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Geomorphology and substrate of Galway Bay, Western Ireland

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ABSTRACT
A combination of multibeam bathymetry and backscatter, LiDAR altimetry and bathymetry, satellite images, and hydrodynamic model outputs were used to map the seafloor and coastline of Galway Bay (western Ireland). This is the first time these multiple datasets have been integrated into a single combined geomorphological and substrate map. The substrate of the bay is predominantly mud and sand with bedrock outcropping extensively around the coastline. The main depositional features are dunes, while the main erosional features are scours and outcropping bedrock. Hydrodynamic model outputs show good correlation between the direction and intensity of prevailing currents and the location and shape of the features in the bay. This indicates that although Galway Bay was shaped glacially through the passage of the British-Irish Ice Sheet across the bay and ensuing glacial and marine sediment deposition, many of the mapped seafloor landforms are modern and current-induced.

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Seafloor; geomorphology; hydrodynamics; habitat mapping; Ireland

1. Introduction

Extensive seabed mapping was carried out in Ireland as part of government-funded initiatives to map its Exclusive Economic Zone: the Irish National Seabed Survey (INSS, 1999–2005) and the Integrated Mapping for the Sustainable Development of Ireland's Marine Resource project (INFOMAR, 2005-present). To date, marine geophysical data have been collected in a large portion of Ireland's territorial waters. The ability to map the seabed at high-resolution continues to improve our understanding of coastal and marine environments and processes. This is essential to implement practical management of marine resources and to promote sustainable development (Barnard, Erikson, Elias, & Dartnell, 2013; Li & King, 2007; Poppe, DiGiacomo-Cohen, Smith, Stewart, & Forfinski, 2006). In this paper, geophysical datasets are combined with satellite images, seafloor samples and hydrological data and integrated into a single geomorphology and substrate map, providing for the first time a coherent picture of the coastline and seabed features of Galway Bay, located on the western Irish seaboard (Figure 1 and Main Map). The geomorphological map (Main Map) provides a complete image of the submarine landscape and gives an insight into the processes active in Galway Bay.

2. Study area

Galway Bay is a large (62 km long, 32 km wide) marine embayment on the west coast of Ireland. It is a high energy, storm-dominated system, protected from the full force of the Atlantic Ocean by the Aran Islands (Inis Mór, Inis Meáin and Inis Óírr) (Figure 1). The bay encounters strong semi-diurnal tides, with a mean spring tidal range of >4.5 m (Booth, 1975; Marine Institute, 2017). Hydrodynamic models show current speeds (both surface and tidal) between the Aran Islands above 45 m/s^{-1} in the ebbing spring tide, while wave models, based on wind speeds from the atmospheric research station at Mace Head, show winter wave heights above 2.5 m in the north and south sounds and mid-bay areas (Joshi, Duffy, & Brown, 2017). The primary inflow of Atlantic water into Galway Bay is through the South Sound, with outflow through the North Sound, creating a counter-clockwise gyre (Harte, Gilroy, & McNamara, 1982; Lei, 1995). The primary freshwater source at the head of the bay is the river Corrib, with volumetric flow rates usually exceeding 311 m^3 s (OPW, 2016). Other freshwater inputs include submarine groundwater drainage streams along the northern shore and the rivers to the east and south of the bay (Smith & Cave, 2012; Cave & Henry, 2011) (Figure 1).

The geology of the northern side of the bay is dominated by granite of Caledonian orogeny age, with the rest of the area (including the Aran Islands) made of Carboniferous Viséan limestone (GSI, 2007). The landscape to the north and east of the bay is flat and low lying, with the majority of areas within 5 km of the coastline generally below 30 m. In contrast, to the south, the landscape is hillier with peaks above

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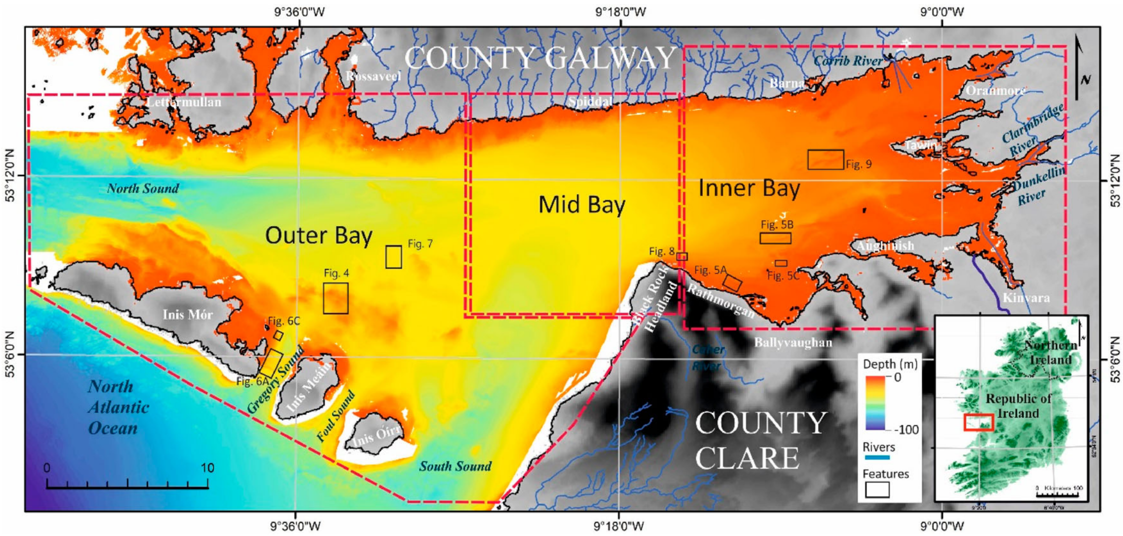

Figure 1. Topo-bathymetric image of the study site from LiDAR and MBES data showing the 0 m contour line in black and subdivided into 3 geographical areas: inner bay, mid bay and outer bay. Examples of features identified in the bay and discussed in the text are outlined in black.

100 m, allowing for a steeper coastline. A fault runs across the northern side of the bay (mapped by Clarke, 2014) (Main Map). During the last glaciation Ireland was covered by the British-Irish Ice Sheet (BIIS) (Clark et al., 2018). This ice sheet extended as far as the shelf edge west of Ireland and resulted in a wide range of glacial landforms across the landscape. Along the inner bay coastline, drumlins are found onshore (GSI, 2013). Offshore, a large morainic complex has been mapped at the mid-shelf (Peters, Benetti, Dunlop, & Ó Cofaigh, 2015).

