SHORELINE EXTRACTION METHODS AND MEGACUSPS IDENTIFICATION FROM SENTINEL-2 IMAGES

Riccardo Angelini, University of Florence, riccardo.angelini@unifi.it
Eduard Angelats, Centre Tecnològic de Telecomunicacions de Catalunya (CTTC\CERCA), eduard.angelats@cttc.cat
Francesca Ribas, Universitat Politècnica de Catalunya, francesca.ribas@upc.edu
Guido Luzi, Centre Tecnològic de Telecomunicacions de Catalunya (CTTC\CERCA), guido.luzi@cttc.cat
Andrea Masiero, University of Florence, andrea.masiero@unifi.it

INTRODUCTION

Coastal regions play a crucial role due to their rich biodiversity and human recreational and economic uses. Monitoring the coastal environment is essential in the present framework of climate change and it typically involves the identification of various indicators, with the shoreline being the most prevalent. There are several definitions for this indicator, but we here refer to the instantaneous shoreline, automatically identified through satellite imagery or digitized by the operator as "ground truth" from orthomosaics.

Conventionally, collecting data in large coastal areas is typically carried out manually by a human operator. This method is often time-intensive, costly, and subject to the limitations and decisions of the individual operator. Conversely, remote sensing has become an invaluable asset for coastal surveillance, offering the advantages of large-scale coverage and frequent data acquisition, all while being economically efficient.

Satellite images can be employed to extract the shoreline with subpixel resolution). Optical images provide a simple way to extract shorelines based on the spectral reflectance of both land and water. Different indices (e.g., NDWI, among others) and different automatization methods (e.g., thresholding and classification schemes) can be applied.

Shorelines on sandy beaches often exhibit diverse morphological features due to variations in hydrodynamic forcing and sediment movement. Examples of such features are megacusps, periodic undulations along the shoreline with wavelengths of hundreds of meters, and cross-shore amplitudes from a few to tens of meters (de Swart et al., 2022). Megacusps development on sandy beaches can be linked to both persistent intermediate wave conditions or to extreme sea states involving strong erosion (Castelle et al., 2015). For this reason, a deeper understanding of these phenomena is necessary.

An existing limitation is that studies on megacusps are often spatially and temporally constrained. The implementation of video monitoring systems can enable extended observation (de Swart et al., 2022), yet they remain geographically and spatially limited. Employing multispectral satellite imagery automatically extracted shorelines could potentially bridge this gap. Thereby, the aim of this study is to develop a methodology for shoreline extraction that allows the detection and characterization of megacusps using Sentinel-2 (S2) optical images.

METHODOLOGY

The first phase of this study was a detailed test and validation of different indices and two types of methods for shoreline extraction: thresholding and classification. A preprocessing step was first conducted on the S2 images: resampling the bands with varying spatial resolutions, cropping the images, and calculating six indices: NDWI, mNDWI, WI, SWM, AWEI-shadow, and AWEI-no-shadow (Ozturk and Sesli, 2015). Thresholding methods tested involved a fixed threshold, Otsu's method, and Niblack's. Regarding classification methods, we applied K-means and GMM (Gaussian Mixture Model), two unsupervised classifiers. The next step involved reading the binarized raster images and identifying the connected regions within them. This was followed by the extraction of contours from these connected regions and the obtained shorelines were smoothed. To conclude the first part of the analysis, the accuracy of the obtained S2 shorelines was assessed by comparing them with reference shorelines from high-resolution aerial orthomosaics and computing several metrics using cross-shore transects spaced every 10 m.

After selecting the most effective shoreline extraction methodology for each site, the study proceeded with the identification of megacusps. First, a stretch of coastline of approximately 3 km long with megacusps was visually identified in one of the available orthomosaics (reference shoreline), and automatically obtained in the corresponding S2 image (using the best previously tested extraction methodology). Both coastlines were first detrended, to subsequently calculate several wave function parameters. First, the standard deviation and the sinuosity (Ojeda et al., 2011) were computed to evaluate the potential alongshore variability in the shoreline. Then, an algorithm of peak detection was used, where oscillations with an amplitude smaller than 3 meters were filtered out to avoid including noise. The alongshore wavelength was then calculated as the mean distance between the horns of the megacusps and the amplitude was determined as half the average cross-shore distance between a bay and its two adjacent horns.

