Leinfelder, R,. McNeill, J.R., Steffen, W., Summerhayes, C., Wagreich, M., Williams, M., Wolfe, A.P. and Yonan, Y. (2016) The geological cycle of plastics and their use as a stratigraphic indicator of Anthropocene. *Anthropocene*, 13, 4-17.