AN INTEGRATED APPROACH FOR MARINE LITTER HOT SPOTS IDENTIFICATION

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Abstract – Marine litter is defined as any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment, and it is among the most important environmental problems which are affecting the sea nowadays. In this work, we present an integrated approach to the marine litter hot spots identification. The results come from a coordinate activity of filed campaigns, satellite monitoring and numerical model simulations. A dynamical view of the marine litter is at the core of the approach, so numerical models for the simulation of the floating pollutants dispersion in the sea are one of the key tools involved in the hot spot identification. Among all the available codes, the class of Lagrangian models is considered the most suitable to simulate the journey of the marine litters; specifically, the NOAA PyGnome software is the tool implemented for the purpose. The ability to monitor wide and hardly accessible coastal areas, using remote sensing imagery, is the second source of independent information used to identify the marine litter accumulation prone area. The routinely and operationally available ESA Sentinel 2 mission data has been considered for the purpose. Due to the coarser spatial resolution of the remote sensing data, with respect the typical marine litter size, the identification of floating or beached debris requires the analyses of the spectral reflectance, for each pixel in an image, searching for spectral signatures of the marine litter presence. Both modelling and satellite results are combined to pick up the coastal areas to be likely candidates for marine litter hot spots. Results of the method are encouraging, since the simulated accumulation areas clearly emerge from the background and the link to the sources is straightforward because of each simulated trajectory allows to know the origin of each beached Lagrangian element. It is expected the presented approach will help in planning actions to remove beached debris and to identify the sources mostly contributing in input the floating waste material in the marine environment. The method currently is applied on the Adriatic basin as part of the MARLESS INTERREG IT-HR project.

Introduction

Marine litter is among the most important environmental problems which are affecting oceans and the sea nowadays. All over the world, there is no sea basin free of solid elements, mostly floating, that are transported and dispersed by currents. Their size ranges from macroscopic dimensions, that is larger than about 2 centimetres, down to nanometres

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and, of all circulating objects, a part has natural origin, for example parts of trees, pollen and other biological stuff, but a relevant amount is litter.

Marine litter is defined as any persistent, manufactured or processed solid material discarded, disposed, or abandoned in the marine and coastal environment, so their origin is strictly identified in human activities. Because of the relevant impact on the marine ecosystem, plastic marine litters are those most monitored and studied.

When a floating litter is released in or it reaches the sea, then it starts a journey that can last for years, according to the sea currents and the surface wind. It is well known that the interaction of water mass with the coast, besides the water circulation patterns, bring marine litters to accumulate in some areas, while they are efficiently dispersed in others.

So, it is extremely important to identify the areas where the marine litter accumulate, which are referred as marine litter hot spots, because restoring action, meant to remove the pollutants from the environment, can be focused of those hot spots. Furthermore, the identification of starting points of the trajectories, showing the litter journey, are helpful to link the sources of pollutants, that is the environmental pressures, with the hot spots.

In this work, we present an integrated approach to the marine litter hot spots identification. The results come from a coordinate activity of filed campaigns, satellite monitoring and numerical model simulations carried on as part of the MARLESS INTERREG IT-HR project [1]. The method integrates the applications of a numerical dispersion model, the NOAA PyGnome code [2], and explores the opportunity to improve the quality of the results using a cutting edge lagrangian model, the PARCELS model [3] and the systematic analyses of satellite images collected by ESA Sentinel missions [4].

The dispersion model runs simulate the litter transport, after the release from known sources of pollutants. We will show that, besides the tuning of the parameterization of physical effects causing the litter to move, to include the litter beaching and refloating action is mandatory to achieve a realistic description of accumulations areas. The likelihood of those areas can be increased using the analysis of the backward trajectory distribution across the studied basin and assuming the main pollutants sources known with high probability, like river mouths and coastal points with high anthropic density.

The simulated hot spots have been monitored systematically using the Sentinel 2 spectral imagery and the probability for a hot spot candidate is included in the identification process. In this content, we will describe in details the process to produce the spectral fingerprint for specific materials, like plastics, and the need of neural network application to elaborate massively all the imagery available from Sentinel mission.