Table 1 - Mean absolute distance (MAD), root mean square error (RMSE), mean distance (MD), and median distance (MeD) obtained for the three best methodologies (index and method). The statistical parameters correspond to all the points from all the dates of each site.

Index	Method	MAD [m]	RMSE [m]	MD [m]	Site
NDWI	GMM	3.78	4.32	-3.22	Castelldefels
AWEI	k-means	4.48	5.51	-0.54	Marina di GR
WI	k-means	3.66	4.57	-1.15	Feniglia

STUDY AREAS AND DATA SOURCES

In this research, three sandy beaches are being analyzed: two located in Italy (Feniglia and Marina di Grosseto beaches in Tuscany) and one in Spain (Castelldefels beach in Catalonia). The segments under study span lengths ranging from 5 to 10 km. In the initial phase of testing and validating the methodology for shoreline extraction, we used three orthomosaics from the Catalan region, provided by the Institut Cartogràfic i Geològic de Catalunya, and two for the Tuscany region, supplied by the Tuscany region authorities. These high-resolution images (20-25 cm) were used to manually digitize shorelines, which served as reference. After confirming the dates of the orthomosaics, multispectral S2 satellite images that had minimal or no cloud cover, and which closely matched the specified dates, were chosen.

RESULTS AND DISCUSSION

Table 1 shows the best result in terms of mean absolute distance between the automatic S2 shorelines and the reference ones, in the three sites. These results correspond to the weighted average across all the dates of each beach analyzed. The results indicate an accuracy of around 5 meters (i.e., sub-pixel accuracy). This is particularly noteworthy considering that the calculations of the indices used bands resampled to 10 m, but with native resolutions also of 20 m and 60 m.

The megacusp analysis was conducted for dates where both a high-resolution orthomosaic and the nearest Sentinel-2 image (within 3 days) were available. Figure 1 shows an example of megacusp detection in an S2 Castelldefels image (23/5/2023), with the automatic location of peaks and valleys. The results for this example, summarized in Table 2, show a remarkable similarity with the characteristics of megacusps obtained from the orthomosaic reference shoreline (of the same day in this case).

This study is being extended to all the available images of the three sites. The automatic nature of the analysis makes it easily applicable to different case studies and purposes. Thereby, it has the potential to allow megacusps characterization in a variety of geographic location and with high spatial and temporal resolutions.

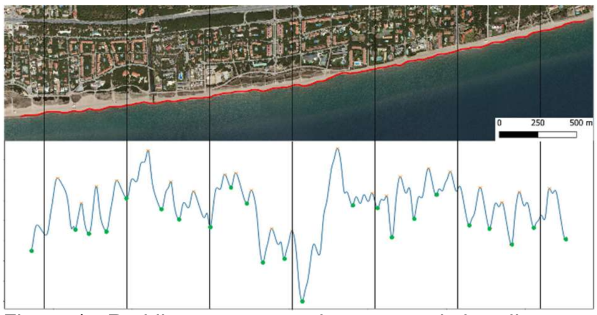

Figure 1 - Red line represents the extracted shoreline over the S2 image on 23/5/2019, using the best methodology in the Castelldefels beach. On the bottom, the detrended line is shown with peaks (cross) and valleys (green dots) used to calculate wavelength and amplitude.

Table 2 - Mean wavelength (MW), mean amplitude (MA), standard deviation (SD) and sinuosity (S) obtained in the Castelldefels S2 image (Figure 1).

Index	Method	MW [m]	MA [m]	SD [m]	S [m]
NDWI	GMM	149.04	14.97	6.37	1.0155
Reference		162.96	11.26	6.18	1.0132

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