Mapping Ireland’s coastal, shelf and deep-water environments using illustrative case studies to highlight the impact of seabed mapping on the generation of blue knowledge

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Abstract: Through Ireland’s national seabed mapping programme, Integrated Mapping for the Sustainable Development of Ireland’s Marine Resource (INFOMAR), the collaboration between Geological Survey Ireland and the Marine Institute continues to comprehensively map Ireland’s marine territory in high resolution. Through its work, the programme builds on earlier Irish seabed mapping efforts, including the Irish National Seabed Survey project in producing seabed mapping products that support Ireland’s blue economy, European marine policy and international efforts to understand our global oceans. INFOMAR uses a variety of marine technologies to deliver accurate bathymetric maps and useful data products to end users through a free and open source licensing agreement. To reflect the diversity of applications these data products serve, a series of four case studies are presented here focusing on marine geophysical and geological data from locations within Ireland’s marine territories. The case studies illustrate how data generated through seabed mapping may be interpreted to directly impact the generation of blue knowledge across a variety of marine environments ranging from shallow coastal and shelf waters to the deep oceanic depths of the continental slope of Ireland’s marine area. The impact of Ireland’s seabed mapping efforts is further considered in the context of national, European and international initiatives where Ireland’s marine knowledge resource is leveraged to deliver positive benefit to the programme’s stakeholders.

A history of Irish seabed mapping

Deep-water hydrographic and geophysical survey operations to designate the boundaries of the Irish continental margin in support of Ireland’s United Nations Convention on the Law of the Sea (UNCLOS) maritime territorial claims began offshore Ireland in 1996 (Naylor et al. 1999), conducted by Ireland’s Petroleum Affairs Division on behalf of the Government of Ireland. Findings reinforced the need for a comprehensive assessment of the entire Irish seabed. The Geological Survey Ireland (GSI)-managed Irish National Seabed Survey followed (INSS, 2000–06), an ambitious but successful programme to survey Ireland’s entire deep-water territory beyond 200 m water depth (Verbruggen and Cullen 2008). With national interests and development opportunities largely coastal and shelf based, and with one of the most detailed offshore cohesive seabed mapping knowledge resources available globally in 2006, mapping the gaps naturally evolved into a follow-on national seabed survey initiative through a joint venture between GSI and the Marine Institute. The INtegrated mapping FOr the sustainable development of Ireland’s MaRine Resource (INFOMAR) programme was initiated to survey the remaining shelf and coastal waters between 2006 and 2026, to deliver a seamless baseline bathymetry dataset to underpin the future management of Ireland’s marine resource (Dorschel et al. 2010).

To leverage the €80 m financial support required after INSS for mapping the gaps in the coastal, shelf and inshore waters of Ireland, a comprehensive review was commissioned to consider the programme approach, cost and survey priorities. This informed a two-phase programme strategy subsequently developed (INFOMAR 2007) that outlined the approach, outputs and anticipated beneficiaries. Phase 1, which was completed in 2015, focused on mapping 26 priority bays and 3 priority offshore areas that were deemed to be of most economic
significance to the country. Phase 2, which commenced in 2016, is focused on mapping the remaining unsurveyed marine areas and building on the knowledge and expertise generated through the initial project phase.

Following Government of Ireland approval and INFOMAR’s commencement in 2006, the joint programme management of GSI and Marine Institute coordinated a seminal cost benefit analysis (CBA) to investigate the economic impact of the seabed mapping initiative across all marine sectors (PwC 2008). Taking a conservative approach, a 4–6 times return on investment was reported, depending on the duration over which the programme was completed. This proved to be a critical assessment in securing future annual programme investment, particularly despite national fiscal challenges from 2008 onwards. Subsequent independent reviews commissioned by the programme carried out by PwC and Risk Solutions have further supported the case for continued seabed mapping, with key recommendations tabled and implemented incrementally year-on-year (PwC 2013; Risk Solutions 2016).

INFOMAR is a key cross-sectoral enabling action in Ireland’s integrated marine plan, ‘Harnessing Our Ocean Wealth’ (Government of Ireland 2012) with an oversight Board and Technical Advisory Committee (TAC) governance structure ensuring its relevance to all key stakeholders nationally. The primary marine bathymetry dataset derived from full coverage high-resolution multibeam echosounder surveying, is critical for the development of Ireland’s marine knowledge, economy and policy, as well as the protection of its marine environment. With an ethos of improving efficiency and embracing innovation, domestically the programme supports the needs of Irish society, industry and government, while internationally it contributes to numerous EU Directive-related reporting, regulatory and monitoring obligations (PwC 2013).

Knowledge as a marine resource

Ireland’s seabed mapping efforts initially began with the aim of developing a marine baseline dataset to underpin national security as well as future economic, environmental, infrastructural and policy decisions for Ireland as set out in the INFOMAR Proposal and Strategy. With more than 20 years of seabed mapping undertaken to date, this endeavour is being steadily achieved with over 700,000 km² of the seafloor within the Irish designated area mapped to date in high resolution (Fig. 1).

Shallow water mapping reveals uncharted rocks and unknown shipwrecks, delivering safe navigation data within the busiest zones for marine traffic. Data describing the geomorphology of the seabed enable accurate oceanographic modelling to assess coastal flooding and erosion risk, as well as state-of-the-art ecosystem investigations such as assessing the aquaculture-carrying capacity of inshore waters. Shelf and offshore mapping provides a foundation for aggregate resource and habitat assessments, informing permitting and development decisions, while enabling protection of key fish spawning and nursery grounds (Sutton 2008). Collectively, these coastal and offshore marine data enrich the efforts of Ireland’s research community who analyse the bathymetry data for a multitude of applications.

As of 2019, Ireland’s database of marine data has grown in excess of 120 terabytes (TB) and continues to expand. The database comprises a range of geophysical data measurements including multibeam echosounder (MBES) bathymetry and backscatter, shallow seismic profiles, gravity, magnetics, sidescan sonar and oceanographic water column profiles. It also houses information on the many physical ground-truthing samples and interpreted observations including, for example, shipwreck discoveries of which there are currently 426 listed in the INFOMAR database.

One of the key drivers behind the successful uptake of Ireland’s seafloor mapping data has been the Irish government’s Open Data Initiative (DPER 2017). Supported by the Union (EU) Open Data Directive (EU 2019), this major government initiative ensures that INFOMAR data are freely available to the public. Online access is favoured as a direct route to the range of high-quality data and data products produced. The revised programme website, relaunched in November 2018 has been developed with the aim of providing a contemporary feel for the end user, while strengthening the value of programme outputs. Provision of straightforward access to the data is a key objective. This has been accomplished through the production of web map services (WMS) and availability of embedded data viewers. A simple web-viewer available on the website homepage allows for the visualization and exploration of Ireland’s marine territory in detail and is capable of displaying multiple layers of seafloor information. The programme’s official data download portal is the Interactive Web Data Delivery System (IWDDS), which is accessible through the INFOMAR website and provides free and open data to programme stakeholders.

Key products, designed around stakeholder requirements include Geographical Information System (GIS)-compatible datasets: bathymetry, backscatter and shaded relief as geo-referenced images; sediment samples and shipwrecks as point files; sediment classification and survey coverage as polygon files; and survey track lines as polyline files. In addition, raw data are made available on request for those working with non-standard applications and
software. For users who are unfamiliar with GIS processes or other technical software, the data are available in formats that can be easily displayed on widely available free software and viewers such as Google Earth.

Integration of regional marine data from the world’s oceans enhances our understanding of the Earth’s coasts, seas and oceans as a globally connected system. To support the integration of marine knowledge for cross-border, European and international collaborations, Ireland’s seabed mapping datasets are analysed and interpreted by programme staff to produce standardized products and metadata compatible with international initiatives. The European Marine Observation and Data Network (EMODnet) is a large-scale pan-European marine data initiative (Kaskela et al. 2019). Funded by the European Commission, it aims to implement the EU’s Marine Knowledge 2020 strategy (EU 2010). The INFOMAR seabed-mapping programme has contributed data to EMODnet’s Bathymetry, Geology and Seabed Habitats lots. Through these projects, pan-European data products that include Irish data are freely available for global dissemination and usage.

