MAPPING OF THE RISK OF COASTAL EROSION FOR TWO CASE STUDIES: PIANOSA ISLAND (TUSCANY) AND PISCINAS (SARDINIA)

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Abstract – This study focuses on the use of satellite remote sensing to map coastal erosion vulnerability in two Italian sites: Pianosa Island (Tuscany) and Piscinas (Sardinia). For both areas we focused on the land/water transitional ecosystem, with the aim of identifying potential coastal erosion phenomena and to demonstrate the role of benthic habitats in preserving the value of coastal environments. The method made use of ancillary and multi-spectral satellite data from 2016 to 2018. For this study, the first 7 bands of the VIS–NIR region of Sentinel-2 were used, all reprocessed at the spatial resolution of 10 m. The TOA (Top of Atmosphere) radiance products were atmospherically corrected and processed using the Sen2Coral add-on-tool and the BOMBER code (Bio-Optical Model-Based tool for Estimating water quality and bottom properties from Remote sensing images). Maps of marine substrates and bathymetry were obtained and revealed their influence on the coastal dynamics. Then, in case of Piscinas, SAR images (COSMO SkyMed and Sentinel-1B) were added to the analyses. COSMO-SkyMed allowed us to identify the coastline and to obtain qualitative indicators about the absence/presence of changes in coastal dune system, the most relevant terrestrial element of the site. Sentinel-1B supported, by adopting an inversion process scheme, the analysis of the wave state impacting the coast. By merging the satellite products, the coastal erosion vulnerability maps have been generated based on substrate type in shallow waters and sand volume variation on land: rocky bottoms and stable meadows of phanerogams seemed preserving the coast, while the substrate characterized by a loss of phanerogams and a decrease in sand volumes might be considered more vulnerable. The results confirm that the coast of Pianosa is not suffering from coastal erosion, while the vulnerability maps of Piscinas seem to be closely linked to episodic events so that the Piscinas dune system might be considered safe from coastal erosion processes.

Introduction

Coastal processes are the result of forces acting on coastal areas and leading to the modification of these environments. Both natural and anthropogenic activities can lead to the degradation of these environments and consequently to other hazards such as: shoreline changes, sea-level rise, sea water intrusion, coastal erosion and floods [8]. Italy comprises ~8000 km of coastline of which approximately 25 % consists of low-lying plains, some of

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which are subsiding with a potential for flooding. Coastline mapping and change detection are essential for safe navigation, resource management, environmental protection, and sustainable coastal development and planning [2]. In this context, satellite remote sensing has been used for about 50 years to obtain environmental information to support effective management for such landscape. The use of remote sensing techniques has many advantages including the ability to perform repeated captures on the same site and to instantly display large areas, overcoming many limitations imposed by in-situ sampling techniques. Recently, the Italian Space Agency funded the CosteLAB project (Contract Number 2017-I-8.0). The primary goal of the project is the creation of a virtual laboratory to analyse, develop and test applications and products for monitoring and managing coastal risk. The most common methods to estimate vulnerability and coastal erosion risk can be based on different indicators and model dynamics [10]. The added value related to the proposed research activity is represented by the mapping of different substrates (e.g. sand, rock, phanerogams) in correlation with bathymetry that influenced the dynamics of coastal erosion. As well as the use of radar images characterized by high frequency and spatial resolution, which can represent a turning point in mapping and monitoring of coastal areas [9]. Two case studies are developed to demonstrate the role of benthic habitats in preserving the value of coastal environments and in particular to mitigate the coastal erosion. The first is focused on Pianosa island starting from optical satellite data, while the second case study is focused on Piscinas and involves the use of both optical and radar imagery.

