Recent and Future Trends in Marine Geomorphometry

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Abstract— **For the 71% of our planet that lies beneath the ocean, the use of spatial analytical techniques for explaining and classifying underwater topography has become increasingly widespread in recent years. Marine acoustic technologies have now developed to a point where it is possible to capture underwater landscapes and their habitats at multiple scales, whereas other technologies are being increasingly adopted where acoustic data are lacking or hard to obtain. Processing techniques for handling these data have also developed significantly and many analytical techniques have been adopted from terrestrial studies. Technologically speaking, we have now entered the age where we can virtually drain the water from the oceans and make the seafloor "visible" as an extension of land. One of the major challenges remaining is acquiring bathymetry data across the entire ocean floor, not just in economically developed areas or those with industrial interests in the seabed. Moving forward into the next decade, we hope that new opportunities for seabed mapping can challenge some of the current paradigms. This will allow marine geomorphometry not only to play catch up with its terrestrial counterpart, but perhaps to begin treading its own path as a sub-discipline.**

I. INTRODUCTION

Since semi-automated tools for deriving terrain attributes (*e.g.* slope, orientation) from Digital Bathymetric Models (DBM) in GIS were developed, the marine environment has been the focus of many studies involving aspects of geomorphometry [1,2]. The growing interest of marine scientists from all around the world to classify and understand seafloor environments (e.g. glaciated continental shelves, fjords, deep sea), combined with the set of challenges that are particular to the application of geomorphometry to the marine environment, have given rise to the sub-discipline of marine geomorphometry. This paper reviews the most recent trends in marine geomorphometry. Recent contributions to the literature in the last five years are summarized for each of the five steps of geomorphometry identified by Pike *et al.* [3] and adapted for marine studies by Lecours *et al.* [1]: sampling the depth of the seafloor, generating a surface model from sampled depths, correcting errors and artifacts in DBMs, deriving terrain attributes (*i.e.* continuous measures) and terrain features (*i.e.* discrete objects), and using the attributes or features for seafloor mapping in applications like habitat mapping and submarine geomorphology.

II. SAMPLING THE DEPTH OF THE SEAFLOOR

It is now widely recognized that our knowledge of ocean bathymetry lags behind when compared to our knowledge of the topography on Earth and other celestial bodies in our solar system. This can be explained historically by the lack of political commitment to map the seafloor beyond national jurisdictions, resulting in a deficiency in sampling effort. However, many nations and organizations now recognize the critical environmental, social, political, and economic roles of the oceans, which have led many of them to commit resources to fill the knowledge gaps in the near future [4].

One of the most promising endeavors for bathymetric (depth) mapping is the Nippon Foundation's GEBCO Seabed 2030 Project. This is an international effort to create a bathymetric map of the Earth's oceans by 2030 to 100 m or 200 m resolution, depending on depths. Still in its infancy, this project will provide a framework for the identification of major gaps in current bathymetry and enable international collaborations to fill such gaps. A review paper by Mayer *et al.* [5] presents this ambitious effort and the associated issues in the context of geomorphometric analyses. It is estimated that an investment of the order of magnitude of the typical cost of a mission to Mars ($3B U.S.) would enable mapping 93% of the bathymetry deeper than 200 m [5].

TABLE I. ESTIMATED PROPORTION OF THE OCEAN BY DEPTH RANGE [5]

Depth range	Percentage of the ocean	Target resolution
< 200 m	10.0%	100 m
200 m to 1,500 m	3.7%	100 m
1,500 m to 3,000 m	11.0%	200 m
3,000 m to 5,750 m	72.6%	200 m
5,750 m to 11,000 m	2.7%	200 m