INFOMAR programme data are further distributed through international open-access data portals: for example, the National Oceanic and Atmospheric Administration (NOAA) archives, where the NOAA Bathymetric Data Viewer enables users to view and download raw and processed seabed mapping data from Ireland’s past and present seabed programmes. Through this well-known facility, Irish seabed data reach a broad global network of potential end users. These data resources are also integrated in the Nippon Foundation’s Generalised Bathymetric Chart of the Ocean (GEBCO) compilation and are one of the largest data contributors to the Seabed 2030 initiative (Mayer et al. 2018). Additionally, through participation in international partnerships such as AORA (Atlantic Ocean Research Alliance), ASMIWG (Atlantic Seabed Mapping International Working Group) and CHERISH (Climate, Heritage and Environments of Reefs, Islands and...
Headlands) Ireland’s seabed mapping results are further distributed to a broad international community of multidisciplinary data end users.

Irish seabed mapping case studies: enhancing our knowledge of Ireland’s marine environment

Gauging the impact of Ireland’s marine data dissemination strategy and wider activity at national, European and international levels is a subject that will be considered further in this paper; however, to illustrate the impact of how baseline seabed mapping datasets and products can be utilized to enhance our understanding of the marine environment, generating new knowledge and insights, a series of four case studies is presented in this paper.

The case studies focus on a variety of marine environments found within Ireland’s designated marine territory (Fig. 1), traversing from the coastal, shallow waters of the inshore marine areas, progressing across the continental shelf and onwards to the continental slope and deep ocean floor. These case studies consist of four individual interpretations of Irish marine data that illustrate how analysis of Ireland’s marine data resources can enhance the understanding of Ireland’s marine environment, geology and submerged landscapes.

The first case study focuses on the Hook Head peninsula and Waterford Estuary. This study illustrates how high-resolution MBES datasets can be used to explore a potential submerged landscape. Offshore extrapolation of onshore geological features and interpretation of overlaying bathymetric characteristics reveals information about submerged landscapes and the Last Glacial Maximum (LGM). The second case study is located further out to sea, SE of Ireland, on the Irish continental shelf and represents a detailed overview of the programme’s mapping rationale, approach and procedures when surveying and analysing a specific survey block. Geological and geophysical data including multibeam sonar data are recorded to reveal substrate geology and environmental information. As the site is known for its significance to the Irish fishing sector as a Nephrops fishery, the impact of the blue knowledge generated through seafloor, substrate and habitat mapping is also described, facilitating enhanced stock assessments. The third case study presented focuses on a dynamic shelf environment offshore North Donegal. The study details interpretation of baseline multibeam sonar data that infer a high-energy dynamic environment from mobile sedimentary seabed features. A resurveying of the area is used in correlation with existing hydrographic models to examine the driving forces of sediment mobility in this region. The study is made all the more relevant by the possibility of future development of renewable energy infrastructure at the site and provides a wealth of knowledge on the types of considerations that will be instrumental for future offshore development plans. The fourth case study details an overview of deep-water geological and geophysical data. These data were used in conjunction with INSS and INFOMAR bathymetry data to produce the first bedrock map of Ireland’s offshore Exclusive Economic Zone (EEZ) as part of work undertaken for the EMODnet Geology project. Now complete, the map details a chronology of Ireland’s geological history dating back to the Grampian. Geological knowledge of this kind can be applied in support of multiple applications including: habitat mapping; marine spatial planning; environmental conservation; and resource mapping.

Taken together, these case studies are effective in demonstrating the value of seabed mapping in furthering our understanding of the broad range of marine environments that make up Ireland’s marine resource. Finally, this paper considers the impact of Ireland’s seabed mapping efforts as they relate to national, European and international initiatives, education, research and industry and reflects on Ireland’s future activities and prospects in the sphere of marine and ocean science at the beginning of the United Nations Decade of Ocean Science for Sustainable Development (2020–30) movement as Ireland continues in its aim to map, observe and predict its coasts, seas and oceans.

Case study 1: a coastal submerged landscape; Hook Head – a seabed within a seabed

The extent of exposure of Ireland’s continental shelf due to a lower sea-level during and following the last glaciation is still being understood, but bathymetry data from Ireland’s seabed mapping data resource present compelling evidence for potential submerged landscapes in the country’s coastal and near-shore environment. Submerged landscapes are features on or below the seafloor that can be reasonably deduced to have been subaerially exposed in the past, before sea-level rose to where it is today. One place where INFOMAR bathymetry data help build a strong case for the presence of submerged landscapes is Waterford Estuary on the south coast of Ireland. In this study, high-resolution shaded relief bathymetry from Waterford Estuary and its surrounding area has been used to infer the presence of these submerged seafloor features in conjunction with contemporary geological knowledge from the area in order to consider the relationship between terrestrial observations and the potential submerged landscape features identifiable in the shaded relief...
bathymetry data. By visualizing bathymetry data at high resolution and adjusting parameters such as hill shading and water depth colour-scale, these data can be used to identify and represent images of underwater outcrop and submerged, ancient landscape features.

High-resolution MBES bathymetry data featured in this study were acquired during ongoing INFO-MAR inshore survey operations. Acoustic soundings data were processed using a Teledyne-CARIS HIPS & SIPS™ hydrographic software package. Tidal and navigation corrections, sound velocity and noise cleaning processes were applied to the data in order to generate a high resolution bathymetric grid of the study area in the World Geodetic System 1984 (WGS84) Coordinate Reference System (CRS) and vertically referenced to Lowest Astronomical Tide (LAT) using the United Kingdom Hydrographic Office (UKHO) Vertical Offshore Reference Frame (VORF) model (Ziebart et al. 2007). The resulting bathymetric grids were exported in a standard ESRI™ format and brought into ARC-GIS™ software for further analysis and juxtaposition with GSI’s 1:100 000-scale geological map series. This methodology allowed for a broad examination of the study area’s seafloor morphology in the context of potential submerged landscapes and the area’s geological history as determined from terrestrial-based studies.

Hook Head, County Wexford is a prominent peninsula in the SE of Ireland located at the eastern bank of Waterford Estuary (Fig. 2). It is comprised of rocks ranging from Cambrian in age to Devonian and continues upwards into a Lower Carboniferous limestone assemblage (GSI 2018). The geological record of Hook Head and its modern, adjacent seabed details an evolution through continental collision, both ancient and modern sea-level as well as glaciation. Around the base of its scenic lighthouse, Carboniferous coral fossils are exposed in abundance in subaerial conditions (Sleeman et al. 1974). One can walk over rocks that were once submerged calcareous deposits on a tropical seafloor akin to the present-day Bahamas. This once coral-rich seabed, however, now lithified and uplifted, forms the modern limestone seabed as we move from the headland, underwater, down below contemporary sea-level. This rock, detailed using high-resolution nearshore bathymetry (Fig. 3), is a substrate for modern sea life. Modern geological processes and sea-level change have facilitated the phenomenon where the modern seabed sits directly atop the ancient Carboniferous seabed, each separated in time by more than 300 Ma.