Materials and Methods

The basics of the two approaches for marine litter hot spots identification are describe in this section. In particular, first we present the modelling procedure and then that based on the satellite imagery.

Lagrangian models are the widely adopted tools in simulation of material dispersion in the sea; they simulate the motion of each Lagrangian Element (LE) as a point like parcel, therefore they focus on individual particle's trajectories. The Lagrangian models use (pre-computed) Eulerian velocity data derived from observations or models to compute the pathways of particles, by integrating the equation of motion given the velocity field.

Their application to nearshore systems with complicated geometry are less mature and it has been shown that the Lagrangian connectivity of nearshore flows depends strongly on the horizontal resolution of the underlying Eulerian hydrodynamic data [5]. The data required to simulate the dispersion are the wind field and the sea surface currents; the turbulence motion needs to be represented by ad hoc random motions. Static boundary condition, such as coastlines maps, are relevant to get a realistic scenario on the shoreline and to consider the possible beaching of the dispersed elements.

The Lagrangian model chosen to conduct this research is GNOME (General NOAA Operational Modelling Environment), a simulation system designed for the modelling of pollutant trajectories in the marine environment [6].

GNOME is a modular and integrated software system that accepts inputs in the form of maps, bathymetry, outputs of numerical circulation models, location, oceanographic and meteorological observations and other environmental data. The LEs are modelled in GNOME as particles, whose trajectories depend on “movers” (winds, currents and horizontal diffusion). The model generates two results one called the “best estimate” solution, that shows each LE position evolution, with all of the input data assumed to not affected by uncertainty, and another called the “minimum regret” solution, which displays the Les trajectories that incorporate the uncertainties, since models, observations and forecasts are not uncertainty free.

Moreover, there is the possibility to use the set of python bindings and utilities which are called pyGNOME, that can be used to write customized models using the GNOME code base [7]. The advantages of this model are the possibility to implement the hindcast simulation mode, in order to traceback from where the possible marine litter came from; the chance to simulate turbulent horizontal diffusive processes by a random walk; the possibility to adjust the wind action on the LE depending on how much the litter is above the sea surface. The latter function is called windage: different percentage of wind speed can be selected in such a way to simulate different material, e.g., fishing nets will have low windage (1% of the wind speed) since they are prevalently under the sea surface as shown in figure 1.

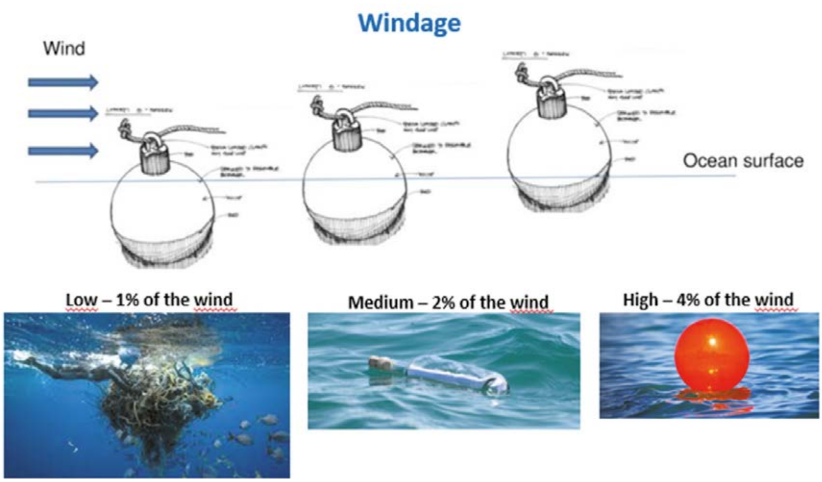


Figure 1 – Windage values that depends on the litter buoyancy.

Another important parameter that is used to simulate different marine litter is the "refloat half-life parameter". It empirically describes the adhesiveness of the litter to the shoreline. It summarized different parameters (such as substrate porosity, the presence or absence of vegetation and other physical properties and processes of the environment). It represents the number of hours in which half of the material on a given shoreline is expected to be removed, thus higher values of refloat simulates litter that generally stay beached for longer time. The half-life parameter could be set to different values along different segments of the shoreline depending on the beach type.

