An Ocean of Possibilities: Applications and Challenges of Marine Geomorphometry

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Abstract— **An increase in the use of geomorphometry in the marine environment has occurred in the last decade. This has been fueled by a dramatic increase in digital bathymetric data, which have become widely available as digital terrain models (DTM) at a variety of spatial resolutions. Despite many similarities, the nature of the input DTM is slightly different than terrestrial DTM. This gives rise to different sources of uncertainties in bathymetric data from various sources that will have particular implications for geomorphometric analysis. With this contribution, we aim to raise awareness of applications and challenges of marine geomorphometry.**

I. INTRODUCTION

Exploration and characterization of the ocean floor continuously presents new possibilities and challenges. Thanks to recent and ongoing improvements in acoustic remote sensing technology, seabed relief can now be measured rapidly, extensively and at fine spatial scales [1]. Among these technologies, multibeam echosounder systems (MBES) provide some of the most detailed and accurate data currently available [2]. Most of the MBES data are collected during navigational charting efforts, with a particular focus on shallower coastal waters where the seabed relief can pose a hazard to navigation. Due to potential safety concerns, standards regarding data quality and uncertainty are high for these shallow datasets. Datasets from deeper waters, however, still lag behind in terms of quality and quantity. Owing to the technological challenges and high costs associated with bathymetric mapping of large and deeper parts of the seabed, it is estimated that only 5-10% of the oceans are mapped with a resolution comparable to that on land [3].

The adoption of terrestrial geomorphometric techniques to investigate marine environments increased in the past decade [e.g 4]. The primary digital terrain model (DTM) data source for marine geomorphometry has been bathymetry (depth) grids generated from MBES data. These DTMs are analyzed to characterize geomorphological features of the seabed, which can at times be sources of biological information (e.g. coral reefs). Bathymetric data have proven their potential to help the scientific community and government agencies advance their understanding of seabed ecosystems and geomorphological processes [5].

The terrestrial geomorphometric literature provides a rich source of potential analytical techniques for marine studies [6]. It is important, however, to acknowledge that different data collection and processing techniques used to create underwater DTM makes the nature of the input DTM different. In addition, it is more difficult to capture terrain variability underwater since changes in topography are more subdued in comparison to terrestrial landscapes. Issues encountered in terrestrial geomorphometry, such as underlying data uncertainty and the choice of the analysis algorithm and scale (resolution and neighborhood size), are also relevant underwater, but they manifest themselves differently due to the differences in the input data.

In this contribution, we review some of the most common applications and challenges encountered in marine geomorphometry and explore potential future directions.

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II. Applications

A. Geohazards, Hydrodynamic and Geomorphological Mapping

In dynamic environments such as the ocean, monitoring and detecting change is often crucial. The action of hydrodynamics on the seabed can cause changes in bathymetry that can become hazards for navigation in coastal waters. Hydrographic conditions, on the other hand, are directly related to the morphology of the seabed at all scales [7]. For instance, banks are known to have far-reaching effects on currents and circulation patterns, which in turn can modify bedforms [7].

Local geomorphometric attributes have been used to develop seabed hydrodynamic models. For instance, aspect can be used as proxy for local and regional currents and gives information on the exposure of the seabed at a particular location. Curvature is thought to influence local hydrodynamics. The ruggedness of the seabed affects sedimentation and hydrological patterns near the seabed by the drag or bottom friction that influences the currents. These terrain attributes can also assist geomorphic and physiographic classifications of the seabed, as demonstrated by [8]. Regional geomorphometry can be used to study the legacy of glaciations in the geomorphology of continental shelves. The retreat of under sea ice margins leaves different geomorphic evidences than terrestrial-based ice margins, which can be found on the seabed [9] and identified using geomorphometric classifications. For instance, submarine glacial landforms, captured by multibeam bathymetric data in areas of hypothetic ice-streams, provide evidence on the style of deglaciation, the extent of ice-margins, the calving rates, and the sea level at specific periods in time [10].

Mapping subaqueous geomorphological features is also crucial in identifying potential underwater geohazards. Adaptation of terrestrial geomorphometric techniques, such as morphometric attributes and their statistical analyses, feature-based quantitative representation, and automated topographic classification, has been shown to be effective in improving current understanding of the morphology and physical processes that characterize submarine mass movements in passive glaciated margins [e.g. 11, 12].

B. Habitat Mapping

Seabed habitat mapping is probably the field that has benefitted the most from techniques of geomorphometry to date. Habitat mapping involves characterizing a habitat in terms of its physical, chemical and biological attributes [13]. Many of these attributes are known to be linked to terrain morphology, thus highlighting the potential of terrain derivatives to describe marine habitats. The abundance and distribution of marine species can be strongly influenced by many biotic and abiotic factors, but topography and geomorphology are among the most important drivers of their distribution at many scales [14]. Slope, aspect, curvatures and measures of seabed roughness have all been used in habitat mapping studies [15]. MBES data have become essential in studying marine habitats due to their remoteness and the difficulties in sampling them. Consequently, geomorphometric analysis performed on bathymetric data is also increasingly used to find surrogates (i.e. proxies) of species distribution [14, 15]. Seabed complexity and heterogeneity can allow us to numerically quantify the spatial arrangement and structure of habitats. Since the complexity of the seabed has been linked to the distribution of species at different scales, terrain attributes can be used as surrogates of species distribution [15]. The quantitative nature of terrain attributes also facilitates the analysis of relationships between environmental and biological factors and provides a mean to compare between geographic regions and also the same region over multiple time steps.