Materials and Methods

In this work two Italian study areas were analysed: Pianosa Island (Tuscany) and the coastal dune system of Piscinas (Sardinia) (Fig 1). Pianosa Island is the fifth, by extension, of the seven islands of the Tuscan Archipelago National Park with a total area of 10.2 km^2 and a coastal perimeter of approximately 20 km. The island is almost completely flat, with some small undulations. The highest elevation is 29 m above sea level (a.s.l.), while the average is about 18 m a.s.l. while, the coastal dune system of Piscinas is an area of about 1.5 km^2 located in the South of the Oristano Gulf in the Sardinia Island, near Arbus. It has one of the highest dune systems in Europe (for this reason it is part of the UNESCO World Heritage) and therefore has been selected for conducting the experiments about the use of satellite remote sensing for beach and dunes variation. The coastline extends for about 7 km and the maximum height is about 100 m. The surface is continuously remodelled by strong winds blowing from the West regularly over the whole year. A peculiarity of this area, clearly visible in each optical satellite image analysed in this study, is the presence of semi-circular depressed areas along the entire sandy coast at a variable distance (200÷500 m) from the coastline.

The remote sensing data used to develop this research theme were basically acquired by the Multispectral Imager (MSI) on-board of Sentinel-2A (S2). For the case of Pianosa, the selected images were acquired on 18/07/2016, 04/05/2017, 11/05/2017, 03/06/2017, 13/02/2018, 19/04/2018, 18/07/2018. While for Piscinas on 29/10/2016, 15/11/2016, 28/12/2016, 18/03/2017, 04/05/2017, 28/12/2018. For this second site, SAR images (COSMO SkyMed and Sentinel-1B) were added to the analyses. All these images were chosen because cloud-free, without sun-glint and other radiometric noise. Before processing the optical images, a comparison between Level 1 (L1) and Level 2 (L2) products was performed

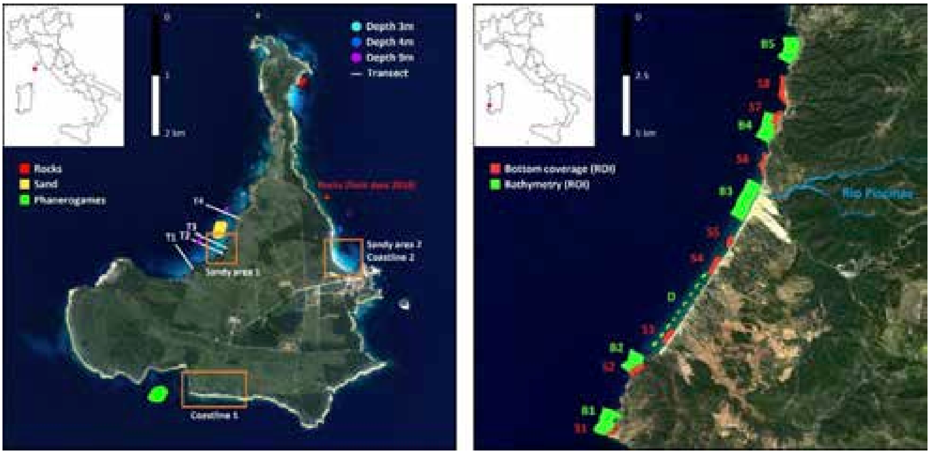

Figure 1 - Case study areas from Sentinel-2 images of 03/06/2017 (Pianosa) and 18/03/2017 (Piscinas). On the left the island of Pianosa: the two sandy areas and the coast segments analysed are squared in orange; bathymetric transects are represented as white lines (T1-T4) and the other coloured areas represent the regions selected as ground truths for validation of bathymetry and substrates. On the right the Piscinas coastal dune system: in red the regions of interest (S1-S8) used for the analysis of the bottom coverage classes; in green the regions of interest (B1-B5 + D) used for the bathymetric analysis; in light blue the Rio Piscinas torrent.

