MONITORING OF THE EVOLUTION OF "BARENE" BORDERS AND THE SAFEGUARD OF THE VENICE LAGOON MORPHOLOGY: A CONTRIBUTION FROM THE 'COASTAL CHANGE FROM SPACE' PROJECT RESULTS

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Abstract – Optical satellite imagery is widely used to monitor various earth phenomena and to understand their evolution. Thanks to the Copernicus program and the Landsat missions we can access a huge amount of data over a wide time and area span and with high revisit frequency.
This research proposes the acquisition of a time series from optical satellites to observe changes in the Venice lagoon, an ecosystem which is very challenging to monitor by means of in situ survey activities, let alone using remote sensing techniques, given the presence of land and sandbars (vegetated intertidal areas), very difficult to discern.
Following the successful delivery of the Coastal Erosion from Space project [1] an extension has been commissioned by the European Space Agency, which brought in ISPRA as a new partner and user community representative and included additional sites in Italy, among which, the Venice Lagoon.
We will present the manner in which co-registration improves image spatial accuracy and allows us to obtain a long time-period, high revisit rate and highly accurate waterline/shoreline time series. The work that will be presented describes the specific validation process performed by ISPRA on the results obtained by this method as applied on some target sites of the Venice Lagoon, both natural and partially artificial islands, using fully artificial islands as reference.
The evolution of the natural structures of the Lagoon is normally slow, but some anthropogenic actions may force rapid change in such dynamics; examples of this are the navigation channels and the vessels-induced waves.
An important role in safeguarding the morphology of the Venice Lagoon, with respect to both anthropogenic drivers and sea level rise (expected as the result of climate change), can be managed by the possibility of developing tools to provide frequent monitoring of the evolution of the sandbars in the Lagoon.

Introduction

Since time immemorial, the beauty and the life itself of Venice has been linked to the balance that the city could build-up and maintain with the lagoon environment it inhabits. This unique balance has been officially recognised as a World Heritage Site by

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UNESCO in 1987. According to the "Lagoon Atlas" [2], the Venice Lagoon system is composed by about 60 islands, over an area of about 550 000 km^2. From 2014, its northern part has been included into a regional environmental and anthropological Park, with protection measures set by the regional and national laws.

The ecosystem is very peculiar and full of many specific bio/ecotopes, like the "barena" (vegetated saltmarsh), "velma" (sandbar emerged at low tide), "ghebo" (tidal creek), "chiaro" (salt pan), along with many semi-natural or artificial landscapes. In Figure 1, we show an overall view of the whole Lagoon area, with the study areas highlighted and with a characterisation of the land cover/land use obtained by a semi-automatic classification procedure which will be further described in the following chapters.

Needless to say, this eco/anthropic system is very fragile, both from the anthropic and the environmental point of view, as each component is strictly interlinked and exposed to peculiar stresses, again, both natural and man-made; nevertheless, the vulnerability of the natural environment is much higher than that of the human settlements/activities, so that a strong focus on protection measures is needed, taking into account all of the drivers acting on the area.

The evolution of the natural structures is normally slow, but some anthropogenic actions may force rapid change in such dynamics; throughout the past century and more, this delicate balance has been increasingly compromised by human actions, especially industrial activities, the use of motorized vessels and cruise liners and the construction of protection constructions. A substantial part of the natural areas of the lagoon have disappeared as a result of these actions; as these natural settings are very important in the hydraulic and environmental balance of the Lagoon system, the national and local governments were forced to act, both assessing the impacts and considering mitigating actions to reduce or reverse their effects. Presently, the defence of the lagoon environment is addressed by means of several regulations and laws, limiting human activities, thus trying to prevent the loss of natural habitats [3-5].

Particular reference should be made to the Morphological Plan for the Venice Lagoon, a tool for combating lagoon degradation and an update of the first Morphological Plan drawn up in 1993 [4]. The main objective of the update developed in these years is to use new knowledge and the results of previous interventions to combat and minimise erosion of intertidal lagoon forms, identifying the entirety of restoration and conservation measures [5-6].