On land, the solid geology of Hook Head is well documented (Tietzch-Tyler and Sleeman 1994). The peninsula is long and narrow, consisting of

![Fig. 2. Geology of Hook Head peninsula, Co. Wexford overlaying grey-scale hillshade bathymetric layer.](http://sp.lyellcollection.org/Downloaded from)
geological formations that, as we step in a southward direction off the ancient Cambrian basement of the mainland, span from the Devonian through to the Carboniferous. The story of sea-level and environmental change here begins with the ancient Cambrian rock, formed from the accumulation of deep-water slope sediments on a continental margin of the long-gone Iapetus Ocean around 500 Ma ago (Tietzsch-Tyler and Sleeman 1994). Following this, continental collision resulted in the building of an ancient mountain chain – the Caledonian Orogeny – during which the Iapetus Ocean was closed and a large continental landmass formed (Tietzsch-Tyler and Sleeman 1994). The Old Red Sandstones of the Devonian, comprising the peninsula’s landward end (Fig. 2), were originally laid down in an alluvial setting as these Caledonian mountains were eroded (Woodcock and Strachan 2002). The Lower Carboniferous then saw a gradually northward-advancing sea, with the sedimentary rocks overlying the Old Red Sandstones formed in marine conditions (Tietzsch-Tyler and Sleeman 1994). The Old Red Sandstones of the Devonian, comprising the peninsula’s landward end (Fig. 2), were originally laid down in an alluvial setting as these Caledonian mountains were eroded (Woodcock and Strachan 2002). The Lower Carboniferous then saw a gradually northward-advancing sea, with the sedimentary rocks overlying the Old Red Sandstones formed in marine conditions again. At this point, continental drift had brought Ireland’s ancestral basement rocks close to the equator and so these shallow seas were tropical and teeming with prehistoric life, such as corals, brachiopods, crinoids and bryozoans (Meere et al. 2013). These are the fossils underfoot as one stands on the shoreline below Hook Head lighthouse. As we depart the southernmost tip of the peninsula and proceed underwater, detailed seafloor bathymetry illustrates the probable continuation of these stratigraphic units offshore (Fig. 3).

Deposits that were once laid down in a warm tropical environment now form the hard substrate below the present-day Celtic Sea. This same substrate was only recently inundated, however, on a geological timescale. During the last ice age, the area was glaciated, with evidence for the advance of a grounded Irish Sea glacier (Ó Cofaigh and Evans 2001). Following the LGM, 27 000 ka BP (Clark et al. 2012), the ice sheets receded rapidly, albeit unevenly, due to climatic warming (Chiverrell et al. 2013). However, sea-level remained low during a period of isostatic rebound that temporarily outpaced the inevitable sea-level rise due to meltwater (Edwards and Brooks 2008).

Waterford Estuary extended further out to sea and the coastline in the area was further south. This is clearly visible in the bathymetry data in Figure 4. Interpretation of the shaded relief bathymetry (Fig. 4) allows the erosion pattern of the bedrock to be visualized as a possible palaeochannel extension. Beyond the harbour mouth, despite recent marine sedimentation, the expression of the palaeochannel is visible in the bathymetric imagery in the mouth of Waterford Estuary (between Dunmore...
Fig. 4. Coastal bathymetry around Waterford estuary displaying: (1) possible palaeochannel extension; (2) submerged meandering channel feature; and (3) ridge features interpreted as possible eskers.
East and Hook Head) as a readily identifiable seafloor feature, a bathymetric low, between areas of bedrock. Studies have traced this palaeochannel further offshore and indicate that the channel contained much higher water flows than the present day and so may have been formed by discharges of meltwater, flowing with great energy from the ice and out over the exposed shelf (Gallagher 2002).

Along with the palaeochannel, the ridge features interpreted from the bathymetry marked in Figure 4 have been suggested to be eskers, laid down during glaciation in tunnels of meltwater below the ice (Tóth et al. 2016). As the ice retreated, these may have formed prominent subaerial landscape features for a time before the sea transgressed northwards. So, in addition to the Carboniferous transgression, examination of the seabed features in the study area suggests a story of more recent sea-level change too.

High-resolution bathymetry acquired in the region, highlights additional channel features cutting through the bedrock (Fig. 4). Also interpreted from the seafloor imagery is a meandering gap in the bedrock with a ribbon-like geometry. This feature may be related to terrestrial drainage systems, much like the rivers we see on land today. This is inferred as a relic of the terrestrial landscape that post-dates the ice age and pre-dates the significant sea-level rise. Sea-level rise lagged behind the receding ice (Edwards and Brooks 2008).

In summary, high-quality bathymetry data reveal the exposed bedrock offshore Hook Head (Fig. 2), the lithology and structure of which can be extrapolated from detailed geological mapping on land. Here the stratigraphy reveals Cambrian deep-water sedimentation giving way to terrestrial conditions in the Devonian. These are sequentially followed by fossiliferous lithologies laid down in Carboniferous shallow tropical seas. More recent potential Esker deposits result from the last ice age, now drowned by recent sea-level rise. Further offshore, the deepening seafloor disappears under a blanket of recent Holocene marine sedimentation. By combining terrestrial geological observations and studies with state-of-the-art bathymetric seafloor imagery in the manner described, a picture of ancient and more recent coastal change and evolution can be generated.

In mapping the spatial distribution of probable submerged landscape features to a high degree of accuracy and resolution, data products from the INFOMAR programme support research into past climate change. The dating and further interpretation and study of these features may help constrain the position of Ireland’s palaeocoastline at different times in the geological record, thus helping to recreate past sea-level curves. Such information is important for informing models of future sea-level rise and the coastline’s response to a changing climate. In addition, using modern bathymetric imagery to enhance the understanding of our ancient and fascinating heritage beyond the coastline and sharing that knowledge with the public promotes Ocean Literacy, which presently aims to raise awareness of the ocean’s impact on our lives (NOAA 2013) at a vital time for the protection of the marine environment.

Case study 2: characterizing underwater channels on the Celtic Sea shelf, Southern Ireland

As part of the INFOMAR programme’s 2018 seabed mapping campaign, the RV Celtic Voyager mapped seabed adjacent to the Ireland/UK EEZ in the Celtic Sea. Figure 5a shows the chart outlining the designated survey area prior to commencement of survey operations. Mapping was conducted over 74 charter days and 3 separate surveys. It is an important area for a number of commercial fish species. Figure 5b shows the final multibeam bathymetry survey coverage for the campaign with prominent channels annotated.

As with all INFOMAR seabed mapping campaigns conducted on the RV Celtic Voyager, geophysical datasets acquired included multibeam bathymetry, backscatter and sub-bottom profiler data. Shaded relief and substrate slope angle products are produced from the multibeam bathymetry data and ground-truth data from sediment grabs augmented the backscatter data. For these three surveys in 2018 the RV Celtic Voyager mapped a total area of 5650 km$^2$ in water depths ranging from 78 to 124 m as shown in Figure 5b.

Three large-scale channels are observed within this region of Ireland’s continental shelf (Fig. 5b). One of the channels, known colloquially as ‘The Trench’, had not been previously well defined. As a result of the survey campaign, ‘The Trench’ is now mapped in high resolution and charted with two additional channels close by. All three channels are detailed here with data acquisition methodology and scientific results. They are significant geomorphological features and form a part of the important Nephrops fishery of the Celtic Sea Mud patch. The Trench comprises 177 km$^2$ of the 14 469 km$^2$ Celtic Sea Mud patch area currently surveyed for Nephrops stock assessment. It is a fishery yielding landings in the region of approximately 5000 tonnes annually over the last decade (Doyle et al. 2019) and, in 2018, Irish landings were worth around €56 m (White et al. 2019) at first sale.

High-resolution multibeam bathymetry and backscatter (Fig. 6) data were acquired and presented along with the derived shaded relief images illustrated in Figure 7, while substrate slope angle
Fig. 5. (a) RV *Celtic Voyager*-designated survey area, Celtic Sea shelf, Southern Ireland and bathymetry chart of mapped area (b).
products documented in Figure 8 were derived from the underlying bathymetry. Sub-bottom profiler data (Fig. 9) from channels 1 and 2 have been analysed and interpreted resulting in overburden thickness plots, which are displayed over the backscatter and shaded relief imagery respectively in Figures 6 and 7. Ground-truth data and sub-bottom track lines of interpreted profiles are overlain on both the backscatter and shaded relief data. For this study, a combination of bathymetry, backscatter, sub-bottom profiler and ground-truthing data are analysed and interpreted in order to illustrate the impact of integrating multiple data sources for the characterization of a commercially and environmentally significant area of Ireland’s marine territory.

The standard survey line pattern selected for this operation represented east–west reciprocal lines with a line spacing of approximately 400 m. A Kongsberg EM2040 high resolution MBES mounted on a retractable pole was used for swathe acoustic acquisition. Backscatter acquired by multibeam sonars contains important information about the seafloor and its physical properties (Lurton et al. 2015). This information provided valuable data for seafloor classification and important auxiliary information for a bathymetric survey. A hull-mounted pinger source 2 × 2 transducer array sub-bottom profiler operating at 3.5 kHz was used for sub-bottom data acquisition. The sweep time was varied appropriately with water depth to maximize ping rate and resolution. The pinger source is chosen as most effective in investigations of the top 20 or 30 m sub-seabed and where sediments are fine to medium grained as readings indicated for this area.