(Copernicus Open Access: https://scihub.copernicus.eu/dhus). L2 images containing bottom-of-atmosphere (BOA) reflectance as computed by Sen2Cor. Since this tool is not optimised for retrieving water reflectance above water, a comparison with the L1 images corrected atmospherically using the 6SV code (Second Simulation of the Satellite Signal in the Solar Spectrum code-vector version) [12] was performed. The spectra obtained with the procedures were in agreement and showed an aware deviation of 0.01 %. The 6SV output was chosen as reference due to its good performances in retrieving water leaving reflectance in inland and coastal waters [5,1]. To run 6SV, all bands of L1 images were reprocessed at the spatial resolution of 10 m through SNAP S2-toolbox, with nearest neighbour method. TOA radiance products, obtained using the SNAP tool ReflectanceToRadianceOp, were then atmospherically corrected with 6SV code. Finally, the 6SV output were converted into Remote Sensing Reflectances (Rrs) above water dividing the bands by π. The Rrs products were then processed using the Sen2Coral add-on-tool (Pianosa) and the non-linear optimization algorithm called BOMBER (Piscinas) in order to obtain maps of three different substrates (sand, rocks and phanerogams) and bathymetry. The described tools were applied to S2 images acquired between 2016 and 2018, a temporal range in which we do expect to observe recent possible erosion processes. The Sen2Coral tool is developed according to the state-of-the-art of spectra inversion of semi-analytical (SA) bio-optical modelling. This method relies on some form of spectrum matching of modelled reflectance spectrum using a set of bathymetry, bottom classification, and water column IOPs values, optimized to match the image Rrs (λ) spectra. Materials used for this site also include ancillary data such as: a bathymetric map and a georeferenced coastline of 2014 (ISPRA's website); a nautical chart published by *Istituto Idrografico della Marina*; a RapidEye image of summer 2017 and Google Earth imagery. BOMBER [4] is instead a non-linear optimization algorithm used, like Sen2Coral, for the classification of the bathymetry and of the substrate coverage. The Rrs images were used as input and the bio-optical modelling system was applied in shallow water mode and, for each image, was applied to a mask that includes water up to 1000 m from the coastline (maximum depth between 10 m and 12 m). The bathymetric outputs obtained with the BOMBER were compared with a bathymetric map available at "https://webapp.navionics.com" website.

In addition, for the site of Piscinas, three SAR images from COSMO SkyMed mission (synchronous or as much as possible close to the optical images acquisition; 27/12/2016, 17/03/2017 and 04/05/2017) were also analysed to better identify the coastline (Fig 2). The coastline was identified using two approaches: one based only on optical images (Rrs images) and one merging bands of Rrs images (band2-490 nm and band6-740 nm) with SAR COSMO SkyMed. To obtain the Rrs+SAR outputs, the available SAR images were first georeferenced. Then a "write function memory" was performed to obtain a product characterized by both Rrs and SAR bands. This method consists of inserting individual bands of remotely sensed data into specific bands of image processing (red, green and blue) to highlight change [11]. This process is mainly used to highlight temporal changes between images of the same sensor [7], while in this work it has been used to highlight changes between different sensors (Sentinel-2 and COSMO SkyMed). As a result, an RGB output was displayed to identify the coastline: Red=band2 (Sentinel-2 Rrs), Green=band6 (Sentinel-2 Rrs) and Blue=SAR (COSMO SkyMed). No synchronous SAR images were available for the Pianosa site, so the coastline was identified through the Sentinel-2 NIR bands and by comparison with the ISPRA map. In particular, the temporal evolution of the Pianosa coastline in 2016-2018 was analysed in two segments: the sandy beach of Cala della Giovanna and a rocky segment in the south of the island (Fig 2).

The research theme concerning the beach and dunes volume changes has been integrated by COSMO-SkyMed SAR data acquired over repeated orbits. To this aim, the research activity has been performed in the site of Piscinas. The analysis is concentrated on the use of the multitemporal amplitude and phase response, which allows characterizing the coherence properties as well as the presence or absence of deformation. A stack of 62 COSMO-SkyMed images acquired in 3 years from 16/06/2015 to 24/06/2018 has been analysed. Data have been processed with a two-step interferometric processing method implemented at small (low) and large (high) scale (resolution) [3]. The deformation analysis provides information about the areas that shows constant characteristics over the time and that are therefore less affected by the erosion factors, particularly the action of the wind.