More than a constant monitoring, accessing historical data is essential to understand the natural evolution of the lagoon and the impact of anthropogenic pressure on its natural balance. Freely accessible satellite mission such as Landsat and Sentinel-2 allow us to access EO data starting in 1984 with the launch of Landsat 5. Their temporal resolution and spatial extend provide frequent snapshots of large area to analyse dynamics at a regional scale. The Coastal Erosion from Space project, 4000126603/19/I-LG, was commissioned under the Science for Society slice of the 5th Earth Observation Envelope Programme (EOEP-5) of the European Space Agency. The aim is to develop innovative EO derived products to improve coastal monitoring and better support policies maker and the stakeholders communities. Within the Coastal Erosion from Space project the delivered waterline, shoreline and coastal classification map have been evaluated and validated by national hydraulic and geological experts for various tests sites. The resulting data set was validated by the British Geological Survey, the Institute of Hydraulics at Cantabria, ARCTUS working alongside the University of Quebec at Rimouski and the Geological Survey of Ireland.

Materials and Methods

Optical satellite imagery is widely used to monitor various earth phenomenon and to understand their evolution. Thanks to the Copernicus program and the Landsat missions we can access up to 25 years of data at high temporal frequency, almost one image every 5 days in optimum conditions for the Sentinel-2 constellation [7] with high pixel resolution, 10m for Sentinel-2, 15 m for Landsat 8 and 30 m for Landsat 5. Moreover, their wide acquisition extent allows us to easily access a large snapshot (100 km x 100 km for Sentinel-2) and thus repeatedly monitor multiple sites at the same time and under the same conditions. This research proposes to use a time series of satellite derived products to monitor changes in the Venice Lagoon.

Following the successful delivery of the Coastal Erosion from Space project by ARGANS Limited and its partners IsardSAT, AdwäisEO, the British Geological Survey, Geological Survey Ireland, IHCantabria (Spain) and Arctus (Canada), the European Space Agency has initiated a change note to the contract 4000126603/19/I-LG commissioned under the Science for Society slice of the 5th Earth Observation Envelope Program (EOEP-5). The extension is supported by the user community and aims to:

- Extend the coverage of satellite derived product over the past 25 years for new sites, for the four countries engaged in initial contract: UK, Spain, Ireland and Canada;
- Add additional sites in a new country and a new partner ISPRA (Italy);
- Update the key coastal state indicators delivered in the initial contract by improving and enhancing the algorithms part of the processing chain.

Waterlines represent the instantaneous land/ sea boundary at the time the satellite pass over the scene. The waterline shape and extent are thus link with the coastal morphology and the water level at that time. This general principle, in the Lagoon, mainly applies to the morphological element velma; differently, the vegetation of the barena, as well as the artificial works form a vertical barrier, so that the shape is not varying with the tide.

Waterlines are extracted from every suitable satellite images available to build a dense and continuous data set. Image selection is essentially based on cloud coverage, a minimum of 70% of could free coastline is required to keep the image. Once all images have been selected, a pre-processing step is required to co-locate the full data set. If all satellites acquire data for the same scene, the resulting images are not perfectly overlapping each other. Only between Sentinel-2 acquisition, this spatial shift can reach 12 m [8]. A co-registration step first re-locate all acquisition on a highly spatial accurate very high resolution (VHR) reference image such as SPOT, WorldView, etc [9]. First, a Sentinel-2 clear image is co-registered on the VHR and is then used to co-register the remaining HR data set (Landsat and Sentinel-2). Thanks to the spatial accuracy of the VHR, co-registered Landsat and Sentienl-2 reach a vertical and horizontal spatial accuracy within 3 m. Satellite derived waterlines showed a higher precision accuracy within the mission pixel resolution.

The validation of the WL performed by ISPRA has been based on two main references: the layers provided by the “Lagoon Atlas”, focused on the morphology of the lagoon elements [2], and the layers produced by ISPRA on coastal survey and planning [10].