Ground-truthing stations for validating the multibeam interpretations were acquired using a Day grab sampler. The Day grab was deployed from the starboard side of the vessel and gave consistently full samples with no empty returns during the operation. Grab-sample locations were selected based on expert interpretation of the multibeam backscatter data and geographical spread when possible; however, opportunistic samples were also acquired at Sound Velocity Profile (SVP) stations occasionally. A total of ten grab samples were acquired within or proximal to the channels. Samples were photographed and

Fig. 6. Sub-bottom profiler lines overlain on backscatter for (a & b) Channel 1 and (c) Channel 2.

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described. All samples will undergo particle size analysis, the results of which will be used to create substrate maps which become available through the INFOMAR website as they are generated and finalized. Substrate maps are important for the purposes of fisheries management. They help plan the locations of sampling stations for stock assessment surveys and also can be used to correlate catch data with sediment type in order to estimate the abundance of the stock. Currently, the map for the Celtic Sea channel slope analysis for (a) Channel 1 and (b) Channels 2 and 3.
Sea is a broadscale European Nature Information System (EUNIS) habitat map made up from interpolated benthic samples and known sediment types based on data from Vessel Monitoring System (VMS) on targeted fisheries (e.g. Nephrops). This map is currently being updated using interpreted high-resolution acoustic data from newly acquired MBES data and opportunistic samples. The new map will be classified to Folk and will be refined into a broad benthic habitat map using bathymetry and other environmental data as part of the programme’s ongoing commitment to produce high-quality data products from its mapping outputs.

Bathymetry grids, shaded relief and bathymetry geotiff images were created in Teledyne CARIS HIPS & SIPS™ software. Backscatter mosaics were created in QPS FMGT™ software. Geotiffs and grids were imported into ESRI ArcGIS™ software where substrate slope maps can be created from the respective bathymetry grids using the ‘Surface Slope’ function in ArcToolbox™.

Figure 5b displays the resulting multibeam bathymetry data with the most prominent channels in the area annotated. Channel 1 stretches from the NE to the SW in a sinuous shape spanning a distance of nearly 50 km. Its margins are well defined for the most part. Channel seafloor depth varies from approximately 100 to 120 m and its width varies from 400 m to 2.5 km. The northern limit of this channel extends beyond the boundary of our data. Channel 2 is orientated along a NE to SW axis. It is approximately 18 km in length with well-defined channel margins. An elevated area of substrate separates it from Channels 1 and 3. Seafloor depth ranges from 103 to 124 m in Channel 2. Channel 3 runs from the north of the area in a south-southwesterly direction where it intersects with the elevated area between Channels 1 and 2. Bathymetry varies from 87 to 106 m within this channel and it deepens from north to south. Channel 3 spans approximately 30 km. All three channels terminate in the same area. A number of other large-scale channels are also observed in the multibeam bathymetry data.

Sub-bottom profiler data for four selected channel infill survey lines were played back through CodaOctopus GeoSurvey™, which is an advanced software package for processing and interpretation of sub-bottom data. Seabed tracking, a bandpass filter with low-cut 1000 Hz and high-cut 4700 Hz, heave correction and a suitable display gain were applied to the data. The bedrock horizon was digitized on each profile using the tagging function in CodaOctopus GeoSurvey™. Two-way travel time to the bedrock horizon was used to calculate overburden thickness. Text files were exported containing position and overburden thickness. The files were imported into ArcGIS, overburden thickness was plotted and then overlain on multibeam backscatter (Fig. 6) and shaded relief data (Fig. 7). Figure 9a and b show raw data for sub-bottom profiler lines 280 and 282 (Channel 1) and Figure 9c and d show raw data for sub-bottom profiler lines 138 and 141 (Channel 2). These four lines were selected for interpretation and analysis. All lines were acquired in the centre of the channels and parallel to channel axes.

Figure 7a and b show the interpreted sub-bottom profiler data for lines 282 and 280 respectively.

![Sub-Bottom Profiler Data](image)

**Fig. 9.** Sub-bottom profiler data for lines (a) 0138, (b) 0141, (c) 0280 and (d) 0282.
overlain on multibeam shaded relief data. Each node on the images represents the overburden thickness at those locations. Bedrock is evident throughout the entire length of both survey lines, mostly at depth but sporadically as seabed outcrop. The maximum overburden thickness on profile line 280 is 7.4 m and 9.2 m on line 282. Greatest overburden thickness correlates with topographic lows on the bedrock horizon, where sediments infill these depressions. Figure 7c shows sub-bottom profiler lines 138 and 141 overlain on multibeam shaded relief data. Outcropping bedrock is signified by an absence of interpreted nodes. The survey track lines are shown in black. Bedrock is evident throughout the entire length of both survey lines; mostly as sub-crop but outcropping bedrock is common. There is a correlation between overburden thickness and bathymetry on Figure 7c with greatest thickness occurring under the greatest water depths. Deepest water depths also coincide with topographic lows in the bedrock horizon. Digital imagery (Fig. 9) of the sub-bottom profiler lines infers that bedrock forms the base unit of each survey line. Sub-bottom line 138 (Fig. 9a) has a clearly defined bedrock horizon. Between the top of bedrock and base of the Quaternary is an unconformity. Bedrock outcrops in two distinct sections on the northern half of the line. The bedrock is unconformably overlain by unconsolidated sediments. This unit contains a number of internal reflectors. It is the topmost unit except where bedrock outcrops. Sub-bottom line 141 (Fig. 9b) shows the bedrock unconformity surface to be rugged in character. The digital imagery also shows that the bedrock is unconformably overlain by the unconsolidated sedimentary unit. This unit forms two large infills separated by outcropping bedrock. The maximum thickness of the soft sediment unit is almost 20 m. Several internal reflectors are present within this unit. Sub-bottom line 280 (Fig. 9c) indicates the top of bedrock surface on this profile is smoother in character than that of the previous two analysed profiles. Bedrock only outcrops near the northern end of the profile and it is unconformably overlain by an unconsolidated sedimentary unit elsewhere. This sedimentary unit attains a maximum thickness of over 7 m. Sporadic internal reflectors are present in the unit. The sub-bottom line 281 profile (Fig. 9d) shows that bedrock outcrops at the southern end and in several locations along the profile. The bedrock horizon is rather smooth, similar to the adjacent profile 280. The unconsolidated sedimentary unit attains a maximum thickness of over 9 m.

The channel substrates appear as relatively low-intensity backscatter returns (Fig. 6). These low-intensity backscatter returns coincide with smooth bathymetry data, suggesting fine-grained sediments. Small localized areas of relatively high backscatter returns are also evident within the channels and along channel margins. Correlating backscatter data with the bathymetry suggests that the high backscatter returns along channel margins and within parts of the channels comprise bedrock.

The substrate slope map of Channel 1 and surrounding areas is presented in Figure 8a. A slope scale of 0 to >10° is used with corresponding green to red colour coding. The dark red colour indicates a substrate slope of at least 10°. The substrate in the broad area surrounding the channels is characterized by having a very gentle slope. These gently sloping areas are shaded green. Channel margins are very well defined on the substrate slope map, showing up as yellow and red shading. The substrate slope angles along the channel margins, while well defined, are for the most part moderately sloping, with localized steep slopes. Channel margins with slopes of less than 10° are typical but localized slopes greater than 20° are found within the area. The northern margin of Channel 1 contains the steepest slope angles and is best defined. Maximum slope angles of over 20° are observed. Figure 8b is the substrate slope map for Channels 2 and 3 and their surroundings. Channel 2 is better defined than Channel 3 in terms of slope angles along channel margins. Channel 3 margins are almost all less than 10° but slope angles greater than 10° are evident along Channel 2 margins. Maximum slope angles of over 15° are found along Channel 2.