For the Piscinas site, the wave state impacting on the coast was also analysed. Sentinel-1B SAR image gathered on 06/05/2019 at 05:28 UTC and showing a sharp wave-modulated backscatter was analysed. The backscatter analysis performed with CMOD algorithm returned a wind speed of 16 m/s impinging with direction toward the coast (330° N), a result comparable with ERA5 reanalysis data provided by ECMWF. The retrieved wind field was then used to estimate the sea surface wave spectrum from a SAR image's subregion of 512x512 pixels centred at 39.5° N, 8.25° E. The Hasselmann's procedure to extract the sea surface wave spectrum from the measured SAR spectrum [6] was finally applied. A complex wave spectrum composed by a wind sea component with dominant wave with 140 m wavelength coming from 311° N and a swell of 135 m wavelength coming from 341° N with total wave height of 4.82 m was obtained. This SAR retrieved wave state was comparable with the respective prediction by the wave model WAM provided by ECMWF.

The bottom depths of Pianosa obtained as output by Sen2Coral were tide corrected and compared for validation with bathymetric data obtained from the nautical chart. Data were extracted from the output maps through linear transects (T1-T4) (Fig 1). Depth values were extracted and analysed from the output also in small areas around points of know-bathymetry (Fig 1). Maps of reflectance at 550 nm produced by Sen2Coral were classified on the basis of substrate type expected in each reflectance range. The substrate maps obtained were analysed with confusion matrices built on the ground truth areas (based on visual interpretation), to evaluate the accuracy of the substrate classification. Based on Sen2Coral output maps of bathymetry and substrates, two sandy areas (Fig 1) were selected to evaluate the variation of water volumes contained in the bays. This methodology could be used to define the erosion process, as the increase of water volumes indicates the progression of the coastline toward the land. For the classification of the Piscinas bottom coverage and bathymetry, a series of ROI's were analysed (Fig 1). In detail, 8 ROI's (S1-S8) were evaluated for the bottom coverage maps and 5 ROI's (B1-B5, in addition to the semi-circular depressed zones "D.") for the bathymetric maps (Fig 1). For the first 8 ROI's, the percentage of coverage of each class (sand, rocks and phanerogams) was assessed. The 5 ROI's of the bathymetric maps were divided into 4 subclasses based on the distance from the coast (10÷200 m, 201÷400 m, 401÷600 m and 601÷800 m). Moreover, the variation of the average depth and the water volume were assessed, also considering the tidal phenomena. Besides, the first two images of 2016 (29/10 and 15/11) were used to evaluate the effects of a strong wind event that occurred in the time interval of acquisition of the satellite.

Results

With respect to the downloaded images, three of them were considered optimal for the analysis of the benthic habitats of Pianosa Island (18/07/2016, 03/06/2017 and 19/04/2018). The analysis of the temporal evolution of the coastline obtained from NIR bands, shows that the position of rocky segments doesn't change in time; also, shows that no significant modifications to the shoreline occurred for the two sandy area analysed in the period 2016-2018 (Fig 2). For the Piscinas site it was possible to make a comparison between the coastline produced by optical images and that produced by SAR+Rrs (Fig 2). This comparison shows differences in the range from a few meters up to 20 m between the two coastlines. In fact, the interpretation of optical images was complex, especially in the so-called "mixed" pixels, located at the water/sand interface, while SAR+Rrs images allow to better distinguish between these two surfaces. As a result, the coastline derived from SAR+Rrs images was more accurate. For this reason, the coastline obtained in three different date (27/12/2016, 17/03/2017, 04/05/2017) from SAR+Rrs images was compared (Fig 2) showing that along the sandy coast the coastline had a greater variability (up to 20 m) than near the rocky shores (up to 5 m).