3. Methods

3.1. Geomorphological mapping

Multibeam echo-sounder (MBES) bathymetric and backscatter data were acquired by the INSS and INFOMAR projects between 2006 and 2014 on board the RV *Celtic Voyager* using a Kongsberg Simrad EM3002D MBES (300 kHz). These data were processed and tidally corrected using CARIS HIPS & SIPS and gridded at 5 m resolution by INFOMAR. LiDAR (Light detection and ranging) altimetry data were collected for INFOMAR between 2006 and 2010 by Tenix LADS Corporation. These datasets were combined to create a detailed altimetric/bathymetric map of Galway Bay (Main map and Figure 1) that was used, together with backscatter classification and satellite images from Google Earth (2017 images), to identify and map submarine features and coastline type (following Ashley, 1990; Duarte, 2017; Fairbridge, 2004; Huggett, 2011; Livingstone & Warren, 1996; Ó Cofaigh, Dunlop, & Benetti, 2016; Van Rijn, 1984; Whitehouse, Harris, Sutherland, & Rees, 2011). Shaded relief with vertical exaggeration (×10) and different illuminations were generated in ESRI ArcGIS 10.1. In order to avoid azimuth biasing, features were considered with numerous illuminations as well as without azimuth (Hillier & Smith, 2008; Smith & Clark, 2005). This, alongside substrate identification, contour lines (10 m spacing) and slope angle (inset in main map) were used to aid geomorphological classification and interpretation.

3.2. Substrate mapping

The substrate classification included in the main map is derived from the interpretation of MBES bathymetric and backscatter data for subtidal depths >20 m and the interpolation of biological samples and subtidal and intertidal data traced from orthoimagery and LiDAR datasets. Rock outcrops have been traced from orthoimagery, LiDAR data and MBES bathymetric shaded relief data.

The seabed classification of Galway Bay done by INFOMAR combined automated and manual methods of classification. The data were collected in 6 survey legs from 2006 to 2014 and the data types include MBES and LiDAR. As a result, the seabed classification work has been done in stages and has incorporated more than one technique. The software used to classify the MBES data was QTC Image Multiview.

The next step was to classify the first MBES dataset (CV07_01) using an automated software called QTC Multiview. The processing strategy of QTC Multiview has been described in principal and demonstrated in the literature (Preston, Christney, Collins, & Bloomer, 2004; McGonigle, Brown, Quinn, & Grabowski, 2009). In summary, the software applies image-based classification techniques to MBES backscatter imagery. The data are cleaned and depth filtered to produce a compensated backscatter image for classification. Rectangular patches of the compensated backscatter imagery are interrogated using a suite of algorithms to extract a series of (132) variables. These are then reduced by principal components analysis to three values (*Q*-values), which best summarise the variance for each rectangular patch. Thereafter, these point data (referred to as Full Feature Vectors or FFVs) are clustered in a 3-D vector space into optimally defined units of common characteristics, which result in a final series of classified points (McGonigle, Brown, & Quinn, 2010). The point data are then interpolated in ArcGIS to produce a raster image displaying the acoustic classes. The raster data are then converted into polygon format and any noise is removed by manual edits in ArcGIS.

The backscatter data does not distinguish rock from coarse sediments, therefore, the rock layer previously manually generated was used to 'cookie-cut' and update the Image Classification data. The final step was to groundtruth the acoustic classes using sediment samples. The sediment sample data underwent Particle size Analysis (PSA) and the resulting granulometric data were classified initially to Folk and then to a modified Folk as used by EMODnet Geology (Kaskela et al., 2019). The resulting seabed classification layer displays 4 substrate classes: rock, coarse sediment, sand and muddy sand to mud.

(Additional seabed classification data for inner Galway Bay was provided by the National Parks and Wildlife Service (NPWS) Marine Community Type spatial data layer. These data were created by interpolating results from a biological sampling survey. The data are classified as broad benthic habitat types).

3.3. Hydrodynamic mapping

Modelled current and wave outputs were provided by the Marine Institute of Ireland (Figure 2). The hydrodynamic model is an implementation of the Regional Ocean Modelling System (ROMS; Jackson et al., 2012), based on the INFOMAR dataset. It has a horizontal resolution of 200 m, 20 vertical levels and provides depth-averaged and three-dimensional velocity fields at a temporal resolution of three hours. The model includes atmospheric and tidal forcing, and climatological river input. One year (taken in 2016) of data was used to calculate mean and maximum depth-averaged and bottom current velocities for Galway Bay. Two different grids were applied to the bottom and depth-averaged current data. The highest resolution 200 m grid was used to closely investigate the relationship between hydrodynamic forces and specific seabed landforms in the bay (Figures 4–8), however, a 1000 m grid was interpolated for current velocity data for the entire bay as it is impossible to distinguish current directions at a 200 m grid over this scale. Modelled wave orbital velocities were taken from the regional wave model (SWAN) supplied by the Marine Institute. The domain covers all Irish waters in the northeast Atlantic at a resolution of 0.025 degrees and is available at three-hourly intervals (Marine Institute, 2018). The model outputs use one year of data and provide an overview of the general trend of the bottom and depth-averaged currents, and the mean speed of the orbital wave velocity in 2800 m grids (Figure 2D). Both the average current velocities (Main Map; Figure 2C), and the maximum current velocities (Figure 2A,B), are important in the formation and preservation of seabed features (Belderson, Johnson, & Kenyon, 1982; Van Rijn, 1984, 1993).

4. Results and discussion

4.1. Hydrodynamic modelling

Across Galway Bay, the annual mean bottom current ranges from 0.01 to 10 cm/s (Main Map) with the highest velocities occurring around the Aran Islands, near the headland of Black Rock, in the inlets of the inner-bay and along the north shore. The annual mean bottom current velocity for the majority of the bay is <2 cm/s (Main Map), while the annual maximum bottom current can reach up to 130 cm/s (Figure 2A). The annual mean depth-averaged currents range between 0.01 and 17 cm/s (Figure 2C), while the annual maximum depth-averaged current reaches up to 230 cm/s (Figure 2B). The highest velocities are located in the same general areas in both the mean and maximum bottom and depth-averaged currents, indicating a similar overall pattern of flow. However, the influence of the various streams and rivers, particularly the river Corrib, can be seen in the inner-bay, with higher speeds in these areas evident in the depth-averaged current (Figure 2B,C).