Coming to the satellite source of information, in the latest years, several studies have demonstrated the advantages of imaging Earth's surface with space-borne instruments to search for marine litter accumulation over the sea or shorelines. [8][9] Among all the space missions operating nowadays, the ESA Sentinel-2 mission is the major one adopted and addressed to be a valid choice to monitor marine and coastal areas. In particular, the monitoring campaigns conducted by Topouzelis and Themistocleous in Mytilene and Cyprus have shown the potential and tested the limits of Sentinel-2 to detect plastic marine litter by imaging floating artificial handmade rafts made of plastics. [10][11][12]

Sentinel-2 is a space mission that consists of a pair of identical satellites placed in sun-synchronous and polar orbits. They orbit around Earth with a phase of 180°, letting this little constellation passing over the same area on the globe's surface almost every five days. [13]

The two satellites are equipped with an imaging instrument, the Multispectral Instrument (MSI), which acts as a passive sensor, i.e., collects reflected light by objects on the ground when the sun illuminates them. MSI cameras allow to record those signals from the Visible up to the Near-Infrared part of the electromagnetic spectrum with 13 bands heterogeneously distributed and having three different spatial resolutions (see Fig. 2) [14]. The arrangement of the camera lens and the height of the satellite let it to have a swath width of about 300 km, this causes a partial overlapping within two consequential orbits which is particularly relevant at the middle-high latitudes. Sentinel-2 imaged globe's surface is ultimately divided into a grid of tiles of 100 x 100 km^2 size that are partly or completely filled with the sensed surface.

Sentinel-2 data are available to download under free data policy via the Sentinel mission web portal (https://scihub.copernicus.eu/); here the user can retrieve a zip file containing all the bands data plus auxiliary information about the sensing conditions for each recorded image. Each band data is provided as a raster image where each pixel is referred to lat/lon geographical coordinates and its content corresponds to the reflectance measured at the same location[1]. At the best spatial resolution, a single band pixel contains all the light collected within the band wavelength range from a real-world area of 10 x 10 m^2. Unwanted effects such as adjacency light incoming from the surrounding pixels or atmospheric disturbance can alter the original signal emitted from the surface although several techniques are available to correct those disturbs if needed. To speed up the aforementioned corrections a cut of the original tile is usually done, by means of a single or multiple polygonal shape that have to contain the area we are interested to analyse. When all these steps are done, i.e., the pre-processing phase of the image is concluded, we can proceed with the extraction and the analysis of the physical information we are interested in.

[1] Sentinel-2 products are provided already georeferenced and orthorectified, moreover the MSI cameras recordings are already converted into dimensionless reflectance values. Products with all these corrections are labelled as 'Level-1C products' and are freely downloadable by Users.