The Atlas provides high-definition layers with the characterization of the lagoon elements; in particular, those reporting the morphological elements "Natural Barena", "Artificial Barena", "Velma" and "Emerged Land" were used. The layers were published in 2013, based on data covering the time period 2003-2009 for the natural elements and 2012-2013 in the case of "Artificial Barena" and emerged land.

For about twenty years ISPRA has been producing information layers that serve for the environmental analysis of the entire Italian coastline; the main layers are the Coastline, the Backshore Line and the Emerged Beaches. Such data constitute the national reference for the INSPIRE regulation and have been adopted in various European (Marine Strategy, EmodnetGeology, etc.) and national (ISTAT, Ministry of Health, etc.) contexts, as well as being the basis for the elaboration of the environmental indicators provided by ISPRA for the coastal subject matter. Recently, the data series have been included in ISPRA's “Portal of the Coasts”, where they can be freely consulted and downloaded.

For the present case, the Coastline layer referring to the years 2000 and 2020 was taken as the reference. The layer for the year 2000 is the result of the digitization and characterization of the 1998-99-2000 aerial images made available after a Ministry of Environment (MiTE)-funded survey: the panchromatic images, with 1 metre resolution, are accessed through the WMS services of MiTE’s National Cartographic Portal. The update of the coverage, mostly referring to the period 2017-20, has been performed using the Google Maps satellite images, with a definition in the range of tens of centimetres, as reference.

The objective of the validation was to show how the WL drawn up by Argans can “read” the reality of the lagoon structure and its changes over time. The method was carried out in two main steps: relating the polygons of the morphological elements provided by the Lagoon Atlas to those defined on the basis of the ISPRA Coastlines, then comparing those two references with the set of WLs provided by Argans.

First of all, an area of interest was defined in which much of the territory is made up of natural barene and velme, but where intense human activity is also observed, with various built, inhabited and cultivated areas, hence the consequent vessel traffic, sources of pollution and disturbance to lagoon habitats. The choice fell on the area around the island of Burano, north-east of Venice (Fig.1).

Within that area, eight islands and Barene were selected, some of them classified as natural, some artificial. The aim was to be able to analyse a sample of elements large enough to detect some of the main phenomena in the evolution of natural elements, also having some fully artificial, mostly stable, land as a reference.

In particular, the set of areas of interest consisted of three islets, Burano, Santa Cristina and Crevan, and five natural formations, identified by fancy names.

As mentioned above, thanks to the availability of the Lagoon Atlas shapefiles, the first step was to compare the Atlas data with those derived by ISPRA Coastline (LC00 and LC20), in terms of shape and classification.

Figure 1 – Overall view of the north-east part of the Venice Lagoon. The thematic layers of natural and artificial "barene" and "velme" from the Lagoon Atlas are shown. The white box corresponds to the study area of figure 2.

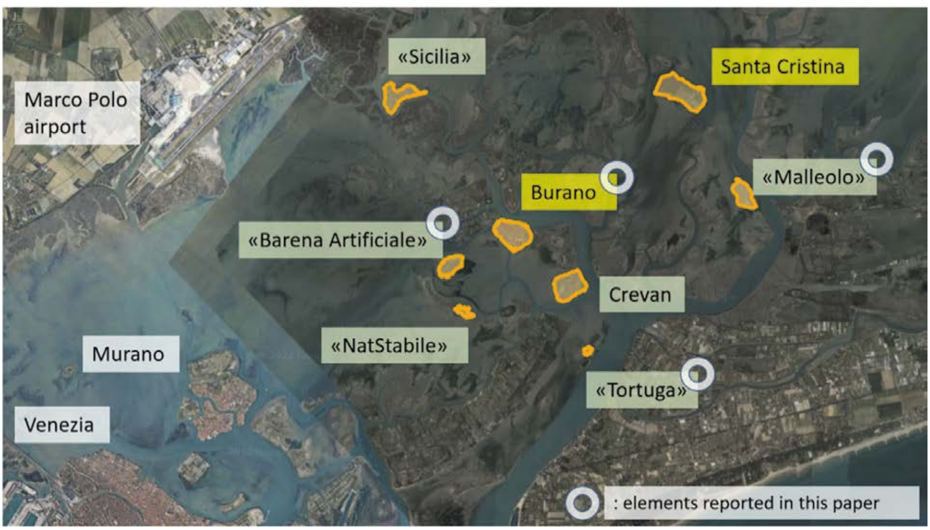

Figure 2 – Study area locating the 8 islands studied; yellowish box indicates fully artificial islands.