Gyres are present in the bottom current model in the mid- and inner-bay areas as well as along the northern shoreline (Figure 3). This circulation pattern correlates with the presence of outcropping bedrock and coastal inlets, as the water flows fastest around these features. The contrast between the directions of the bottom- and depth-averaged currents suggests that the bedrock outcrops are influencing the circulation of bottom water in the bay, by forcing it in a different direction.

The orbital wave velocity is highest in the inner-bay area, near Kinvarra Bay, along the northern shoreline and in the North Sound, reaching an average velocity of 20 cm/s (Figure 2D). The lowest wave velocities occur behind the Aran Islands and towards the mid-bay area (Figure 2D). The wave velocities broadly correspond with the current velocities.

4.2. Coastline mapping

Rocky shores, defined as areas composed mainly of boulders and cobbles, with variable gradients, are present along up to 75% of the bay coastline. They are the dominant type of coastline, particularly in the outer-

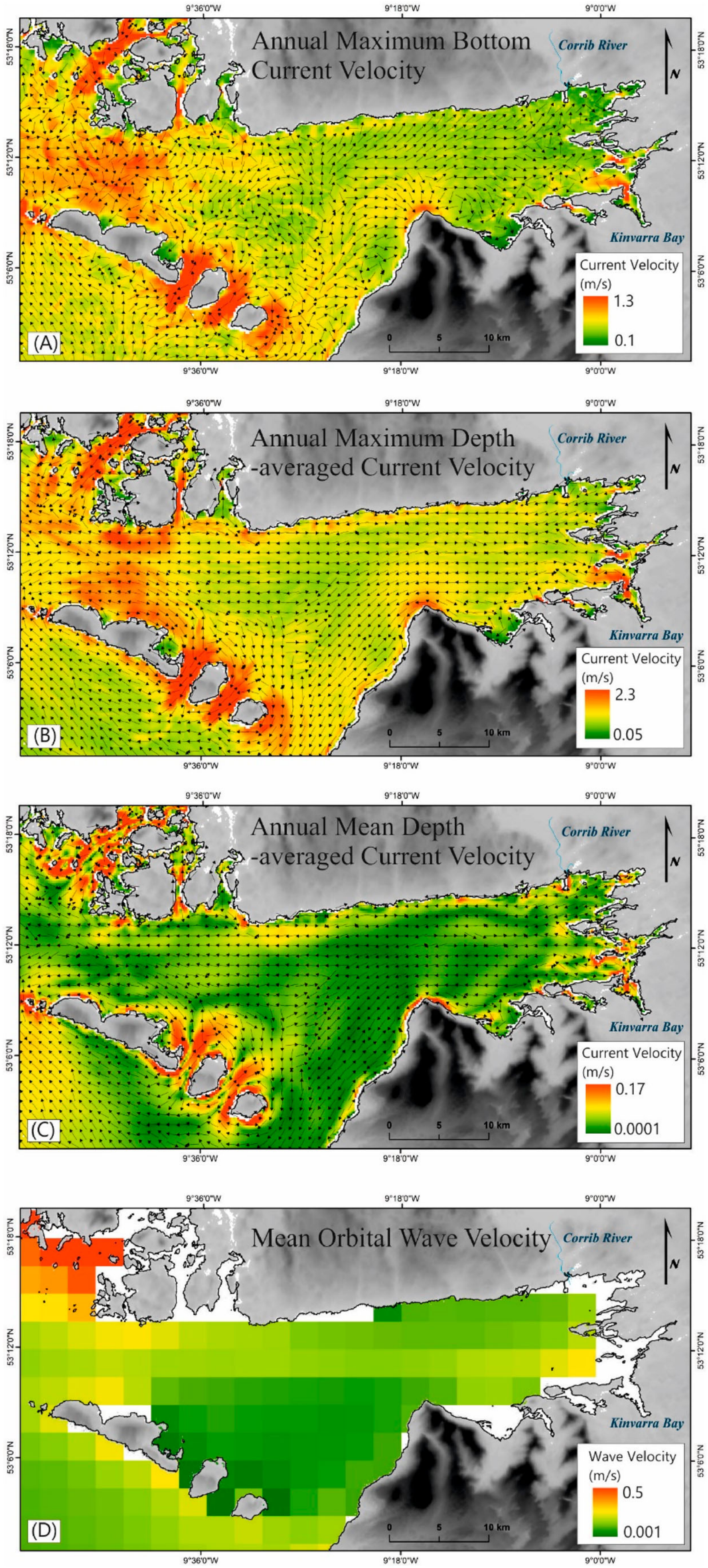

Figure 2. (A) annual maximum residual bottom current velocity in a 200 m grid and current direction in a 1000 m grid, (B) annual maximum residual depth-averaged current velocity in a 200 m grid and current direction in a 1000 m grid, (C) annual mean residual depth-averaged current velocity in a 200 m grid and current direction in a 1000 m grid, and (D) annual mean orbital wave velocity in a 2800 m grid. Although 200 m grid resolution is available for the entire bay for current direction, it is impossible to distinguish the directions at bay scale, so 1000 m grids were used instead. The arrows indicate current direction based on frequency. All data was calculated from the year 2016.

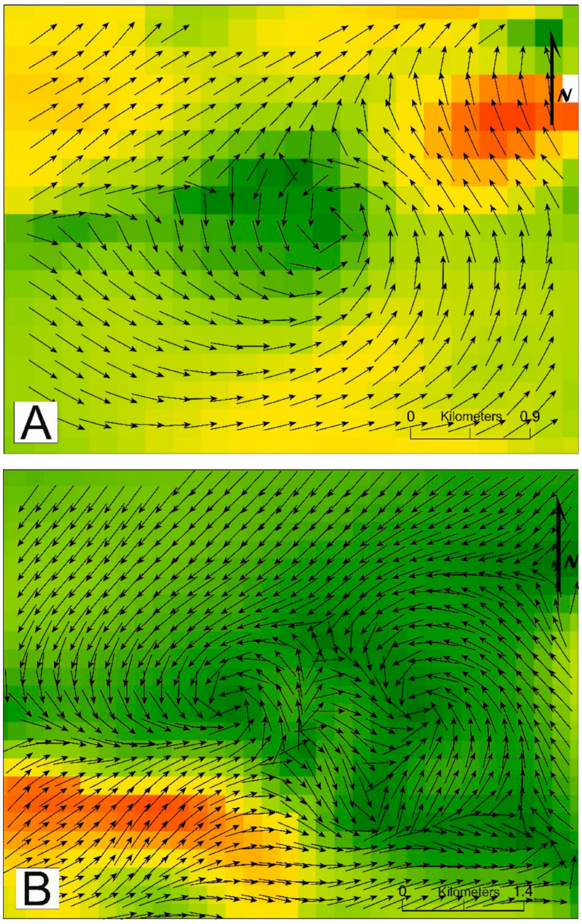

Figure 3. (A) image of an inner-bay gyre and (B) image of an outer-bay gyre.

bay and around the Aran Islands, where the current velocities are strongest (Figure 2; Main Map).