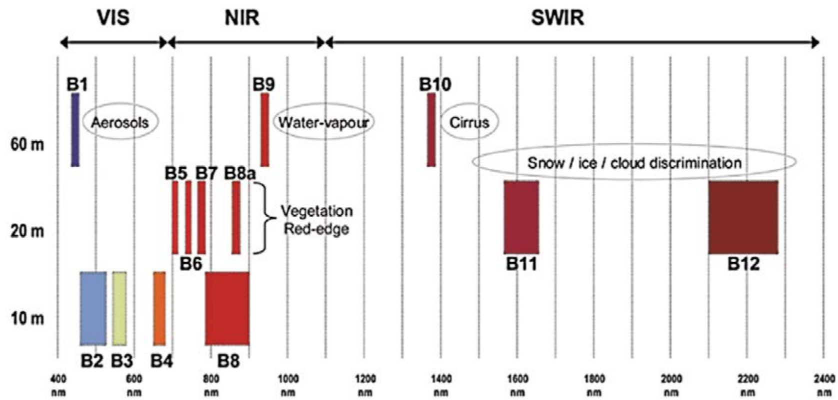


Figure 2 – This picture shows the portion of the electromagnetic spectrum covered by the MSI cameras. The broadening of the Sentinel-2 bands respect to the horizontal axe refers to their FWHM [18]. On the vertical axis are reported the three different spatial resolution allowed by the MSI instrumentation. Bands B2, B3 and B4 corresponds to the blue, green and red colours. The bands from B5 to B8 are dense and thin and serves primarily to investigate surface terrain properties such as vegetation coverage or soils state of health. B11 and B12 are more distant and sparse respect the bulk of the other bands, but they are useful to discriminate ground features such as seawater, since water, in any of his thermodynamic state, is black in the SWIR. The bands at 60 m of resolution are dedicated to the measurement of atmospheric properties and then are not used in the proceeding of this work. Picture taken from [10].

Collecting all the reflectance values of every band and putting them in a Reflectance vs Wavelength plot produces the *spectra* of that given pixel; the shape of such spectra depends on the amount of reflected light emitted from the different objects into and near the pixel and their extension. Each material produces its own particular spectra, which is usually referred as the material *spectral signature*. Laboratory and well-characterized on-field measurements allow recovering spectral signatures of various elements (see figure 3), these samples are the benchmark to investigate the true composition of the mixed spectra pixels extracted from the Sentinel-2 raster.

The final goal of the satellite image analysis, developed in the MARLESS project, is to find marine litter hot spots, that is searching coastal areas looking for spectral signatures that cannot be referred to known environmental features (such as seawater, sand, breakwaters rocks, etc.) and that can be instead associated with a particular marine litter component (wood from beached logs, plastics, and so on). Thus, the reliability and the efficiency of the detection of pixel containing marine litter rely on the richness and the accuracy of the well-known spectral signatures database we use. The spatial extent of sub-pixel scale objects is also an important limit in marine litter detection, as already proved for plastic litter by Topouzelis [11].

To construct our own database and test the spatial detection limits of Sentinel-2, we have defined two classes of case study areas, i.e., the "*high confidence*" and the "*medium confidence*" ones (see Table 1). Only with the characterization of such case of study is possible to proceed with the analysis of the most generic cases ("*open scenario*") whose extensions and positions are provided by the results of the model outputs.

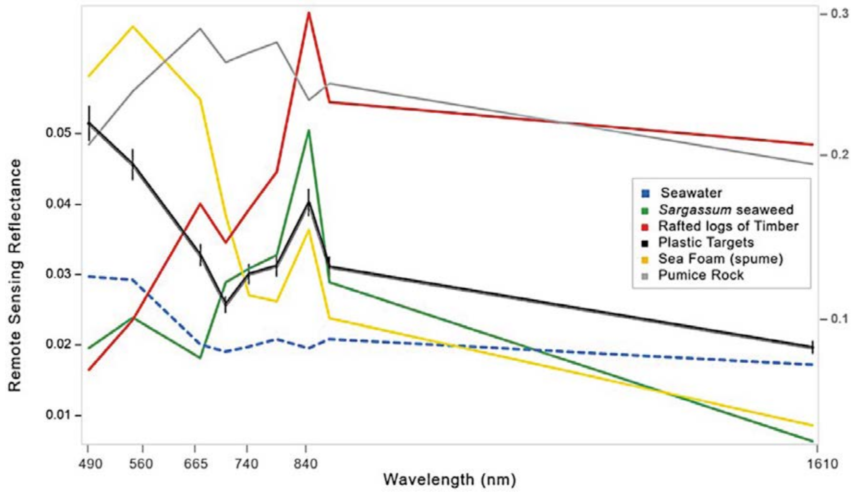


Figure 3 – This picture shows a sample of averaged spectral signatures for different materials as detected by Sentinel-2. The log and pumice rock spectra have higher intensity than the other materials and their reflectance axis is on the right of the plot. Further details are provided in [10].

Table 1 – Properties of the different case study classes defined to: i) create a reliable database of spectral signatures, ii) test limits of identification of sub-pixels scale objects, iii) search marine litter following modeling prompts.