In summary, INFOMAR hydrographic and geophysical regional mapping surveys carried out in an area of the Celtic Sea, known to be an important fisheries ground for Nephrops (Marine Institute 2009), observed large-scale channel seafloor features on the multibeam and sub-bottom profiler data. Analysis of sub-bottom profiler data acquired within Channels 1 and 2 shows unconsolidated sediments with a maximum thickness of over 19 m and sporadic bedrock outcrop. The unconsolidated sediments unconformably overlie bedrock. Multibeam bathymetry data from Channels 1 and 2 indicate that water depths exceed 120 m. Channel 3 is shallower, attaining a maximum depth of 106 m. Relief from channel tops to channel seafloor exceeds 30 m in places. Multibeam backscatter data show that the majority of channel substrate sediments exhibit a relatively low-intensity backscatter. Preliminary inspection of grab samples from Channels 1 and 2 shows that mud and sandy mud sediment compositions are dominant. Substrate slope analysis indicates that the channel seafloors have predominantly gentle slopes. Channel 1 margins show widespread slopes of 10° or more and occasionally slopes of over 20° are found. Channel 2 margins are mostly less than 5° but slopes of over 20° are also noted. Slopes...
observed in Channel 3 are very gentle, mostly less than 5° and its margins are less well defined than Channels 1 and 2.

In conclusion, Nephrops are a common commercial species in the Celtic Sea, occurring in geographically distinct sandy/muddy substrates where the sediment is suitable for them to construct their burrows. VMS data from fishing vessels have historically been used to determine the geographical extent of the fishery, but in recent years the knowledge generated through the interpretation of MBES backscatter and associated sediment data is being used to redefine this extent. This has improved the efficiency and validity of the stock assessment and helped target new areas for underwater video tows, which are an essential part of the stock assessment. The analysis presented here demonstrates how the composition of the seafloor and its associated geomorphological and sedimentological properties may be characterized and interpreted over regional scales using state-of-the-art seabed mapping technology and software processes resulting in an enhanced understanding of the features and structure of Ireland’s continental shelf and the generation of knowledge to support the blue economy.

Case study 3: mapping the mobile seabed of Ireland’s north coast; a source of risk for locating potential renewable energy sites

Around the world, large sediment waves are still poorly understood seabed features despite being relatively common in many shelf seas (Knaapen and Hulscher 2002; Morellsen et al. 2003; Thiébot et al. 2015). Early attempts in the 1970s and 1980s to describe sediment movement on European continental shelves relied largely on the interpretation of side-scan sonar data (Kenyon and Stride 1970) and the analysis of bedform asymmetry to determine transport potential and direction (Belderson et al. 1982). More recently, thanks to the advent of new technologies such as MBES sensors coupled with improvements in GPS positioning, highly detailed investigations on sediment transport have been conducted on continental shelves globally, in particular thanks to large-scale national mapping initiatives such as the INSS and the INFOMAR programmes (Feldens et al. 2012; Denny et al. 2013).

The INFOMAR programme places a strong emphasis on the acquisition of high-resolution bathymetry data derived from MBES mapping systems to high degrees of horizontal and vertical accuracy so that the resulting information meets international hydrographic standards to support safe navigation of shipping (IHO 2008). The benefit of adhering to these standards for measuring water depth is that the resulting bathymetric data products can be gridded to produce comprehensive visualizations of seafloor features that can be used for both qualitative and quantitative analysis (Guinan et al. 2009). Furthermore, these mapping endeavours provide the ideal baseline data for any sediment dynamic study when coupled with repeated surveys over the same area at different instances in time.

The understanding of how sediment moves over a continental shelf has critical relevance due to our continuous interaction with and exploitation of the marine environment (EU 2014). The evaluation of the overall sediment volume and its physical characteristics is important for managing economic resources such as aggregates (Alder et al. 2010). Equally important is our ability to monitor temporal and spatial sediment movement since this has documented implications for many sectors such as shipping, dredging (Knaapen and Hulscher 2002; Dorst et al. 2013) and management of coastal areas under normal and extreme hydrodynamic conditions (Staneva et al. 2009). These implications extend further in the context of a developing renewable-energy sector where mobile sediments may pose a risk to renewable energy infrastructure through their interactions on the seabed (Thiébot et al. 2015).

Comparing repeat surveys can be used to measure sediment movement from kilometre- to centimetre-scale and to reveal changes in surficial sediment composition through MBES backscatter data (e.g. Németh et al. 2002; Ma et al. 2014). Additionally the above-mentioned measurements can be used to validate hydrodynamic simulations of water movement, often utilized to provide information about near-seafloor flow velocities (Sheng and Yang 2010; Young et al. 2011; Feldens et al. 2012).

In Ireland, very large sediment waves, capable of reaching heights of 30 m and able to migrate tens of metres per year have been documented, in particular in the Irish Sea (Evans 2018) and around the Inishowen peninsula (Fig. 10). This case study uses bathymetry acquired during the INSS in 2004 and INFOMAR in 2013 to focus on an area between the north Irish coast and Scotland, where underwater morphologies vary widely from shallow platforms near the coastline in c. 20 m water depths to deep troughs up to c. 100 m as depicted in Figure 10. Here strong hydrodynamic conditions have the potential to facilitate vast renewable-energy development, but the presence of mobile sediments make this challenging unless sediment transport mechanisms are well understood.

Baseline bathymetric data collected by both mapping initiatives display a range of bedforms including large sediment waves, barchan dunes and gravel waves, all with a range of amplitudes and crest morphologies (Evans et al. 2015; Fig. 10). Exposed bedrock, known to be Palaeoproterozoic granitic gneiss, is also present in the NE of the area.
and forms part of the Inishtrahull Island rock complex (Fig. 10) (Muir et al. 1994).

Nine years after the original INSS survey, a joint collaboration between INFOMAR and Ulster University resurveyed these sites in light of future marine plans for the development of renewable energy infrastructure. The resulting high accuracy time-lapse bathymetric data were used to measure horizontal and vertical changes in bedform dimensions. The analysis of multibeam backscatter and sediment data enabled development of a better understanding of sediment distribution, sediment wave composition and allowed inferences on the forces necessary to initiate and sustain sediment transport. All this information was then used in correlation with existing hydrodynamic models to examine the driving forces of sediment mobility in this region. The results of this study indicate that the investigated area has highly mobile sediments with distinct migration directions controlled by local hydrodynamic conditions (Fig. 11).

Initial findings indicate that sediment transport is not linear across the site with crest displacement following a clockwise, rotational movement. Despite the features being highly mobile, surface difference models also suggest that there has not been considerable loss of sediment from the bedform over the nine-year lapse, adding weight to the assumption that while a bidirectional current is in effect across the bedform, hydrodynamic reworking of the sediment remains mostly confined within the bedform boundaries. The use of multiple repeat surveys has also highlighted oscillation of sand waves at a spatial scale longer than their wavelengths. This suggests the need for shorter time intervals between successive surveys and improved spatial data resolution for both hydrodynamic conditions and sediment distribution to improve the validity of inferences made regarding sediment transport. In summary, the study provides useful knowledge that will have to be taken into account for any future offshore development plans in the area and the results will also hold relevance for other areas identified for the potential development of offshore renewable energy in Ireland (DCENR 2014).

In conclusion, comparison of repeat bathymetric surveys from the INSS and INFOMAR programmes over a nine-year window highlights the advantages of acquiring a high-precision baseline seafloor dataset where subsequent repeat survey activity can be used to measure changes in seafloor properties with a high degree of confidence. The study shows how geomorphological analysis of MBES-generated data provides further insight into the behaviour of sedimentary bedforms within the study area. Analysis of high-precision MBES data coupled with contemporary hydrodynamic models also allows for inferences to be drawn in terms of sediment dynamics, bedform boundaries and the likely requirements for repeat surveys necessary for a comprehensive monitoring campaign within the study area. This knowledge is particularly beneficial in the context
of evaluating prospective renewable energy sites for suitability and risk, where the ability to identify and monitor specific sedimentary seafloor features from seafloor mapping data may help with future site selection or guide design solutions for infrastructure associated with offshore renewable energy devices.