Sandy beaches are found mainly in the inner bay, especially around the river Corrib, and other smaller rivers and streams. They are composed of finer substrate and have a gently sloping gradient. The input of sediment from rivers and the strong tidal and medium wave energy acting upon the inner-bay are interpreted as contributing factors to the formation of these beaches.

Coastal rock cliffs are found only along the southern side of the bay, beginning just east of Rathmorgan and continuing intermittently as far as the outer-bay (Main Map). They have shear gradients and are composed primarily of rock. They are located where the current velocities are highest along this coastline and wave velocities are of medium strength (Figure 2) and appear only in the higher-elevation limestone areas. This correlates with previous studies which suggest that the geology, wave and current action and ground and surface water runoff are the major drivers in the formation of cliffs (Benumof & Griggs, 1999; Pierre & Lahousse, 2006; Sunamura, 1992).

4.3. Substrate classification

Bedrock outcropping at the seafloor is clearly visible on both the bathymetry and backscatter, particularly in the Sounds, eastwards of the Aran Islands, in the inner-bay, near Twain Island and along the northern coastline. In total, ~20% of the seafloor of Galway Bay consists of exposed bedrock. These outcrops are dominated by very high backscatter levels and tend to protrude 10–15 m above the immediate surrounding areas, with slope angles >23° on most of the outcrops (Figure 4). North of the fault line, the outcrops are expected to be granite and south of the fault line, limestone (GSI, 2007). Medium orbital wave (16 cm/s) velocity and high current velocities for both bottom (~100 cm/s) and depth-averaged (~170 cm/s) currents (Figure 2; Main Map) generally correspond with the bedrock outcrops in the North and South Sounds

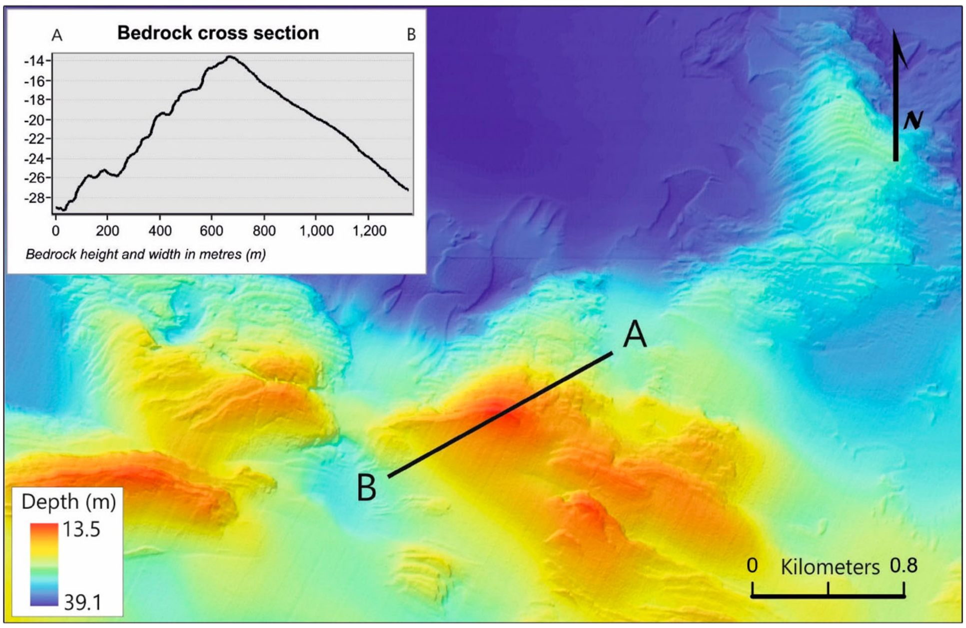

Figure 4. Cross section and bathymetric image of outcropping limestone bedrock, located in the outer central bay area.

and the inner-bay areas. In the mid-bay area, the bottom current velocities tend to be much lower (~40 cm/s), although there are a small number of outcrops. This suggests that the bedrock is influencing currents in the bay, resulting in sediment erosion or transport, which in turn is reinforcing bedrock exposure at the seabed.

Coarse sediment (cobbles, pebbles and coarse sand) is predominantly found in the mid-bay and to the north east of Inis Meáin and Inis Óírr, covering ~10% of the bay. Patches of coarse sediments correlate closely with areas of outcropping bedrock and scouring (Main Map), where there is medium average bottom current velocity (~1.5 cm/s). Along the north coast, coarse sediments frequently occur near the mouth of the channels originating from western Co. Galway, and it is possible that the coarser material has been transported into the bay via fluvial processes. In the mid bay, coarse sediment patches do not appear to be connected to any other features and lie in areas of low current and wave velocities. It is likely these coarse sediments are related to the recorded occurrence of severe storms that can mobilise such sediment to depths beyond the effect of fair-weather waves and currents (Williams & Hall, 2004). Studies on the connection of gravel patches and palaeo-channels (Browder & McNinch, 2006) indicate that the palaeo-channel running along the northern coastline (McCullagh, 2019), may be influencing the position of the coarser sediment in this area.

Sand makes up ~25% of the surficial sediment and tends to surround areas of coarser material (Main Map). The mid-bay has the highest concentration of sand, which extends toward the outer bay in an elongated pattern along the northern coastline, and is found across a range of current velocities, from high to low, in both the bottom and depth-averaged currents.