	High confidence	Medium Confidence	Open Scenario
Main Objective	Computing spectral signatures of selected materials	Testing limits in detection of sub-pixel scale objects	Finding marine litter hot spots along shorelines
Surface properties	Extended areas (more than 5x5 in pixel size) occupied homogeneously by the same material	Area mostly occupied by an "high confidence" material but including sub-pixels features of different materials	Areas with mixed composition pixels mostly of unknown origin.
In-situ information	Mandatory to correctly detect the materials extension and their environmental status	Mandatory to correctly detect the materials extension and their environmental status	Not available or not referred to the same day of the satellite image.

Results

The application of the modelling approach has been conducted using three different half-life parameters, namely: 76 days, i.e. the resuspension timescale obtained for the Mediterranean with analysis of GPS trajectories of drifter buoys [6]; 150 days and 273 days considering the resuspension timescale of plastic debris with different size found in this research [16]. No variations in the beach type are implemented and the windage is selected randomly from a range of 1 %-4 % of the wind speed. The LEs are released from 16 sources (see Table 3) (harbours, rivers, city near the shorelines) using the PyGNOME utilities; the release is continuous with 10 particles per hour for a temporal duration of 9 months. The "minimum regret" solutions are considered.

The points with more accumulation of LEs have been studied and specific evaluations are made in order to select beaches to be analysed with the satellite analysis. Only the areas with less anthropic material and with less vegetation coverage are taken (see Table 2): one is located near the Reno's mouth, one near the Tagliamento's mouth, another near the Grado lagoon's mouth (Bando d'Orio beach), one near the Marano lagoon's mouth (Isola della Marinetta beach).

Table 2 – Location with the greatest amount of accumulation of beached marine litter.

Location	LEs counts
Tagliamento's mouth beaches	82087
Reno's mouth beaches	20428
Isola della marinetta's beach	11248
Bando d'Orio beach	7917

For each of these studied areas, considering the different half-life parameters (76 days, 150 days and 273 days), a statistical analysis was performed computing the minimum, maximum and median daily values from the hourly beached LEs. Finally, for each source the extreme minimum, maximum and mean values are identified; these results are available for each area and for each half-life parameter. The same statistical values are computed for the median daily values too including the 5 % and the 95 % percentiles. From that statistics, we evaluate the contribution of each source in the accumulation of beached material.

The results of each half-life parameter have been aggregated to get the overall contribution of all the marine litter type (Table 3).

Table 3 – Contribution of the LEs accumulation of each source considering all the reflaot half-life parameters.

Source	Contribution (%)			
	Banco D'Orio	Isola della Marinetta	Tagliamento's mouth beaches	Reno's mouth beaches
Trieste	5.44	3.66	1.10	1.23
Monfalcone	0.08	0.07	0.20	0.04
Isonzo	2.80	3.77	1.20	1.80
Grado	69.79	6.27	3.38	2.81
Laguna di Marano	0.88	74.31	5.59	1.01
Tagliamento	1.13	1.68	84.94	1.07
Livenza	0.15	1.06	0.61	1.62
Piave	0.01	0.04	0.13	1.45
Laguna di Venezia	0.01	0.01	0.01	0.26
Brenta-Adige	0.48	0.53	0.12	0.27
Po	0.53	0.09	0.21	2.97
Reno	0.08	0.55	0.05	82.30
Koper	5.88	2.11	0.81	1.34
Piran	8.79	3.29	1.06	1.05
Rovinj	2.97	1.85	0.44	0.30
Pula	0.98	0.73	0.15	0.48

In the following, for two accumulation points, that is the Tagliamento's mouth and the Reno's mouth beaches, the contributions of each source is shown in two maps considering all the kinds of marine litter (Figure 4 and Figure 5).