Once the reference levels of the Lagoon Atlas and ISPRA's LC00/20 had been compared, and - if necessary - adjusted, we proceeded with the actual validation of the Argans WLs, for which an indirect method was used, i.e. comparing the surfaces of the polygons obtained by the "convex envelopes" of the LC00/LC20 contours of the chosen lagoon elements with those similarly obtained from the hundreds of WLs provided by Argans, as processed from the Landsat 5-8/Sentinel 2 images. In this way, through simple statistical comparison of the surfaces, we investigated how and to what extent these WLs follow the definition of the areas under investigation and their evolution over time.

For this purpose, the ArcGIS tool 'Minimum Bounding Geometry' was used, which creates a feature class containing polygons which represent a specified minimum bounding geometry enclosing each input feature. The 'Convex Hull' option was chosen as the type of geometry that allows the shape of the islands to be approximated by creating convex polygons: this approximation makes it possible to evaluate shape variations in all those cases in which a variation would lead to null values. In other words: if for an island a surface variation that leads to a null difference (the same quantity is lost and accumulated) occurs over the observation time, the envelope curves of the two areas can still describe the variation.

With such a huge amount of WLs available, it was necessary to make a selection on the basis of the Quality Coefficients defined by Argans as an attribute of each line, related to length and shape. We chose to evaluate only the envelopes of lines with a QC_intern >= 50, not a very high threshold, in order not to exclude too many lines derived from Landsat 5 data, which cover the entire temporal period 2000-2012 but are fewer than those derived from Landsat 8/Sentinel 2 images, covering only more recent years, though. But not only the "quality" indicator has been used as a driver for the selection of the WLs because, especially for the natural elements, quite a few of the computed WLs showed a large deviation from the shape of other WLs in the same spot, probably due to the very peculiar environment in terms of water-mud (or sand, or vegetation) interface. The initial idea was to set up "influence buffers" capable of intercepting the WLs with respect to a certain morphological element identified by the LC00/20, choosing as a reference half the distance between an island/barena and the adjacent one. This approach proved to be limiting because it assumes that the ISPRA lines are correct, whereas they are WLs, too, and therefore variable with the tide in the case of the presence of mudflats. For this reason, user-defined 'clip areas' were set, both to select and clip the WL with respect to the morphological element being analysed.

In this case, too, the analysis of the various elements started by comparing the elements that have not changed over the years and are not affected by the tidal excursion, i.e. the two fully artificial islands of Burano and Santa Cristina, and then the work moved on to the natural or semi-natural elements selected.

Results

Table 1 shows the absolute and relative difference values of the surface areas as calculated according to the various methods and data sources described in the previous section. The first elements to be compared were the recorded surfaces of the two artificial islands of Burano and Santa Cristina (columns 4 and 5) by the GIS data from the Lagoon Atlas classification, and from the ISPRA Coastlines, as these are the lagoon elements that have practically remained unchanged over the years and are not affected by tidal excursion. The comparison of the two methods is important in order to understand the issues arising when working on datasets deriving from surveys at different scale and precision, and it will be the basis also for the assessment of the reliability of the computed WLs by Argans.

Table 1 – Area of the surface of the islands studied and of the envelopes built as defined in the text, along with relative differences.