These efforts, however, mostly concern the deeper waters that can be mapped with acoustic technologies, leaving many shallow coastal areas poorly sampled. In the context of climate change, the often-dynamic coastal areas require repeatable, high-resolution mapping with high degrees of accuracy (in both vertical and horizontal resolutions). Developments in bathymetric Lidar acquisition and data processing for coastal environments has increased in the last five years [6,7], and the use of such a system will likely increase once their price falls due to technological advancement and increased uptake. At a regional scale, many countries have thus invested in the mapping of coastal areas using topo-bathymetric Lidar. In the United States for example, the goal of the Interagency Working Group on Ocean and Coastal Mapping is to survey and map the country's coasts and nearshore areas for multipurpose use. This group involves over a dozen members (*e.g.* Army Corps of Engineers, USGS, NOAA, EPA, NSF). In Australia, these efforts have been initiated through the Australian Hydrographic Office, the National Environmental Science Program marine biodiversity hub, universities and government agencies such as Geoscience Australia. Many other countries have also begun using similar technologies with pilot projects being conducted, such as the GLaSS project in Norway.

III. GENERATING A SURFACE MODEL FROM SAMPLED DEPTHS

Optical remote sensing has previously been identified as the least common method for deriving bathymetry [1]. In the last few years, however, the scientific community has found a renewed interest in using optical remote sensing to estimate bathymetry in coastal areas [8,9]. A meta-analysis performed using the Scopus database highlighted that 50% of articles with "satellite-derived bathymetry" in their title, abstract or keywords have been published in the last five years (n = 113). These methods remain challenging, as they often require *in situ* calibration data of water parameters to be collected simultaneously with the satellite data. The newly developed techniques for bathymetry estimation from optical images will likely gain traction once they are implemented in user-friendly tools accessible to the wider marine science community. By comparison, fewer developments have been made in the past 5 years in acoustic bathymetric data processing to generate DBMs where rapid developments occurred in the previous decade. There is, however, a noteworthy trend towards open source and open access tools and software. For a long time, most software used for the production of DBMs from acoustic data were proprietary. Recently, a collaborative effort led by the Center for Coastal and Ocean Mapping/Joint Hydrographic Center (University of New Hampshire/NOAA) made available a framework of libraries and tools for bathymetric data processing that is freely available online (HydrOffice.org) [10].

The integration of multisource terrain data to create a seamless surface model has been identified as one of the main challenges to coastal applications of geomorphometry [1]. However, our increased ability to derive DBMs from satellite images and bathymetric Lidar systems have driven new research in coastal geomorphometry; the recent literature has demonstrated the successful integration of acoustic-based bathymetry with optically-derived bathymetry [11] and acoustic-based bathymetry with Lidar bathymetry [12] for geomorphometric applications in the coastal zone.

IV. CORRECTING ERRORS AND ARTEFACTS IN DBMS

It is generally recognized that even when proper post-processing of DBMs is performed, artifacts and errors often remain prevalent in the bathymetric data as a consequence of data acquisition. As highlighted in [1], most marine geomorphometry applications disregard, or find a means to overcome, the presence of the remaining errors and artifacts as they are often impossible to remove, or because survey data for some regions is limited and they might be the only data available. Recent work has looked at the impacts of artifacts in bathymetric data on geomorphometric analyses. One of the main results from this work is that while artifacts in DBMs propagate significantly to the derived terrain attributes [13] and their applications [14], their impact on a given application is not necessarily predictable. Much work remains to be done to improve our understanding of the impacts of data quality on applications of marine geomorphometry. It is worth noting that there has been an increased awareness of the importance of data quality for geomorphometry and its applications; it is becoming acceptable in published articles to acknowledge the presence of errors and artifacts in DBMs and to discuss their implications for given applications [11,15].