Case study 4: mapping Ireland’s offshore geology

The offshore geology map of Ireland has been compiled for the EMODnet Geology project (Judge 2015) specifically under the remit of work package 4 (WP4): Sea-floor Geology and Geomorphology. The Federal Institute for Geosciences and Natural Resources, Germany (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR) coordinated WP4, creating and sharing work-package guidelines and technical documentation to steer project partners with respect to the preparation of harmonized, standardized data that adhere to Infrastructure for the Spatial Information in Europe (INSPIRE) standards. The ensuing 1:250 000-scale map of Ireland’s offshore geology represents the first attempt to characterize the pre-Quaternary stratigraphy offshore Ireland (Fig. 12).

For the purpose of this mapping exercise, pre-Quaternary is defined as the bedrock present directly beneath any Quaternary cover. The area mapped, as defined by EMODnet Geology, represents Ireland’s EEZ with an additional 75 km buffer zone. The map has been produced by consolidating available Irish topographical and geological information into one map. The 1:5 Million International Geological Map of Europe and Adjacent Areas (IGME 5000) map and data were used as an initial baseline dataset (Asch 2005). The IGME 5000 map was completed by the IGME 5000 project comprising 40 European and adjacent countries. The project produced a geological database that includes information on predicted geology offshore Ireland.

INSS and INFOMAR high-resolution MBES data define the bathymetry of the specified area at a resolution of 111 m. These data were used in tandem with the IGME 5000 predictive mapping of Ireland’s offshore geology to constrain many of the obvious morphological seabed features and larger geomorphological provenances. Ireland’s sedimentary basins and troughs, highs and the Porcupine seabight illustrated in Figure 1 are realized by the INSS dataset. Large intrusive features of magmatic origin including seamounts and dykes are also identified in the bathymetric data. While these kinds of features exhibit a geomorphological expression in the bathymetry, much of the pre-Quaternary bedrock geology of offshore Ireland lies buried beneath overlying marine sediments. Correlation of these geomorphological features identified within the bathymetry data with available geological data, geophysical studies and the baseline IGME 5000 map formed a key part of the interpretative process leading to the development of Ireland’s offshore geology map in Figure 12.

The geology of Ireland, as illustrated on the GSI’s 1:100 000 bedrock map of Ireland (GSI 2012) defines the boundaries of terrestrial lithological units. Geological units mapped along the coastal zone that show obvious expression offshore on high-resolution bathymetry, have been extrapolated out to sea. Due to the request from the European
Fig. 12. Ireland’s Offshore Geology Map (1: 250 000 scale), Coordinate Reference System: WGS84 (EPSG code: 4326).
Commission that EMODnet datasets adhere to INSPIRE standards; the nomenclature of onshore geology units mapped with national geological nomenclature and stratigraphic units are transformed in accordance with the INSPIRE vocabulary. These vocabulary define a standardized approach to mapping lithological units, stratigraphic age, event environments and all relevant information recorded in the data attribution fields.

For inshore waters, outcrops, boundaries and faults evident on the high-resolution bathymetry datasets guide the digitization of coastal geological units. In deeper water, structural datasets are available principally due to extensive research and publication over the past three decades, largely fuelled by petroleum potential. Research and publications on deep water (greater than 200 m) areas offshore Ireland have focused on the crustal structure, tectono-stratigraphy, sedimentary development, volcanic province and petroleum potential. Information gleaned from these publications has been incorporated to further constrain the pre-Quaternary outcropping geology of Ireland’s offshore EEZ. A comprehensive literature review of previous work has been conducted and elements of this work are incorporated into the offshore geology map and summarized here.

Information detailed in boreholes (Haughton et al. 2005), dredge samples (Tyrrell et al. 2013), INSS-acquired sub-bottom profiles, seismic profiles (Naylor and Shannon 2005) and deep-towed side-scan sonar (PIP 2004) are used to interpret, identify or track lithological units beneath Quaternary cover. Petroleum Affairs Division (PAD) and Petroleum Infrastructure Programme (PIP) seismic profiles (Morewood et al. 2005; O’Reilly et al. 2006) as well as GSI gravity and magnetic data are summarized by research endeavours including the Rockall Studies Group (Readman et al. 1997; Rockall Studies Group 1998; Hopper et al. 2014). Combining the interpretations from these sources allows for reasonable educated assumptions of outcrop types, where other robust ground-truth samples were not available. This material formed the basis of geological edits performed on the baseline IGME 5000 dataset that ultimately resulted in the 1:250 000 map of Ireland’s offshore geology (Fig. 9).

Offshore potential field data, refraction and reflection profiles, and well data (Brock et al. 1991; Shannon 1991; Naylor et al. 1999, 2002; Reston et al. 2001; Stoker et al. 2005; O’Reilly et al. 2006; Shannon et al. 2007) provide a comprehensive account of the deep geology of Ireland and its continental margin. This contextual information describes multiple episodes of tectonism through Phanerozoic time (Naylor and Shannon 2011), including failed rifting and subsequent break-up that ultimately resulted in the opening of the Atlantic. These interpreted geological and geophysical data describe a chronological narrative that lends context to the major geomorphological features we observe offshore Ireland. Detailed Irish data and observations have most recently been incorporated into the first regional systematic compilation and coordinated interpretation of the NE Atlantic for the NAGTEC project (Hopper et al. 2014). Marine geological and geophysical datasets were used to build regional models and publish a comprehensive tectonostratigraphic atlas. The NAGTEC Atlas describes in detail the most recent interpretation of the evolution of the NE Atlantic and its conjugate margin pairs. It represents a comprehensive reappraisal of historical studies in the NE Atlantic from the earliest plate tectonic studies. Understanding of how the NE Atlantic region and its continental margins hold unique information is important for many aspects of Earth science, from global geodynamics, palaeoeceanography and environmental change (Péron-Pinvidic et al. 2017).

The overall seabed surface morphology offshore Ireland as illustrated by the PAD, INSS and INFOMAR bathymetric datasets, summarized in Figure 1, vastly improved knowledge and understanding for the detail of Ireland’s continental shelf and Atlantic margin by allowing for a detailed visualization of large-scale seabed features and structures (Dorschel et al. 2010). At the westernmost edge of European continent, this region has been affected by multiple orogenic episodes throughout geological history (Naylor and Shannon 2011). The broad continental shelf (greater than 350 km) surrounding Ireland is wide by mean-world standards. Gravity and magnetic data demonstrate that the Moho beneath Ireland lies 30 km below the terrestrial surface (Brock et al. 1991). The continental platform surrounding Ireland connects the Irish landmass with Europe to the east and slopes gently westward from terrestrial Ireland to the edge of the shelf break. Along the shelf water depths are in excess of 300 m and here the seabed is generally devoid of major bathymetric features; it has a curved and linear shelf edge (Naylor and Shannon 1982). The shelf edge is defined by steep cliffs that are incised by large canyon systems. Large steep canyons drop off from continental shelf depth of mean 350–4500 m over a mean distance of 30 km, for all but the Porcupine Basin where the Porcupine Seabight etches a more gradual incision into the shelf edge descending from shelf edge to abyssal plane over hyperextended crust. Along the Porcupine Basin’s axis stretching factors (the factor by which the lithosphere has been thinned) increase southward derived from subsidence data for Middle to Late Jurassic rifting (Tate et al. 1993). Such lithospheric thinning characteristics are normally associated with the highly thinned crust
near the continent–ocean transition of rifted margins (Reston et al. 2001).

In the Porcupine Basin, basement is overlain by a thick Upper Carboniferous succession (Stoker et al. 2005). This sequence is covered by a thick Paleozoic sedimentary material. The bathymetric relief of the Porcupine Seabight cascades from the shelf edge more gently than the rest of the shelf and into the Porcupine Abyssal Plain from c. 350 m water depth in the north to greater than 4000 m water depth in the south. An incised channel clearly evident in the bathymetry drains sediment to the base of the Abyssal Plain, which in turn is characterized by oceanic crustal basalts coated with marine sediment.