C. Human Dimension

It is estimated that more than 40% of all the Earth's ocean floor has already been altered by anthropogenic activities [16]. The physical disturbances of the seabed increase its roughness and produce changes in hydrodynamic patterns and sediment distribution that can then affect bedforms and species distribution [5]. Mapping and analyzing seabed geomorphology using geomorphometry allows monitoring changes in the shape of the seabed and identifying these variations in roughness, thus facilitating the assessment of anthropogenic impacts on some areas and potential new hazards for navigation [5].

Geomorphometric techniques can also be used in search and rescue operations. The difficulties in locating the recently vanished Malaysia Airlines aircraft (flight MH370) highlighted the lack of knowledge of seabed features in the search area [17]. The forecasting of the path of floating debris was limited by the lack of knowledge of seabed roughness and topography from which it is possible to estimate surface current directions and ocean mixing rates, both essential to these predictions [18].

III. Challenges

A. Spatial Scale

As in terrestrial geomorphometry, spatial scale is an important issue to consider in marine applications. Most of the phenomena studied are likely to be observed at different scales, and the scale of analysis should always match the scale of the phenomena being observed [19]. For instance, many terrain attributes used in habitat mapping were found to be useful surrogate for species distribution at a local scale while others were more important at broader scales [14].

The spatial resolution and extent of MBES data is dependent upon the footprint and frequency of the system. As the distance between the seabed and the sensor increases, the footprint gets bigger and the spatial resolution decreases. This makes submarine DTMs more likely to include datasets of different resolutions, meaning that geomorphometric techniques, which are sensitive to data resolution, need to be very robust in marine applications. The integration of different datasets at different scales over large areas is very challenging [13].

B. Technological Challenges

The dynamic nature of the oceans makes collection of bathymetric data dependent upon a lot of different factors that are likely to induce errors or artifacts in the final DTM. Artifacts are common in bathymetric data and can strongly affect the derivation of terrain attributes. Common errors in depth measurements include errors in the acoustic measurement itself, movements of the supporting platform, and inaccuracies in sound velocity corrections [1]. Motion-induced errors are among the most important source of errors and will vary depending on the platform used (e.g. ship or underwater vehicle). Positional accuracy is also an important challenge, especially for the use of underwater vehicles such as remotely operated vehicles (ROV) or autonomous underwater vehicles (AUV). Unlike in satellite and airborne remote sensing, underwater equipment and technologies cannot use the Global Positioning System (GPS) to accurately georeference depth measurements and location. All data are therefore positioned relatively to surface GPS using acoustic telemetry systems: the deeper the survey, the worse the positional accuracy gets [20]. When positional accuracy is lower than the spatial resolution of the DTM, artifacts can be introduced and a mismatch between the locations from different datasets can occur, which is a critical issue in change detection where dataset registration is very important. These challenges are greater in the deep sea than in coastal environments.

IV. Future of Marine Geomorphometry

A. Towards a Complete Coverage

Applications of geomorphometry in the marine environment are likely to increase as more bathymetric data become available in different types of seabed environment. MBES allow for systematic collection of data, but when the water becomes too shallow for surveying systems, it creates a gap in the continuous data. The combination of bathymetric LiDAR data with acoustic surveys will ultimately call for seamless analysis from terrestrial to marine environment. Such continuous dataset is likely to improve the study of large landforms that overlap between land and the ocean and the identification of geohazards in shallower waters, but will also increase the challenge of integrating different datasets together. On the other hand, the collection of higher resolution bathymetric data in the deep sea will become easier and more frequent with the increasing use of underwater vehicles. This will help gain additional knowledge on the structure and geomorphology of deeper environments. There is still much to learn about the complexity of the seabed at different depths and environmental settings. As stated in [5]: "It is generally assumed that seabed structure becomes less complex as one moves from the continental shelf to greater depths, but is it, or does this simply reflect our lack of knowledge?"

B. Advances in Technologies and Techniques

The ability to produce a continuous acoustic image of the surface of the seabed using multibeam acoustics has revolutionized our ability to understand marine morphodynamics and the composition and distribution of sediments, which has in turn significantly improved our knowledge of seabed processes. Technology and equipment to survey the seabed is improving in quality, accuracy and cost-efficiency, which will allow an increase in data availability and quality. Algorithms that consider the specific characteristics of underwater surveying, such as the CUBE (Combined Uncertainty and Bathymetric Estimator) [21], are being developed to improve bathymetric data processing and are likely to become more accessible through processing software. Availability of GIS tools to effectively combine multiple datasets and perform geomorphometric analyses is key in making marine geomorphometry accessible to marine scientists with a wide range of background and experience [22, 23]. Better practices to report data type, quality and scale within metadata will need to be implemented in order to allow the most informed analysis of these data [24]. New techniques are also likely to make the jump from the terrestrial literature to the marine literature. For instance, geographic object based image analysis (Geobia) has been gaining some traction in the seabed mapping community as the spatial resolution of acoustic data improves [e.g. 25, 26].

V. Conclusion

As stated in [6], "One way to promote better practice in the use of quantitative terrain analysis from bathymetric data is to ensure that studies of geomorphometry become more widespread in the marine literature, thereby making the issues surrounding quantitative terrain analysis more accessible to marine scientists from a variety of backgrounds." Marine scientists need to be encouraged to apply geomorphometric techniques underwater to make use of the full potential of their expensive datasets.

With a few exceptions, most issues being investigated in terrestrial geomorphometry, such as uncertainty and error propagation, the choice of algorithms or the multiscale nature of DTMs are rarely considered in marine geomorphometry applications. Since the terrestrial geomorphometry community is currently trying to tackle some of these issues, it will be important for marine scientists to remain aware of developments in this field, and to build up a marine geomorphometry community to draw on experiences from terrestrial techniques.

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