Mixed sediment (a combination of coarse and fine material) covers only a small area in the inner bay (~5%), coinciding closely with the distribution of channels (Main Map). This material is likely the result of fluvial deposition from these active channels, as there does not appear to be any significant correlation with the current velocity data.

Mud/Muddy sand is the dominant sediment in the bay, comprising ~35% of surficial sediment. It is present across the entire area, but less dominant in the inner bay. It is found only in areas where the average current and wave velocities are low (0.1–0.9 cm/s) (Figure 2; Main Map). This suggests that the muddy sediment is relatively cohesive.

Maerl is a calcareous, free-living, red algae (rhodolith) that provides a niche habitat for an abundance of shallow water marine life. *Zostera sp.* is a type of seagrass found in shallow marine environments across the world. Like Maerl, *Zostera sp.* plays an important role in maintaining biodiversity (Dale, McAllen, & Whelan, 2007) and both are protected under annex V of the EC Habitats Directive (EC Council Directive 92/43/EEC). Both these species thrive in the euphotic zone and on heterogeneous sediment types (De Grave, 1999). Collectively, they compose ~5% of the substrate in Galway Bay and are found at depths <20 m and only in the very inner bay areas and in some of the Connemara inlets. They are found to inhabit all sediment types, from coarse to fine substrates. These areas experience a medium average bottom current velocity of 1.4 to 3 cm/s (Main Map) and a medium maximum wave velocity at 16 cm/s (Figure 2D). This moderate velocity appears to provide an environment where the maerl and *zostera sp.* communities are protected from the destructive force of waves and currents, yet fine sediment does not get a chance to settle on, and smother, these communities (Wilson, Blake, Berges, & Maggs, 2004).

4.4. Submerged landforms

Most mapped features occur in the inner- and outer-bay areas, are classified as submerged landforms and are defined by their shape, dimensions, and composition (Table 1). In the centre mid-bay area, no distinct bedforms are present (Main Map). This may be due to

Table 1. Summary of dimensions and other characteristics of submarine landforms in Galway Bay.

Feature	Length (m)	Wavelength (dunes)/width (m)	Depth/ height (m)	Lee slope (°)	Stoss slope (°)	Sediment type	Symmetry/shape
Drumlins	185–1500	60–300	2–6	Variable	Variable	Mixed	Elongate
Outer Bay Dunes-Gregory Sound	403–822	58–120	−8	3.75–26.5	7.15–30.5	Sand	Symmetrical with sharp crests
Outer Bay Dunes -In front of Aran Islands	70–390	6–25	0.1–0.5	Variable	Variable	Sand	Linear
Inner Bay Dunes	60–1370	133–250	1–3	4.3–7.5	1.1–5	Sand/Coarse/ Mixed	Asymmetrical/Crescentic/ Sinuous with rounded crest
Marine Terraces	Up to 23,000	Variable	Variable	Variable	Variable	Sand	Slightly sinuous
Scouring	Variable	Variable	−0.3 to −0.6	Variable – generally >45	Variable – generally >45	–	Variable
Pockmarks	<16–80	<16–80	−0.5 to −8	Variable	Variable	–	Circular/Oval
Channels (meso scale)	Variable – extending inland	2–460	−0.5 to −14	Variable – generally >39	Variable – generally >39	–	Slightly sinuous

weaker waves and currents that are not strong enough to generate them in this area.

4.4.1. Submerged landforms: subaqueous dunes, scours, pockmarks, channels, terraces, drumlins

Subaqueous dunes are large, flow-transverse bedforms and are the most common feature in the shallow shelf environments and are classified based on morphology and composition (Ashley, 1990; Terwindt, 1971). They are good indicators for hydrological conditions as they are controlled by flow depth, grain size, current velocity and direction (Ashley, 1990; Mazumder, 2003; Rubin & Mcculloch, 1980). As sediment transport and water flow and speed varies both spatially and temporally, this has given rise to various bedform sizes and morphologies and a wide range of nomenclature. However, as suggested by Ashley (1990), these bedforms are still a single genetic population and will be subsequently referred to as dunes.

Dunes are present in the inner bay (Figure 5A–D), between the islands of Inis Meáin and Inis Mór (Figure 6A) and located on the landward side of the Aran Islands, in front of Gregory's Sound (Figure 6C). In the inner bay there are 4 examples of dunes, a pair