The reflectance maps of Pianosa at 550 nm produced by Sen2Coral were classified based on reflectance range expected for each substrate type, so that values lower than 0.08 were assigned to phanerogams, values higher than 0.2 to sand and those in between to rocky substrates. Most of rocks are detected in shallow water along the coastline, sandy substrates can reach bottom depths at around 5 m and macrophytes are detected in deeper regions. The output of Sen2Coral was analysed with confusion matrix. The results show good overall accuracy when considering regions corresponding to the three ‘pure’ end-members, sand, macrophytes and rocks. The accuracy decreased when regions of mixed substrates were included in the analysis. This could be due to the procedure used to select ground truth areas, which is not based on field data but on visual interpretation. Comparison of bottom depths obtained with Sen2Coral with data derived from the georeferenced nautical chart shows good agreement between the data and the available ground truths (based on a punctual information from field data acquired by Reparto Ambientale Marino, Livorno). Analysis of the transects showed that no significant modifications of bathymetry occurred in the period 2016-2018. Moreover, comparing the water volumes of the two sandy areas, it emerged that only small volumetric variations occurred during the period considered (about 6÷7 % from 2016 to 2018).

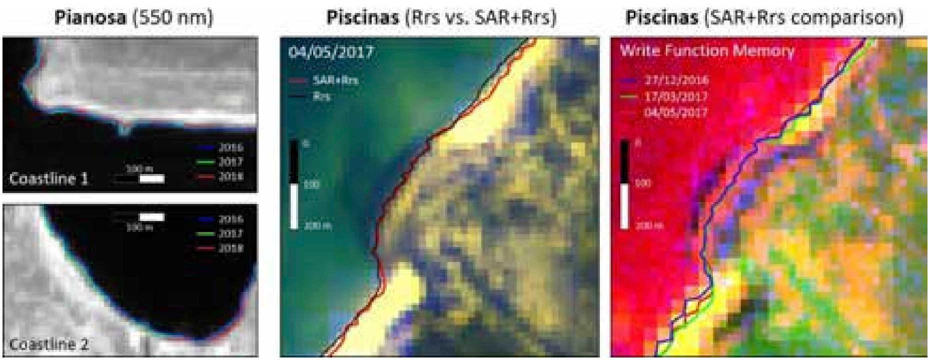

Figure 2 - On the left, the temporal evolution of the coastline (18/07/2016, 03/06/2017, 19/04/2018) obtained from NIR bands in the two segments analysed for Pianosa. In the middle, the comparison between the coastline obtained by Rrs image (black line) and the coastline obtained by SAR+Rrs images (red line), along a fraction of the Piscinas coast on 04/05/2017. On the right, the temporal evolution of the coastline derived from SAR+Rrs images acquired on 27/12/2016 (blue line), 17/03/2017 (green line) and 04/05/2017 (red line).