ISLAND/BARENA	velme	barene naturali	barene artificiali	SUM (ATLAS OF THE LAGOON)	LC00_Polygon	LC00_Envelope	% diff. Poly-Envelope	% diff. Atlante-LC00	LC20_Polygon	LC20_Envelope	% diff. Poly-Envelope	% diff. Atlante-LC20	% diff. LC20-LC00
	area (mq)								area (mq)				
Burano	0	0	0	212238	226631	240115	**5,9**	**-6,4**	226209	244168	**7,9**	**-6,2**	**-0,2**
Santa Cristina	0	0	0	185295	305288	360929	**18,2**	**-39,3**	305097	359989	**18,0**	**-39,3**	**-0,1**
"Sicilia"	26473	146415	0	172888	179566	261117	**45,4**	**-3,7**	154822	233757	**51,0**	**11,7**	**-16,0**
"NatStabile"	32618	9842	0	42460	-	-	-	-	28493	42666	**49,7**	**49,0**	-
"Barena Artificiale"	0	0	137416	137416	-	-	-	-	97481	109828	**12,7**	**41,0**	-
Crevan	120295	71392	62138	253825	149655	193118	**29,0**	**69,6**	202901	213892	**5,4**	**25,1**	**26,2**
"Tortuga"	17712	11693	0	29405	-	-	-	-	13337	15814	**18,6**	**120,5**	-
"Malleolo"	60568	15140	0	75708	63140	72890	**15,4**	**19,9**	116317	131749	**13,3**	**-34,9**	**45,7**

The deviations found for the two islands show quite a different amount, but in both cases it can be explained by the fact that the LC polygons embed the inner channels of Burano and the quite large artificial pools of Santa Cristina. The comparison went on to the surfaces of the natural or semi-natural elements (rows 3-8), which proved to be affected by the time differences of the respective surveys, as declared in the previous section. We observe an increase of the discrepancies, which may arise from two main contrasting factors: firstly, the ISPRA coastlines are defined as waterlines, therefore they suffer from the recognition error in the visual interpretation of the aerial photo when the boundary between land and water is made up of mudflats; the second is the temporal differences between the surveys with the possibility that the variations are truly due to the evolution of the morphological elements, an evolution that may be natural or due to human actions. How to assess the digitisation errors and to discern the real change in the waterlines/areas is definitely the goal of this work and it has been addressed through the validation process, which also included expert judgement over the aerial and satellite images. In this process, we observed both natural (sandbanks "Sicilia", "Tortuga") and anthropic (Crevan Island, "Barena artificiale", "Malleolo") variations, which are recorded by the variations observed in the LC20 dataset, when compared to the LC00 (columns, 9 and 5, respectively).

We now turn to the analysis based on the areas of the envelopes defined from the LC00/20 and Argans' WLs. First, we again checked the effect of approximating the surface of the islands by the forcedly convex envelope defined above, by the analysis of the surfaces of the envelopes built over the ISPRA datasets for the artificial islands (Burano and S. Cristina). The data in Table 1 show the extent of the overestimation of the "true" surface brought about by the envelopes. Due to their shape, the effect is different in the two cases (average 6 % for LC00 and LC20 in Burano, 18 % in S. Cristina). These observed features are taken into account in the next steps of the validation assessment.

The analysis of the envelope surface calculations for the Argans' WLs is shown in Figure 3 for the island of Burano, from which we notice a tendency for the WLs to define larger envelopes. The graph in the right part of the figure plots, for different acquisition dates the relative surface difference between the envelope derived from the 2020 ISPRA Coastline and those computed from the Argans' WLs; bars with negative percent values