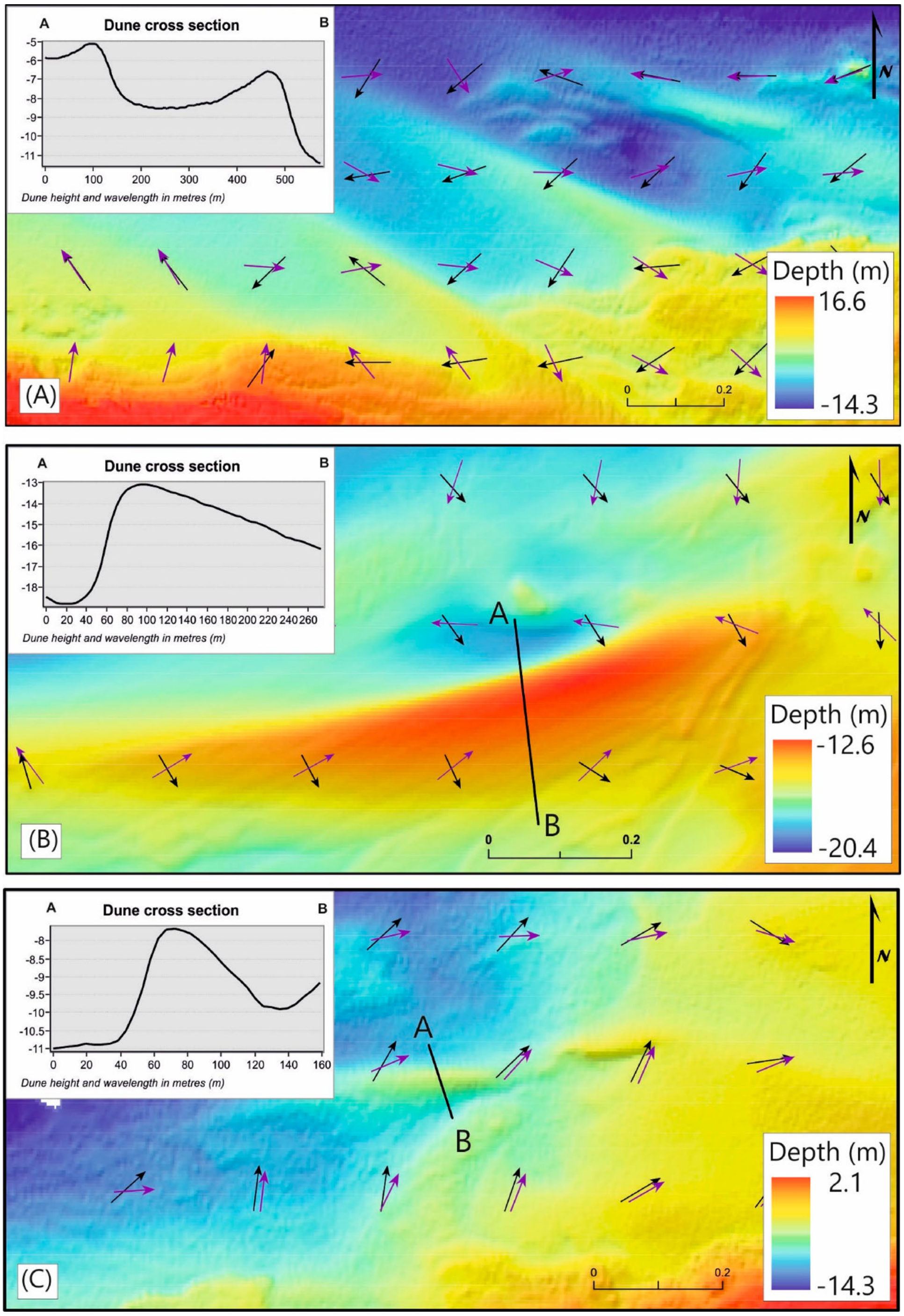

Figure 5. Cross section and bathymetric image of inner bay subaqueous dunes. The black arrows indicate bottom current direction while the purple arrows indicate depth-averaged current direction. The image shows both currents on a 200 m grid using the most frequent direction over a year.

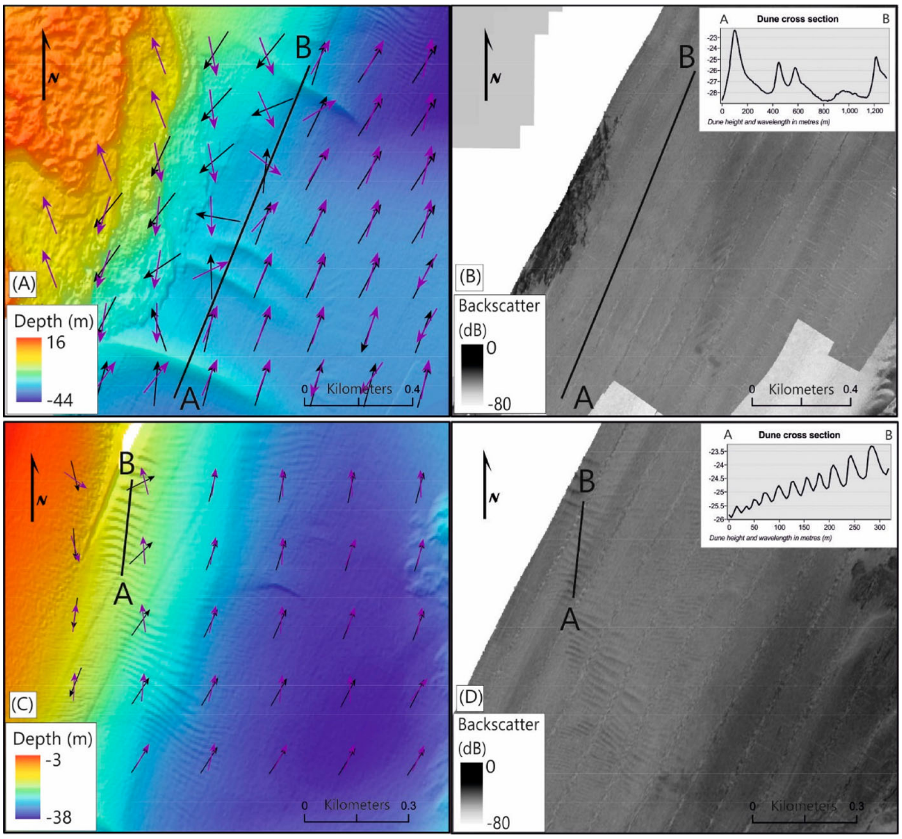

Figure 6. (A) bathymetry and (B) backscatter image of the larger outer bay dunes; (C) bathymetry and (D) backscatter of the smaller outer bay dunes; all including cross sections. The black arrows indicate bottom current direction while the purple arrows indicate depth-averaged current direction. The image shows both currents on a 200 m grid using the most frequent direction over a year.

found north of Rathmorgan along the coastline of Co. Clare (Figure 5A), and 2 isolated dunes directly north of Ballyvaughan (Figure 5B,C). The dunes north of Rathmorgan are linear, elongated and slightly asymmetrical with rounded crests and based on the backscatter return, composed of sand (Main Map). The dunes found directly north of Ballyvaughan (Figure 5B,C) have asymmetrical ridges. One is crescentic in shape, larger in size, and is composed of sand and coarser sediment (Figure 5B), while the other is sinuous in shape and composed entirely of sand (Figure 5C). The smaller dune (Figure 5C) is located in an area of marel/zostera (Main Map). This biological material may provide more cohesion within the dune and make it harder to erode (Parsons et al., 2016). The appearance of solitary dunes in the inner bay also suggests that there may be less sediment available for deposition in this area.

Based on the angles of the lee and stoss slopes (Table 1; Figure 5A–C), the depth-averaged currents, especially those flowing north and west, appear to more significant than the bottom currents in the formation of the dunes in the inner bay. This may be due to the very shallow water depths (<13 and <8 m at low tide) these bedforms are located in. However, as only the modal current over an annual period is displayed, less frequent currents could also be influencing the bedforms.