In each bottom cover maps of Piscinas, the main class is the sand one, followed by the remaining two classes (phanerogams and rocks) which were concentrated near the coast (up to 150÷200 m from the coastline). The phanerogams class was concentrated along the rocky portions of the study area, while along the sandy shores it is easier to find mixed pixels (sand/rock). The analysis of the 8 ROI’s related to the bottom cover classes allowed to suggest that Piscinas was a changing system over time. The two images interspersed with the windy event (29/10/2016 and 15/11/2016) showed in all ROI’s, with the exception of sandy areas S3 and S4, a decrease in phanerogams class (from 2.1 % to 15.7 %). Moreover, the image of 28/12/2018 was characterized by the lowest percentage of phanerogams’ coverage for all ROI's considered. This peculiar picture needs in situ data, to better understand the vegetation dynamics. From the bio-optical model, bathymetric maps were also obtained. Within the analysed area (0÷1000 m from the coastline), the maximum water depth never exceeds 12 m and the slopes are never steep, especially along the dune system. The semi-circular depressed areas (D) are clearly visible in each image, in particular in the south-western part of the dune system. The bathymetry varies considerably along the whole area after the windy event analysed, especially in the sandy area in front of the Rio Piscinas estuary. In particular, the deepest bathymetric class (>8 m) decreased along the coast (from 1170.26 ha to 505.97 ha; -57 %), while the two intermediate classes (from 4 to 8 m deep) widen considerably (from 522.44 ha to 1252.12 ha, +59 %). The bathymetric level variation observed in the areas close to the coast (the first two classes, up to 4 m deep) was not significant. The bathymetric map of 28/12/2018 showed a clear increase in the depth of the semi-circular depressed areas. The results of the analysis of the 6 bathymetry ROI's (B1-B5 + D) showed that the total volume of water (considering the tidal events), vary over time. Focusing on depressed areas, during the observation period, their total area varies from a minimum of 62.5 ha (29/10/2016) to a maximum of 137.7 ha (28/12/2018). Instead, after the windy event, a small variation in the depressed area extension was recorded (62.5 ha on 29/10/2016, and 65.8 ha on 15/11/2016).

The results obtained from the analysis of the wave state impacting on the coast of Piscinas, show that SAR peak has been well captured from the SAR inversion both in terms of wavenumber location and amplitude. The SAR inverted sea surface parameters reported a wave height of 4.82 m, that is compatible with the 4.77 m predicted by WAM. Even the SAR retrieved wave direction (341° N) agrees to WAM predicted one (321° N). Discrepancies with WAM prediction are within the expected sampling variability of the SAR estimate.

Based on bottom type and sand volume variation we have created maps of vulnerability for the two sites under review (Fig 3). For Piscinas it was possible to create a short-term (windy event) and a long-term (comparison between 2016 and 2018) vulnerability map. We have assumed that the rocky bottoms and stable meadows preserve the coast, while substrates characterized by a loss of phanerogams and a decrease in sand volumes might be considered vulnerable. The results confirm that the Pianosa coastal zone doesn't have a problem

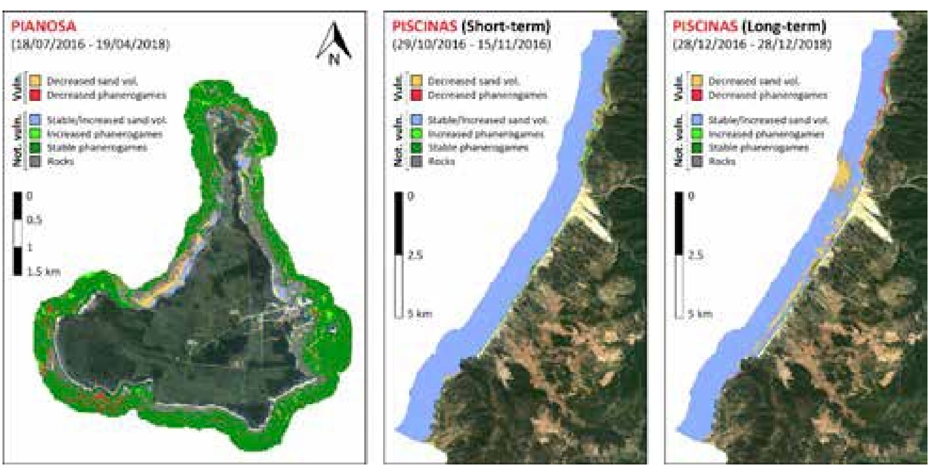

Figure 3 - Vulnerability maps of coastal zones obtained from the classification of substrates and bathymetric analysis. On the left, the vulnerability map of Pianosa (2016-2018); in the middle, the short-term vulnerability map of Piscinas (windy event: 29/10/2016 - 15/11/2016); on the right, the long-term vulnerability map of Piscinas (2016-2018).

with the coastal erosion. For Piscinas the least vulnerable map is the short-term, while the most vulnerable map is the long-term, which is characterized by a marked decrease in sand volume (especially in front of the estuary) and a decrease in phanerogams.