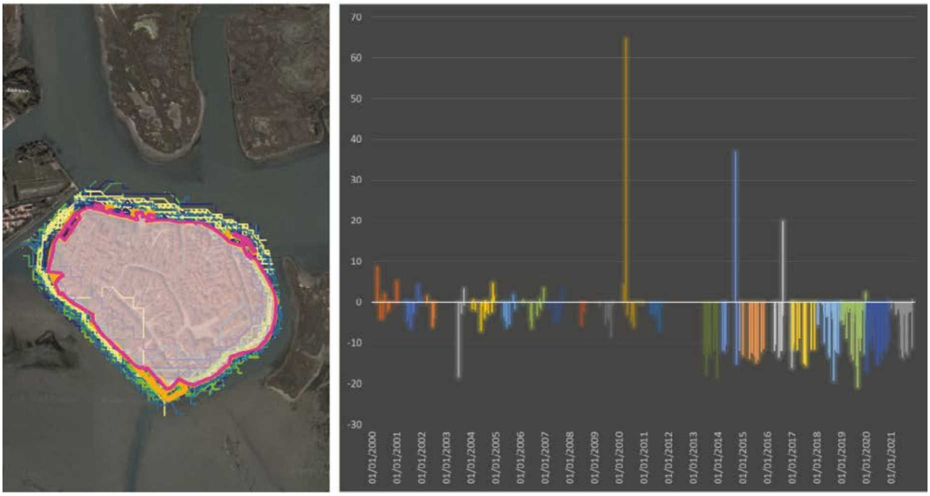

Figure 3 – Analysis of the envelope surfaces for the artificial island of Burano.

means that “Argan’s envelopes” are bigger than the ISPRA LC20 ones: this overestimation is contained to an average of 10 %. Approximately the same overall results was obtained in S. Cristina island.

Going further on, the analysis of the partially artificial islands and salt marshes showed more marked differences. In this case, the differences between the data acquisitions have less influence than in the Atlas-ISPRA comparison, because the data made available by Argans start from 2000, almost at the same time as those of the LC00, which in these areas was defined with respect to images from 1998, and the WL series reach 2021, thus including the period of the survey used for the LC20, i.e. 2019.

That of the sandbar named by us as ‘Sicily’ (figure 4) represents a case in which the two LC20 / WL data are in fairly good agreement, with the bulk of the surveys not deviating by more than 10-15 %. This is a sandbar that from the ISPRA survey appears to be regressing by about 16 % (11 % if estimated by the envelope).

The plot shows negative average values around the year 2000, i.e. it indicates that for those years there are higher average values for the envelopes of the Argans WLs than for those derived from the LCs, while these average differences become positive on the right side of the graph, thus showing differences in favour of the envelopes calculated on the LC20. The presence of a sort of oscillation of the differences in the period 2006-2018 is being further investigated.

A different case concerns the barena we called "Malleolo" which surface grows as a result of specific human actions. In that case, the construction of specific artifacts between the years 2012-13 determined a considerable growth of the area (from ISPRA data about 45 %) and this phenomenon was also recorded in the comparison with the surfaces of the envelopes.

Figure 4 – Analysis of the envelope surfaces for the barena "Sicily" (fancy name).

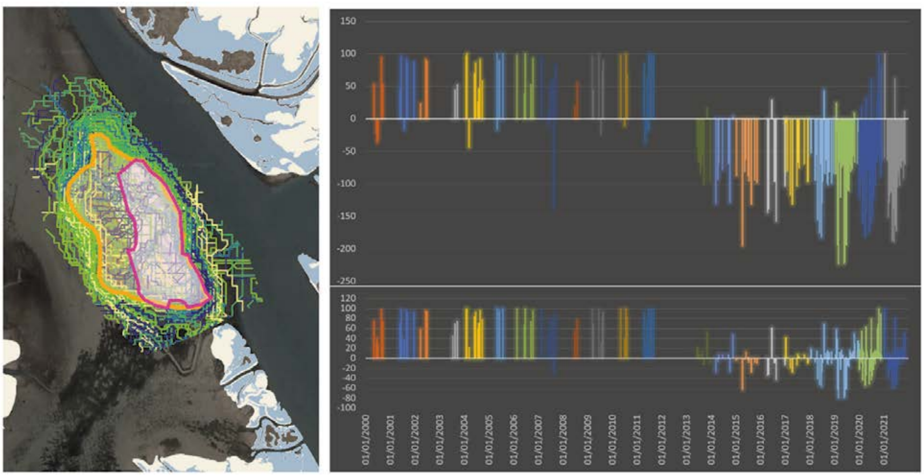

Figure 5 – Analysis of the envelope surfaces for the barena "Malleolo" (fancy name).