In the outer bay, the strong semi-diurnal tide and accelerated flow between the islands in the bay provides a perfect environment for the formation of the 4 large dunes found there (cf. Van Landeghem, Wheeler, Mitchell, & Sutton, 2009). These dunes are all composed of sand, and while 3 are linear (Figure 6A), one is crescentic in shape (the smallest dune, second from the top in Figure 6A). The dunes in front of the Aran Islands are composed of mud and sand, although all show a very low backscatter return but are surrounded by higher backscatter levels (Figure 6D), suggesting that they are surrounded by gravel and bedrock (Main Map). They extend over an area of 2.5 km^2 and have smaller dimensions than those found in the rest of the bay (Figure 6C). These dunes fit the morphology (Table 1) of bedforms under reversing flow by faster-restricted currents rather than by waves (cf. Selley, 2000).

In the deeper water of the outer bay, it is likely that the bottom currents are more influential in the formation of the dunes here, however, as the bottom and depth-averaged currents are flowing in the same direction in the outer bay (Figure 6A,C), we cannot confirm this.

Scour marks are defined as local depressions resulting from local-non-uniform flow over the seabed, around a topographic obstacle (Maity & Mazumder, 2014; Whitehouse, 1998). The pattern of scouring is directly related to the shape of the obstacle, flow direction and velocity, bed material characteristics and water depth (Richardson, Harrison, Richardson & Davis, 1993). Scouring is visible around the bedrock outcrops west of Black Rock Headland and to a lesser extent in the North and South Sounds. The scour marks (Figure 7A) are lined with coarse sediment, suggesting that the finer sediment has been winnowed away. The clear association with the bedrock outcrops in the area suggests that there is a complex interplay between the surrounding topography and the flow of currents related to scouring in the bay.

Pockmarks are concave, conical depressions commonly found along continental margins, shallow waters and deep-water basins worldwide (Rogers, Kelley, Belknap, Gontz, & Barnhardt, 2006; Sumida, Yoshinaga, Madureira, & Hovland, 2004; Wenau, Spieß, Pape, & Fekete, 2017), and are associated with fluid escape (Judd & Hovland, 2007). In Galway Bay, they are found exclusively near Barna and Rathmorgan. In the north, only five small (<16 m in diameter) pockmarks are visible, while in the south over 10 pockmarks are observed (Main Map, Figure 7B; Table 1). The pockmarks, as expected, do not correlate to wave or current velocities in either shape of location, occurring as both circular and elongated under fast and slow flow conditions.

There are meso- and macro-scale channels in the bay. The meso-scale channels are smaller channels confined to the inner-bay and to some areas along the northern coastline (Main Map). These channels are up to 14 m deep, 460 m wide and are clearly visible in intertidal areas. Many of these are either active channels or they are an indication of former active channels during periods of lower sea-level. The macro-scale channels are much larger, over 15 m deep and 1 km wide (i.e. the Sounds; Figure 1) between the Aran Islands and the mainland. The North and South Sounds, as well as, to a lesser extent, the Gregory's and Fowl Sounds provide the inlet for oceanic water into the bay and control water circulation (Main Map). The North Sound is the deepest channel in the bay (~77 m) and extends as far east as the mid-bay (~30 km inland). It is located along a fault line, where the contact point between the granite and limestone could make it prone to erosion by current oceanographic processes and the past movements of the BIIS across the region.

Along the northern edge of the bay from Spiddal to Lettermullan several ridges, up to 23 km in length are observed (Main Map). They show a seaward drop of ~5 m from a relatively flat platform on the landward side. The ridges from Spiddal to Rossaveel are composed of mud and sand, while the ridges found further eastwards are composed of sand (Main Map). Sea-level reconstructions for the region (Bradley, Milne, Shennan, & Edwards, 2011), show that their depth at ~20 and ~27 m coincides with sea-level positions between 11 and 14 ka BP. Due to their shape, depth and parallel position to the shoreline, it is believed that these are marine terraces (Martinez-Martos et al., 2016; Reis et al., 2013), submerged by rising sea levels and that they represent palaeo-shorelines.

Drumlins are elongate oval mounds, generally composed of mixed sediments, formed beneath an ice sheet and streamlined in the direction of the ice-flow (Clark, Hughes, Greenwood, Spagnolo, & Ng, 2009; Ó Cofaigh et al., 2016). Onshore drumlins are found in the inner-bay (Figure 8) and are ~60–300 m in width and ~185–1600 m in length. The submerged drumlins (Figure 8B) follow the same morphology and orientation as those on land (Table 1; Figure 8A). Reworking and flattening of their tops are visible, likely due to their position in the surf zone. Most of the drumlins in Galway Bay are NE-SW aligned, characterised by high backscatter intensity and composed of coarse or mixed sediments

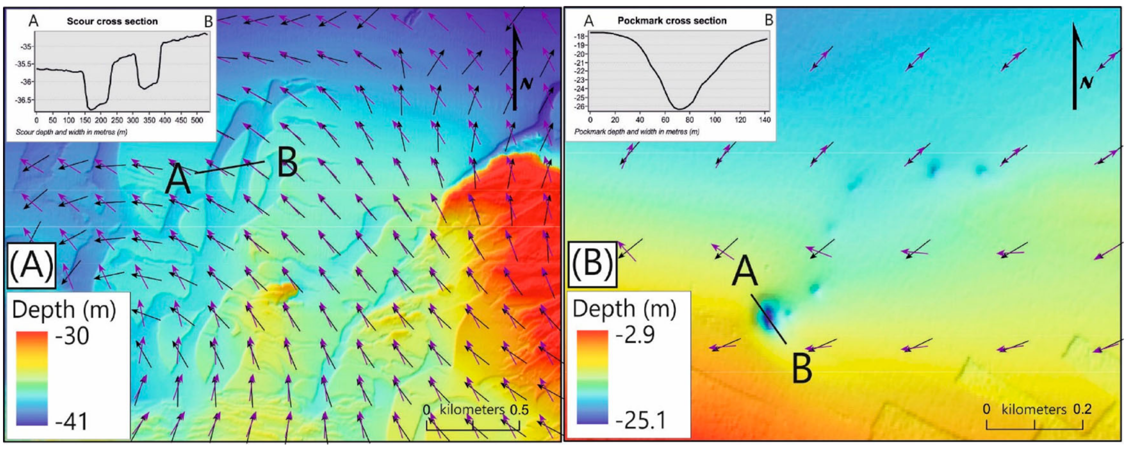

Figure 7. (A) Cross section and bathymetric image of scouring around bedrock in the mid-bay. (B) Cross section and bathymetric image of the largest pockmark visible in the bay. The black arrows indicate bottom current direction while the purple arrows indicate depth-averaged current direction in both images. The image shows both currents on a 200 m grid using the most frequent direction.

