Estuarine, Coastal and Shelf Science 170 (2016) 45–60

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Evaluation of seabed mapping methods for fine-scale classification of extremely shallow benthic habitats — Application to the Venice Lagoon, Italy

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A R T I C L E I N F O

Article history:
Received 21 April 2015
Received in revised form
3 October 2015
Accepted 12 December 2015
Available online 17 December 2015

Keywords:
Benthic habitat mapping
High-resolution sonar
Image segmentation
Very shallow water
Multibeam
Venice Lagoon

A B S T R A C T

Recent technological developments of multibeam echosounder systems (MBES) allow mapping of benthic habitats with unprecedented detail. MBES can now be employed in extremely shallow waters, challenging data acquisition (as these instruments were often designed for deeper waters) and data interpretation (honed on datasets with resolution sometimes orders of magnitude lower). With extremely high-resolution bathymetry and co-located backscatter data, it is now possible to map the spatial distribution of fine scale benthic habitats, even identifying the acoustic signatures of single sponges. In this context, it is necessary to understand which of the commonly used segmentation methods is best suited to account for such level of detail. At the same time, new sampling protocols for precisely geo-referenced ground truth data need to be developed to validate the benthic environmental classification. This study focuses on a dataset collected in a shallow (2–10 m deep) tidal channel of the Lagoon of Venice, Italy. Using 0.05-m and 0.2-m raster grids, we compared a range of classifications, both pixel-based and object-based approaches, including manual, Maximum Likelihood Classifier, Jenks Optimization clustering, textural analysis and Object Based Image Analysis. Through a comprehensive and accurately geo-referenced ground truth dataset, we were able to identify five different classes of the substrate composition, including sponges, mixed submerged aquatic vegetation, mixed detritic bottom (fine and coarse) and unconsolidated bare sediment. We computed estimates of accuracy (namely Overall, User, Producer Accuracies and the Kappa statistic) by cross tabulating predicted and reference instances. Overall, pixel based segmentations produced the highest accuracies and the accuracy assessment is strongly dependent on the number of classes chosen for the thematic output. Tidal channels in the Venice Lagoon are extremely important in terms of habitats and sediment distribution, particularly within the context of the new tidal barrier being built. However, they had remained largely unexplored until now, because of the surveying challenges. The application of this remote sensing approach, combined with targeted sampling, opens a new perspective in the monitoring of benthic habitats in view of a knowledge-based management of natural resources in shallow coastal areas.

1. Introduction

Estuaries and coastal ecosystems are amongst the most productive and valuable environments on Earth (Guelorget and Perthuisot, 1992; Costanza et al., 1998; Barbier et al., 2011; Kirwan and Megonigal, 2013). These ecosystems are particularly susceptible to anthropogenic pressure, with 13 of the 15 world biggest cities located close to the coast (Kennish, 2002; McGlathery et al., 2007; Halpern et al., 2008; Brown and Blondel, 2009; Solidoro et al., 2010). Large national and international programs have started to map these ecosystems, e.g. *Mapping European Seabed Habitats* (*MESH*) (http://www.searchmesh.net), *MESH Atlantic* (http://www.

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http://dx.doi.org/10.1016/j.ecss.2015.12.014

meshatlantic.eu), *EU Seamap* (http://jncc.defra.gov.uk/page-5040), *MAREANO* (http://mareano.no/en), *UK SeaMap* (McBreen et al., 2011), the Irish *INFOMAR* program (http://www.infomar.ie), the *Gulf of Maine Mapping Initiative* (http://www.gulfofmaine.org/gommi), the *Victorian marine habitat mapping project* in Australia (http://hdl.handle.net/10536/DRO/DU:30010514). Accurate mapping of seafloor geomorphology and composition is the basis of marine spatial planning and the implementation of fact-based legislative frameworks (e.g. for the designation of Marine Protected Areas). However, currently, only 5–10% of the seabed has been mapped in detail, the majority of which is deeper than 10 m (Blondel, 2009; NOAA, 2014). This is a concern, particularly in view of European legislative frameworks (i.e. Water Framework Directive, 2000: 60/EC; Marine Strategy Framework Directive, 2008/56/EC; Habitats Directive, 92/43/EEC), as an estimate (based on the EMODnet (2015) bathymetry portal data) shows that 9% of EU coastal waters (bathymetry up to 100 m) are shallower than 10 m.

In the present analyses, we consider habitats as including the physical and environmental conditions (mainly of the seafloor) together with the co-inhabitant biota at a given scale (in line with the definitions set forth by Udvardy, 1959, *inter alia*, and in line with the recommendations set by MESH, 2008). The exploration and mapping of coastal and shallow benthic habitats (depths < 30 m) is significantly limited if using conventional surveying technologies. Satellite and aerial remote sensing techniques have been employed to map the broad-scale spatial organization of littoral ecosystems (e.g. Wang and Philpot, 2007), although water turbidity and lowered light penetration strongly restrict the potential of such applications (Blondel, 2012). Conversely, acoustic remote sensing techniques are constrained by the shallow depths, which limit available coverage away from the surveying platforms and can be affected by strong multiple reflections from the sea surface if using systems designed for deeper waters. Recent developments in underwater acoustic technology can now produce results with a resolution approaching that of photography. Benthic habitat maps based on acoustic data are now commonly used within the context of ecosystem-based management (e.g. Ierodiaconou et al., 2007, Erdey-Heydorn, 2008; Ierodiaconou et al., 2011 Brown et al., 2011; Lucieer et al., 2013).