In particular, the two tiled graphs of fig. 5 show the envelope areas differences as defined before, but this time also that of LC00 is shown (upper graph). The left part of both graphs, corresponding to the years covered by Landsat 5 data (2000-2012) shows most values close to 100 %, meaning that the surfaces subtracted from the envelope values of the LCs are negligible; this, in turn, indicates that the WL data derived from the Landsat 5 in that area fail to identify significant polygons. In contrast, the second part of the graphs refers to the envelopes constructed on the Landsat 8 and Sentinel 2 lines, and they define a very precise phenomenon, in fact while the comparison with the data derived from LC00 returns a constantly higher area for the Argans envelopes (up to more than 100 %), the comparison made with the envelopes derived from LC20 gives, in the average, a much more consistent result.

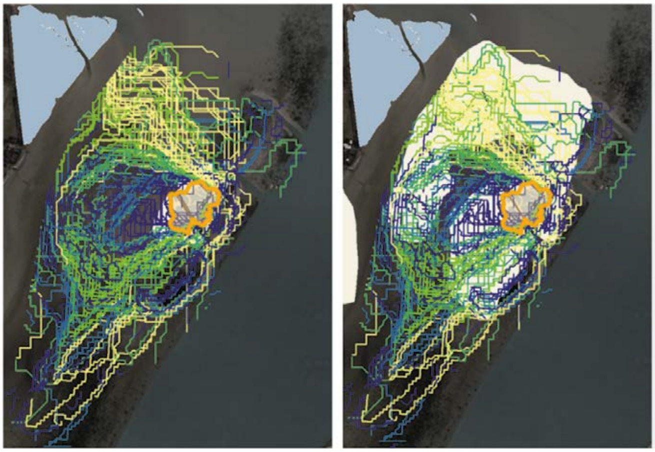

Figure 6 – Analysis of the envelope surfaces for the barena/velma system "Tortuga" (fancy name).

Lastly, the case of the small sandbar we called "Tortuga" (fig. 6) shows another kind of condition. The set of WLs that seems to refer to that lagoon element occupies a very large area, so much so that the envelope polygons that were defined around the lines under consideration outclassed in area those defined by LC20. In this case, however, it is not necessarily a case of data degradation in that area: the concordance shown between the layers of the Lagoon Atlas and that of the LC20 may tell only part of the story. There is a layer that can be loaded via the Lagoon Atlas WMS services, containing further geographical data on the velme, but whose data period could not be retrieved at the moment. This layer shows in some areas substantial differences with the layer published on the webGIS and used in this paper [11]. This alternative layer of the Lagoon Atlas seems to define a large area of velma right in the area affected by the Argans WLs, so as to explain the shape of the computed lines.

Conclusion

We have presented the first results of the validation and analysis of the huge dataset of waterlines, as calculated from satellite images by Argans Ltd algorithms, applied to a very complicated study area, such as the Venice Lagoon. The validation process included the use of the information layers made available by the Lagoon Atlas which contain very accurate information but suffer from referring to data that for salt marshes and natural mudflats go back to 2003-2009. We also used the information layers produced by ISPRA, namely, the Coastline digitised over the whole country, from aerial ortophotographs and satellite images, for two nominal time frames: 2000 and 2020. However, such data are recorded following a method that actually returns Waterlines, which in the Lagoon can lead - for example -to define normally submerged mudflats as dry land.

Although a test phase over additional case studies is still needed, these results showed that the Earth Observation technologies that have been developed within the ESA-funded project "Coastal Erosion from Space", can identify both morphological objects and changes over time due to natural causes or human action. The application of these techniques, integrating them with other field data and applying them to orthophotos of higher definition and with possibly higher acquisition frequency, will be able to be an effective tool for monitoring the coastline and even a territory as complex as the Lagoon.

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