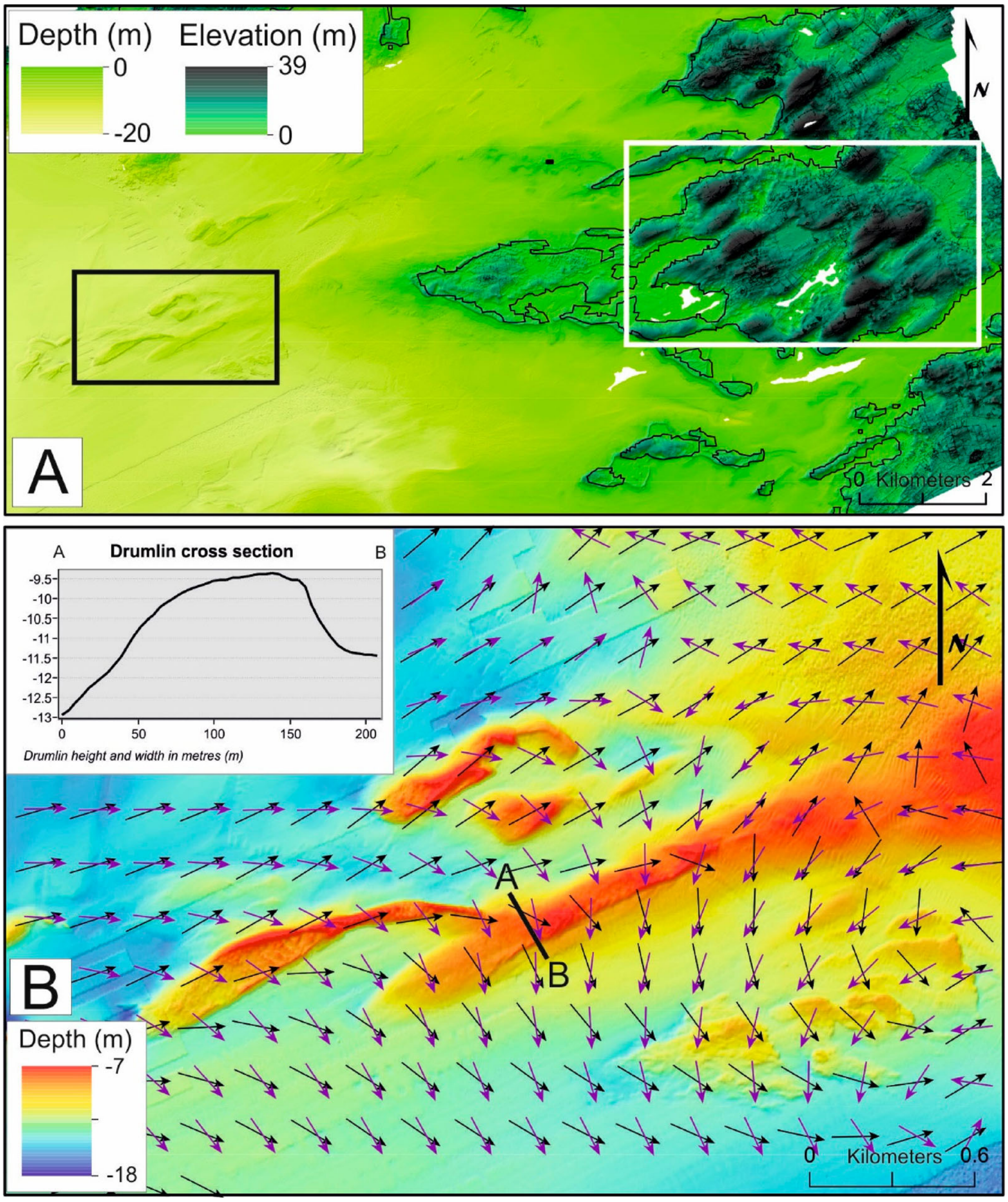

Figure 8. (A) Drumlin field visible onshore (white box) and a zoomed out inset of image B (black box). The black line represents the 0 m contour and present-day coastline. (B) Cross section and bathymetric image of drumlins visible in the bay. The black arrows indicate bottom current direction while the purple arrows indicate depth-averaged current direction. The image shows both currents on a 200 m grid using the most frequent direction.

(Main Map). The drumlins in the bay appear to be an extension of those mapped on land in Co. Galway and Co. Clare (Clark et al., 2018; McCabe & Dardis, 1989) and their orientation suggests ice flowing in an offshore direction.

5. Conclusions

The first geomorphological and substrate map of Galway Bay shows a mix of paleo-landforms, including drumlins and submerged shorelines, and bedforms formed and mobilised under present-day hydrological conditions. Bedforms are located near the Aran Islands, with a few lone dunes in the inner-bay. Erosional features, such as scouring and outcropping bedrock, are located mainly in the outer-bay. Bottom and surface currents as well as wave action all play an important part in the hydrology of the bay, with the depth-averaged currents being more influential on the geomorphology in the shallower inner-bay and bottom currents more influential in the deeper mid- and outer-bay. The substrate classification identifies Maerl and *Zostera sp.* marine habitats, which play an important role in maintaining biodiversity and are both protected under EC Habitats Directives. It is important to note that the data used were collected almost 10 years ago. Based on these interpretations, it is possible for these features to undergo evolution or migration under current hydrodynamic conditions. This research provides a basemap for future assessment of sediment mobility and habitat distribution through repeat surveys and the ensuing analysis of time-series data. It also provides a practical resource to promote sustainable development in the bay, in particular with regards to the planned extension of Galway harbour and for the proposed installation of renewable energy converters in the bay.

Software

The multibeam data were processed and erroneous sounding and outlier points were removed using the dedicated, commercial software CARIS HIPS & SIPS. LiDAR data were also merged with multibeam bathymetric data in CARIS. The processed data were exported as ASCII XYZ datasets and imported in ESRI ArcGIS and ensuing handling of the data was carried out using several of the tools available in ArcGIS including Spatial Analyst and profiling tools. Multibeam backscatter was processed and gridded using the Geocoder algorithm in CARIS HIPS & SIPS and imported into QTC Multiview for the classification of acoustic classes. The results from QTC Multiview were merged with the additional operator's interpretation of rock outcrops in a single habitat map layer in ArcGIS.

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