In particular, multibeam echo sounder systems (MBES) allow co-registering bathymetry and backscatter data. MBES can be designed to operate at very high frequencies (up to 400 kHz) and with tuneable pulse lengths and repetitions, yielding high-resolution measurements over relatively large areas of the seabed (Kenny et al., 2003; Parnum and Gavrilov, 2011). High-resolution MBES has led to a better detection of benthic habitats *sensu lato*, allowing a continuous fine-scale mapping of their distribution (Brown et al., 2011). Whilst MBES have been used extensively in shallow and deep waters, their application in very shallow waters (herein defined as < 10 m depth) is only very recent (e.g. Huvenne et al., 2007; De Falco et al., 2010; Micallef et al., 2012).

In this study, we use very high-resolution MBES data (0.05- and 0.2- m grids), combined with *in situ* observations to map and classify a very shallow benthic environment in the Lagoon of Venice. This lagoon is the largest in the Mediterranean (about 550 km^2, with a mean depth of only 1.2 m). Its tidal channels are virtually unexplored systems with high biodiversity and distinctive biotic communities (Vatova, 1940; Occhipinti Ambrogi and Gola, 2001; Corriero et al., 2007; Sigovini et al., 2014). Up to now, most of the benthic research has been carried out in the mud-flats (e.g. Tagliapietra et al., 1998; Pranovi et al., 2000; Sfriso et al., 2001; Maggiore and Keppel, 2007) which account for the largest lagoon surface area and are logistically easier to access and sample. Tidal channels occupy 15% of the open-lagoon surface with an area of about 64 km^2. Their depths range from less than 1 m up to a maximum of 50 m.

The combination of large areas and very high resolution data justifies the use of automated habitat classification. There have been fast and recent developments in integrating analyses of the acoustic data (bathymetry and/or imagery) with available ground truth, and different manners of presenting habitat maps have been proposed (see Brown et al., 2011; for a review). Promising quantitative and objective new approaches have been developed, using mixed methods, i.e. pixel-, field and object-based image analyses) (e.g. Brown and Blondel, 2009; Brown et al., 2011; Ierodiaconou et al., 2011; Lucieer and Lamarche, 2011; Micallef et al., 2012; Diesing et al., 2014; McGonigle and Collier, 2014).

However, there have been very few comparisons (e.g. Diesing et al., 2014; Calvert et al., 2014; Galparsoro et al., 2015), all focusing on lower-resolution (>1 m) data. The very high grid resolutions (<5 cm) afforded by new systems and new applications, like in the Lagoon of Venice, are setting new challenges for benthic habitat mapping.

In the present study, we apply a few different methods well-established in the realm of classification of remotely sensed data. They were chosen either because of their widespread availability within commercial and open access GIS platforms or because they were successfully applied before. In our choice, we considered both backscatter intensity and textural parameter methods, to see which image characteristic is best to identify the seafloor types of interest. Our aim is therefore to assess which backscatter segmentation method is most suitable to map very fine scale, heterogeneous benthic habitats. At the same time, we investigate the effect of pixel size at varying resolutions (i.e. 0.05 and 0.2 m) as well as the number of thematic classes on classification results. This is supplemented with a combination of ground truth information including free-diving observations, underwater photography and video and benthos samples at the most relevant points.

2. Material and methods

2.1. Study site

The study site is located in the northern part of the Venice Lagoon, Italy (Fig. 1). The Scanello channel is a natural tidal channel, part of a complex tidal system of tidal creeks and coastal salt marshes. The channel flows as a side-branch of a main navigation channel into a salt marsh area. It shows an erosion-deposition pattern characteristic of meandering tidal channels and follows a gentle sloping gradient from north to south. Its bathymetry is complex, with geomorphologic features like scours, ripple-like structures, flat zones, point bars and pools (Dalrymple and Rhodes, 1995).

Following a short straight section of about 200 m, the channel bends to the North for about 300 m, where it separates into two smaller branches flowing into an extremely shallow tidal flat with depths <1 m. These branches are characterized by the relative highest ruggedness, quantified with the Benthic Terrain Modeler for ArcGIS (Wright et al., 2005; Lundblad et al., 2006) as a Vector Ruggedness Measure (VRM) between 3×10^{-3} and 10^{-2} (Fig. 1c). Their VRM isotropic distribution suggests the presence of biogenic features (Ferrini and Flood, 2006). The dune-like fields in the main branch of the channel also have a high ruggedness. Conversely, the rest of the channel is quite smooth (VRM ruggedness between 10^{-5} and 3×10^{-3}).

2.2. Data acquisition and processing

2.2.1. Geophysical data

Bathymetry and backscatter imagery of the Scanello channel