The Porcupine High, a prominent oblong feature orientated ENE–WSW, is inferred to be comprised of granitic orthogneiss on the northern flanks and metasedimentary rocks on the top of the high, comprising low-grade metamorphic green psammites of Grampian age, similar to outcrops in NW Mayo (Tyrrell et al. 2013). Located south of the Porcupine at the southermost region of Ireland’s continental shelf, the Goban Spur is a bathymetric plateau that slopes gently westwards away from the Cretaceous Chalk-dominated Celtic shelf (Naylor and Shannon 2011). The Goban Spur plateau has a thick cover to Upper Paleozoic, probably dominantly Devonian rocks (Naylor and Shannon 2005) with occasions of Mesozoic and Cenozoic cover (Naylor et al. 2002). Small perched basins at the Goban province are expressed by complex fault series of NNE–SSW and NNW–SSE controlled basins (Naylor and Shannon 2005).

To the NW of Ireland’s offshore region the NE–SW-trending Rockall Trough is the dominant bathymetric feature. The general trend of this trough is believed to have a deep pre-Caledonian (600 Ma) structural origin (Hutton and Alsop 1996; Naylor and Shannon 2005). The Rockall margin was produced by rotational opening of the Rockall Basin in Triassic and Late Jurassic rift events (Thomson and McWilliam 2001). A set of small, elongate, probably Mesozoic basins are located in the footwalls of the main Cenozoic Rockall Basin (Naylor et al. 1999). These have a thin Mesozoic and Cenozoic cover (Naylor and Shannon 2005). The Rockall High comprises a distinct province of Precambrian rocks (Naylor and Shannon 2005). It is thought to belong to the Islay terrane, with the boundary against Lewisian rocks lying to the north, in UK waters (Hitchen et al. 1997).

The continental shelf of Ireland bears the geological imprints and structures detailing a history of Variscan, Caledonian and older orogenic events. Reactivation of some of these structures has influenced the orientation of major geomorphological features offshore, many of which can be identified within Ireland’s baseline seabed mapping datasets (Dorschel et al. 2010). While detailed mapping of all lithological units present offshore is still technically impossible, studies and data summarized here have lent a broad overview to the varying geological compositions recorded. These build a colourful record of events that comprise the geology of Ireland’s EEZ as represented on Ireland’s offshore geology map in Figure 9.

Finally, The EMODnet Geology project, which has in this case provided the impetus to further amalgamate and interpret the information gleaned from the studies and knowledge resources described, stands as a powerful example of the benefits of scientific co-operation and partnership in furthering our understanding of the ocean realm. In particular, the combination of contemporary geological knowledge from multiple sources with a broad geomorphological analysis of Ireland’s shelf and deep-water bathymetry (Judge 2015) has resulted in the production of a geology map for Ireland’s offshore area (Fig. 12). This product has been harmonized for compatibility with the EMODnet Geology project’s online data discovery viewers and services (Kaskela et al. 2019) that enhance the reach and impact of this product by making the knowledge freely available to a wider international body of stakeholders. The combination of geological data with bathymetry data allows users to build up a comprehensive picture of the seabed and its subsurface, providing a vital component for seafloor habitat maps and offering essential tools in marine spatial planning, coastline protection, offshore installation design, environmental conservation, risk management and resource mapping (Kaskela et al. 2019).

Discussion: considering the impact of Irish seabed mapping

The collection of four practical interpretative case studies presented in this paper highlights ways in which information developed through Ireland’s seabed mapping efforts can be interpreted to enhance scientific knowledge and understanding of coastal, shelf and deep-water marine environments. Their effect in illustrating how the generation of this blue knowledge creates a positive impact in terms of sustainable development will be discussed further in this section. However, in addition to the acquisition, management and delivery of high-resolution baseline datasets supporting cross-sectoral applications, access to Ireland’s marine knowledge through the INFOMAR programme continues to underpin key areas of Ireland’s blue growth at national, European and international levels (Indecon International Economic Consultants 2017).
The national impact of the INFOMAR programme in this regard can be gauged through its inclusion in Government of Ireland policy, specifically, Harnessing our Ocean Wealth (HOOW) – An Integrated Marine Plan for Ireland (Government of Ireland 2012), the Department of Communications, Climate Action and Environment (DCCAE) Climate Action Plan and Statement of Strategy 2019–21 (DCCAE 2019a, b) and the Draft National Marine Planning Framework (NMPF) for public consultation (DHPLG 2019). HOOW represents a vision of sustainable growth for Ireland’s blue economy underpinned by coherent policy, planning and regulation, managed in an integrated manner. A key enabler of the Plan is the ‘Research, Technology and Innovation’ component, where the completion of the INFOMAR seabed mapping programme is listed as a necessary action (Action 23) to provide data, products and services as critical inputs to maritime spatial planning and enablers of infrastructural development, research, education and value-added products (Government of Ireland 2012). The HOOW Review of Progress 2018 (Government of Ireland 2019) notes that Ireland is already well on target to achieve and even exceed the economic targets set out in the Plan and states that European Commission reporting in May 2019 highlighted significant growth across the blue economy of most EU member states, noting the most significant expansion observed was in Ireland and Malta according to Eurostat figures. The HOOW Review of Progress showed that in 2018 Ireland’s ocean economy had a turnover of €6.2 billion, giving a total Gross Value Added (GVA) (direct and indirect) figure of €4.19 billion, representing 2% of GDP. Additionally at a national level, the DCCAE’s Climate Action Plan 2019 (DCCAE 2019a) also stipulates as an action, the need to support the ocean energy research development demonstration pathway for emerging marine technologies (wave, tidal, floating wind) and associated test infrastructure. The completion of mapping for all Irish offshore waters through the INFOMAR programme to support site selection for offshore energy is listed as a key step necessary for the delivery of this action (Action 26). Furthermore, the NMPF (DHPLG 2019) cites INFOMAR as a key reference under overarching marine planning policies, specifically in relation to seafloor integrity as it relates to Good Environmental Status (GES) as per the Marine Strategy Framework Directive (MSFD) (2008/56, EC).

In the European and international contexts the INFOMAR programme has created positive impact through its involvement with European Territorial Cooperation (INTERREG)-funded initiatives including the Joint Irish Bathymetric Survey (JIBS), INIS-Hydro (Ireland, Northern Ireland and Scotland Hydrographic Survey) and CHERISH projects. Additionally, the programme maintains ongoing Irish collaboration with key cross-border and UK-based organizations and agencies including the UKHO, many of whom sit on the programme’s Technical Advisory Committee (TAC). Involvement in the Directorate-General for Maritime Affairs (DG MARE) European Commission-funded EMODnet Bathymetry Geology and Habitats projects has increased the international reach and impact of Ireland’s national seabed mapping datasets through their inclusion in a harmonized international EU-wide data portal (Kaskela et al. 2019) expanding the discoverability and impact of Ireland’s marine knowledge many-fold. Information generated through Ireland’s seabed mapping efforts represents an important resource for maintaining Ireland’s alignment and commitment to several pieces of European legislation including: the Marine Strategy Framework Directive (2008/56, EC); the Habitats Directive (92/43, EEC); the Maritime Spatial Planning Directive (2014/89, EU); the Water Framework Directive (2000/60, EC); the INSPIRE Directive (2007/2, EC); the Open Data and Public Sector information Directive (2019/1024, EU) where data and products produced by the programme are directly relevant to the stipulations of the legislation. The 1992 OSPAR convention is also included as part of the legislative rationale for the programme identified in PwC’s most recent external evaluation of the programme (PwC 2013). The DG MARE-funded Blue Growth Report into Scenarios and Drivers for Sustainable Growth from the Oceans, Seas and Coasts cites INFOMAR as a positive example of a member state’s Blue Growth initiative (Ecorys 2012). Ireland’s obligations to the UN safety of life at sea (SOLAS) convention (UN 1980) are addressed through INFOMAR’s data acquisition policies whereby seabed mapping data are acquired according to International Hydrographic Office (IHO) standards for data quality and accuracy (IHO 2008). These data have been provided to the relevant authorities so that nautical charts used for safe navigation incorporate updated information. Ireland’s seabed mapping data have also been used to directly support Ireland’s marine territorial claim through the UN Convention for the Law of the Sea (UNCLOS) based on geological boundaries (Nelson 2006) whereby a claim for jurisdiction over marine territory has been made by the Irish nation covering an area ten times the size of Ireland’s landmass (Government of Ireland 2005). Knowledge resources inferred from Ireland’s high-resolution seabed mapping data have been further incorporated in international initiatives and collaborations such as the development of the NAG-TEC Atlas (Péron-Pinvidic et al. 2017) European Geological Surveys Research Area (GeoERA) Seabed Mineral Deposits in European Seas: Metallogeny and Geological Potential for Strategic and
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Critical Raw Materials (MINDeSEA) project (Gonzalez and MINDeSEA 2019) and the Nippon Foundation’s GEBCO Seabed 2030 (Mayer et al. 2018) project.