V. DERIVING TERRAIN ATTRIBUTES AND TERRAIN FEATURES

When it comes to the derivation of terrain attributes and the extraction of terrain features from DBMs, three noteworthy trends can be found in the recent literature. First, an important new trend in marine geomorphometry is the effort in automating the processing workflow to derive terrain attributes and extract terrain features. A number of existing tools to derive terrain attributes have been updated in the last two years [16,17]. For instance, the Benthic Terrain Modeler [17] now offers a slope-corrected surface area to planar area measure and an arc-chord ratio measure [18], among other features. Apart from terrain attributes, protocols have also been established to automate seabed classifications [19] and the extraction of terrain features, for instance underwater dunes [15] and other morphometric classes such as valleys, ridges, slopes, shoulders and foot slopes [19]. The second noticeable trend concerns object-based image analysis (OBIA). The number of marine studies using such techniques has increased significantly in the last few years, with 14 of the 16 papers relating to seafloor mapping published in the past 5 years referring to OBIA (*cf.* Scopus database). Those techniques are either used instead of [20], or in addition to [21] pixel-based approaches and are quickly developing in applications related to coastal habitats such as coral and seagrass mapping. The last major recent trend in marine geomorphometry studies is the increased recognition of the multiscale nature of terrain attributes and features. This has translated in more studies looking at the effects of scale on analyses [13,14,22] and the development of multiscale approaches for using terrain attributes in applications like habitat mapping [22], sediment mapping [23] and geomorphology [19].

VI. Applications

A. *Multidisciplinary Integration*

Despite being a discipline in its own right, marine geomorphometry is most often integrated within the workflow of associated disciplines like marine habitat mapping and marine geomorphology. As a consequence, terrain attributes and features are more often used in combination with other datasets. The most common data type associated with terrain derivatives is backscatter (or reflectivity) [19], which is often collected simultaneously with bathymetric data from acoustic systems [24]. In addition, those data are often analyzed together with data from visual surveys or physical samples. In marine geology and geomorphology, terrain derivatives are often used in combination with seismic data to study the genesis of bedforms [25]. Finally, with the increased availability of regional oceanographic data, geomorphometry can be used to evaluate the influence of seafloor geomorphology on the water column above it [26].

B. *New Applications*

While marine geomorphology and geology, marine habitat mapping and ecology, and hydrodynamic modelling remain the core applications and disciplines using geomorphometry in the marine environment, some innovative applications have been published in the last five years. For instance, broad-scale geomorphometry was used to reconstruct realistic paleobathymetry of the Cenomanian-Turonian Ocean (94Ma) [27]. At finer scales, geomorphometry was applied to underwater cryospheric environments in Antarctica where ice surface topography was mapped using multibeam acoustics at very high resolution (1 cm) to understand microstructural habitats for sea ice algae [28]. Another example is the use of fine-scale 3D geomorphometry to quantify habitat use and availability on small structures like oyster clusters on intertidal reefs [29].

VII. Future Trends

Given the evolution of marine geomorphometry in the last few years, it is encouraging that the tools that we are assessing and developing continue to be taken up by an ever increasing and varying group of stakeholders. Development of standardized tools for geomorphometric classification [30] are gaining momentum aided by several formal and informal collaborations within the marine scientific community. This has also helped to bring about a greater emphasis on bathymetric data quality for seafloor mapping, as well as a rise in the use of objective and (semi) automated methods for delineation and characterization of morphometric features [19,30].

There remain some challenges with GIS tools being so readily available for surface analysis, in particular with regards to the nature by which the results are taken up into models in various applications. For instance, there is a need to raise awareness of the limitations of DBMs for different applications. Whilst issues of data resolution and scale of analysis are becoming better documented, it remains challenging to quantify and convey uncertainty and other data quality assessments in applied map products based on DBMs and derived terrain attributes. However, the future of marine geomorphometry is bright. As more tools and methods are developed and adopted by the community, marine scientists will be better equipped to address ongoing challenges, *e.g.* in relation to scale or data quality. In addition, those methods will give rise to innovative applications, for example in applying geomorphometry to 3D data (as opposed to 2.5D data) [29].

VIII. Conclusion

Perhaps the time for marine spatial analysis has come for it to tread its own path, to break down the comparisons with terrestrial geomorphology, to own its specific limitations, and to accept and celebrate the differences of marine seafloor data. New developments in marine geomorphometry may now be invigorated by the research questions that are developed explicitly for marine research and not adapted or adopted from terrestrial studies. The time has come for marine geomorphometry to step out from the shadows of following its terrestrial cousin and explore some of the more relevant questions of the future for marine research such as those related to the vulnerability of coastal ecosystems. While currently only a relatively small community is addressing such questions, this might be done, for example, by integrating marine geomorphometry into university courses and in workshops to reach the wider scientific community.

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