Finally, the coherence map obtained through the analysis of COSMO-SkyMed images shows the presence of an area, developing along the torrent bed of Rio Piscinas, characterized by low level of coherence. More generally, the measurements seem to indicate about an overall stability of the coastal area, with higher coherence in the southern part respect to the northern part, and higher coherence in coastal areas than in the inner regions.

Discussion

The analysis of the coastline obtained from NIR bands, shows how the position of rocky segments doesn't change in time, thus confirming the hypothesis that this bands can be used to define the land contour. The satellite images of Pianosa showed that no significant modifications to the shoreline occurred in the period 2016-2018. This confirms the hypothesis that phanerogams meadows along the coast help containing the erosion process. However, the interpretation of optical images remains complex, especially in the so-called "mixed" pixels, located at the water/sand interface. The use of SAR+Rrs images for Piscinas, instead, allow to better distinguish between these two surfaces. The results obtained from this analysis on a short temporal window (from winter 2016 to spring 2017), highlight a certain degree of variation in the sandy portions of the coastline. These changes may be due to the tide level variation, the wave motion and the sensors spatial resolution. Consequently, the use of SAR+Rrs images may be useful to study the temporal evolution of the coastline. The analysis of sand volumes variations in the two sandy areas examined for the island of Pianosa, shows overall only minor variations in the period considered, resulting in slight increments of sandy volumes, which confirms a stable situation that is not conditioned by erosion processes. Bathymetry, on the other hand, varies considerably along the entire Piscinas dune system. Consequently, Piscinas can be identified as a not stable at bathymetric level, probably due to the synergistic effect of wind and sea currents on an area characterized principally by sand substrate. In particular, between 29/10/2016 and 15/11/2016 (windy event), the deepest bathymetric class (>8 m) decreased along the coast (reduction of 57 %), while the two intermediate classes (from 4 m to 8 m deep) widen considerably (increase of 59 %). This variation was probably due to the sand mobilization wind induced that once deposited decreased the overall volume of water. This absence of large bathymetric variations close to the coast, during wind events support the speculation that these changes seem to be relevant only far from the coastline. Considering also the distance from the coast, near the shoreline the average depth and total water volume were similar in the two images spaced out by the windy event, while moving away from the coast (from 400 m onwards), these two values were always lower in the post-wind image compared to the pre-wind one. Again, these results reinforce the evidence that the wind event affects mainly areas far from the coast. Finally, based on the bottom type and sand volume variation it was possible to create maps of vulnerability of coastal zone of the two study areas. For Piscinas, a short-term (wind event) and a long-term map has been created. The results show that the least vulnerable map is the short-term, i.e. the one relating to the windy event. The wind has led to the deposition of a large amount of sand, especially away from the coastline, and has not led to a marked decrease in the phanerogams. On the other hand, the most vulnerable map is the long-term, which is characterized by a marked decrease in sand volume and a decrease in phanerogams, especially in the rocky areas to the northeast. However, these results are influenced by the significant extension of the semicircular depressed zones in 2018.

Conclusion

In conclusion, the use of multi-source remote sensing satellite data allowed us to contribute to the assessment of the phenomenon of coastal erosion phenomenon, offering a new perspective and allowing us to overcome some limitations associated with field surveys. In particular, the spatial resolutions of both optical and SAR images, resulted appropriate for the target areas, while the dedicated processing and the use of physically based algorithms provided reliable results, although further activity seems necessary to validate the satellite-inferred maps. The results confirm that the coast of Pianosa has no problems of coastal erosion, while the vulnerability maps of Piscinas seem to be closely linked to episodic events (e.g. strong wind or extension of depressed areas), with minor-to-none impacts on the Piscinas dune system.

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