The pioneering open and free data philosophy of the Irish Government (DPER 2017) has led to further international collaborations, with Ireland’s seabed mapping data also hosted on the NOAA archive, where users can access raw data files in addition to the standard outputs and metadata already available through the GSI-hosted Interactive Web Data Delivery Service (IWDDS). Prospective data users from anywhere in the world may also access Ireland’s seabed data layers and products through a series of web map services (WMS) compatible with standard GIS software packages via the INFOMAR website. Data accessed freely from these resources can be used by the marine and scientific communities under a creative commons licensing agreement, which can be reviewed via the IWDDS.

The INFOMAR programme has supported a wide variety of academia- and industry-led research in Ireland’s marine sector by having input into a series of research short calls and supporting subsequent calls funded by the GSI’s Geoscience Research initiative (GSI 2016). Currently over 190 publications can be accessed directly through the INFOMAR website and the programme has been cited numerous times within the scientific literature. Furthermore, Irish seabed mapping data underpin multiple scientific and oceanographic research cruises in Irish waters where high-resolution maps of seafloor features are used to drive discovery and research collaborations as in the recent Atlantic Ocean Research Alliance (AORA) Transocean Survey North Atlantic (TRASNA) and Sensitive Ecosystem Assessment and ROV Exploration of Reef (SEA-ROVER) expeditions carried out in waters within Ireland’s designated area (Fig. 1).

Demonstrated applications of Ireland’s marine data resource supporting the Irish maritime industry include: the safeguarding of navigation and shipping; de-risking the development of offshore renewable energy; informing fisheries and aquaculture management; supporting the development of offshore infrastructure, energy security and resource management; underpinning environmental modelling and monitoring; and enhancing our understanding of coastal behaviour and heritage (PwC 2008, 2013; White et al. 2019). Irish seabed mapping data will in most cases represent the best available data to inform and underpin decision making for Maritime Spatial Planning (MSP) as set out in the National Marine Planning Framework Baseline Report where the INFOMAR programme is referred to as a useful source of information (DHPLG 2018). Access to high-resolution seabed information will allow MSP decision makers to manage inherent scale issues as they relate to specific cross-sectoral maritime activities and associated data requirements.

The educational impact of Ireland’s seabed mapping efforts includes ongoing training and skills development of graduates and scientific crews in multidisciplinary techniques for seabed mapping, which are applicable worldwide (Government of Ireland 2012). In 2018 the programme was included on the national educational curriculum via a web portal managed by Scoilnet for both junior and senior cycles and, as of 2020, INFOMAR will pilot an MSc module in GIS and remote sensing in partnership with National University of Ireland Maynooth (NUIM).

External appraisals of Ireland’s seabed mapping efforts have been periodically undertaken throughout the life cycle of the INFOMAR programme. The 2008 PwC Marine Mapping Survey Options Appraisal Report included a CBA yielding a ratio of between four and six times to one return on investment in favour of the programme depending on the timeframe. A follow-on 2013 PwC re-evaluation of the programme highlighted a strong rationale for the continued public funding of the INFOMAR programme noting that it supports the attainment of key national and European policy objectives and regulatory obligations. In 2016 a post-project evaluation of INFOMAR Phase 1 (2006–15) carried out by Risk Solutions acknowledged that while the programme is widely respected and that the programme largely achieved its Phase 1 objectives, a radical cut to the programme budget arising from Ireland’s financial crises affected its ability to deliver upon all of its initial aspirations. The report recommended that recent funding cuts should be addressed to allow the programme to deliver to its full potential. A review of the Irish Geosciences sector by Indecon reported that the INFOMAR programme directly contributed €24 million to Ireland’s ocean economy in 2016 (Indecon International Economic Consultants 2017).

The availability of metrics from the Irish experience to appraise the positive impact of a national-scale/EEZ seabed mapping effort over more than two decades of operations will undoubtedly prove beneficial to the international community and a lasting legacy for the blue knowledge developed through these efforts. Other nations weighing up the challenges and associated benefits arising from national baseline seabed mapping programmes will have a useful reference for estimating the impact of this activity on society, the economy and sustainability, potentially underpinning the case for future international seabed mapping initiatives. The opportunity to share, exchange and transfer Ireland’s blue knowledge between other nations and programmes also aligns well with the broader international agenda, especially in the case of the UN Sustainable Development Goals (SDGs) and the complementary
UN Decade of Ocean Science for Sustainable Development (2020–30). In particular, the case studies presented in this paper can be used to illustrate the impact of blue knowledge in supporting some key UN SDGs adopted by all UN member states in 2015.

In summary, Case study 4 highlights how government-based partnership through Ireland’s involvement in the pan-European EMODnet Geology project, has resulted in a harmonized geological data product with multiple applications, supporting UN SDG 17 on Partnership. Case study 3 shows how the study of seabed features through multiple repeat surveys (time-series data) offers crucial risk insights for the development of the offshore renewable-energy sector supporting UN SDG 13 on climate action. Case study 2 shows how the interpretation of integrated seabed mapping products can positively impact the ability of Ireland’s marine scientists to understand and monitor a key fishing ground through improved stock assessment, aligning with UN SDG 14 on life below sea, while Case study 1 shows how the analysis of Ireland’s advanced seabed mapping data allows for the extrapolation of Ireland’s unique geological history into the ocean environment, promoting Ocean Literacy, which is a stated goal of UNESCO’s UN Decade of Ocean Science for Sustainable Development initiative. This case study directly supports two current principles of Ocean Literacy with modern visualizations of the seafloor underscoring that the ocean is largely unexplored (Principle 7), while the complex geological record and marine fossils inferred from land-based studies onto the submerged landscapes off Hook Head, Co. Wexford, remind us that the ocean made the Earth habitable (Principle 4) (NOAA 2013).

Acknowledgements The authors wish to acknowledge the role of colleagues and supporters past and present for their contribution to the development of Ireland’s seabed mapping capabilities. From the seagoing crews charting the seafloor to the scientists and programme staff tasked with turning this information into blue knowledge and putting it out into the world, to the members of the public and individuals in government who through their recognition and support for these efforts have ensured that Ireland continues to expand and enhance our knowledge, understanding and sustainable stewardship of our ocean realm. Thanks also to Eimear O’Keeffe for GIS support rendered and Koen Verbruggen for encouraging the development of this article.

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author contributions ROT: conceptualization (equal), project administration (equal), resources (supporting), supervision (equal), visualization (equal), writing – original draft (lead), writing – review & editing (lead); MJ: conceptualization (supporting), formal analysis (equal), supervision (supporting), writing – original draft (supporting), writing – review & editing (equal); FS: formal analysis (equal), project administration (equal), visualization (equal), writing – original draft (equal), writing – review & editing (supporting); TF: funding acquisition (equal), project administration (equal), resources (equal), writing – original draft (equal), writing – review & editing (supporting); EMC: formal analysis (supporting), visualization (supporting), writing – original draft (supporting); KS: formal analysis (supporting), visualization (supporting), writing – original draft (supporting), SK: writing –
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original draft (supporting); SC: funding acquisition (equal), project administration (equal), resources (equal), writing – review & editing (supporting); FMG: project administration (equal), writing – review & editing (supporting); XM: conceptualization (equal), project administration (equal), supervision (supporting), writing – review & editing (supporting).

Data availability statement The datasets generated during and/or analysed during the current study contain Irish Public Sector Data (Geological Survey Ireland & Marine Institute) licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) licence and are accessible at https://www.infomar.ie/data or upon request from INFOMAR programme management (info@infomar.ie).

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