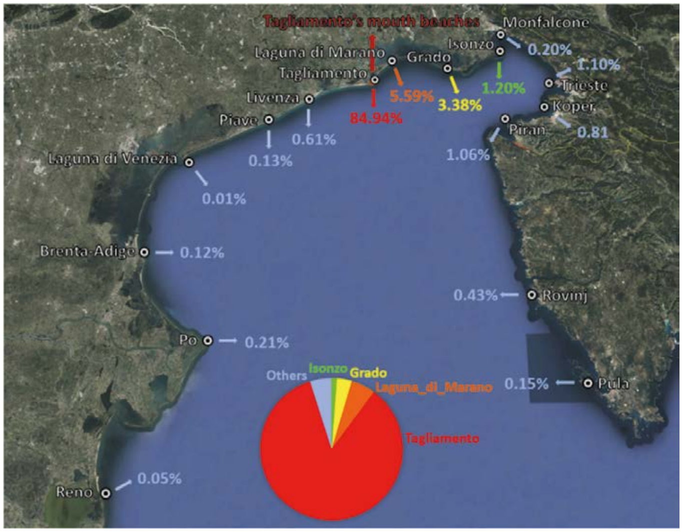


Figure 4 – Source contribution to the accumulation on the Tagliamento's mouth beaches.

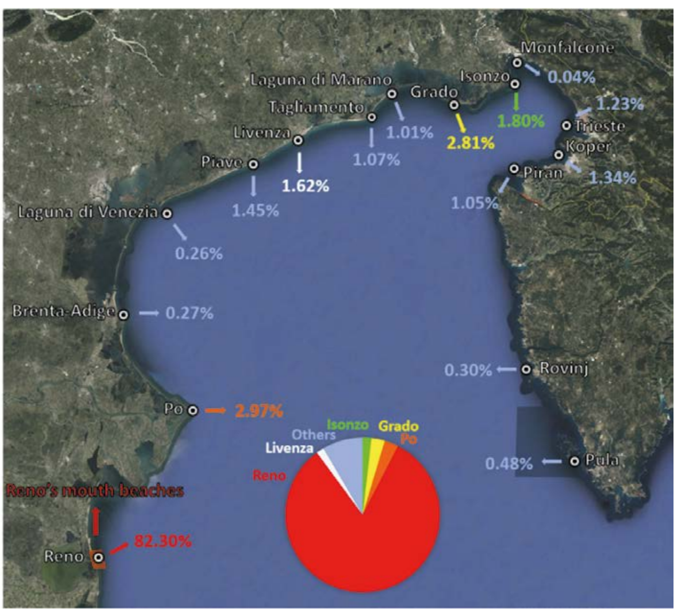


Figure 5 – Source contribution to the accumulation on the Reno's mouth beaches.

In adding the information coming from the satellite data source for the hot spot identification procedure, to understand the preliminary results of the investigation of a beach, we present the average spectral signatures, not atmospherically corrected, for two commonly types of surfaces: seawater and sand (see Figure 6a and Figure 6b). The seawater spectra are attended to decrease towards the SWIR bands and having the reflectance peak in the blue band, conversely sand reach its maximum values in the SWIR bands and the spectra has reflectance values typically an order of magnitude higher than seawater. It is worth to note that, at this stage, only the shape of the signature is relevant, not the absolute values of the reflectance.

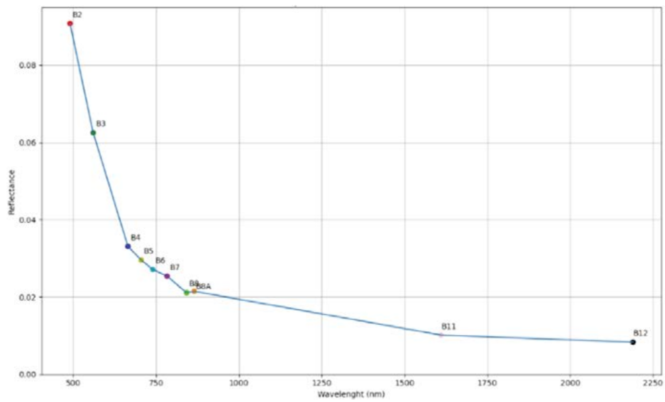


Figure 6a – Mean seawater spectra. The spectra have been collected averaging pixel values within three square areas of 100x100 pixel size located near shorelines of FVG Region at an average bathymetry of about 5 meters. This choice is motivated by the necessity of avoid open water areas but also not to be too much close to shores to avoid not homogeneous water coverage of sand due to tidal level or presence of sea foam.

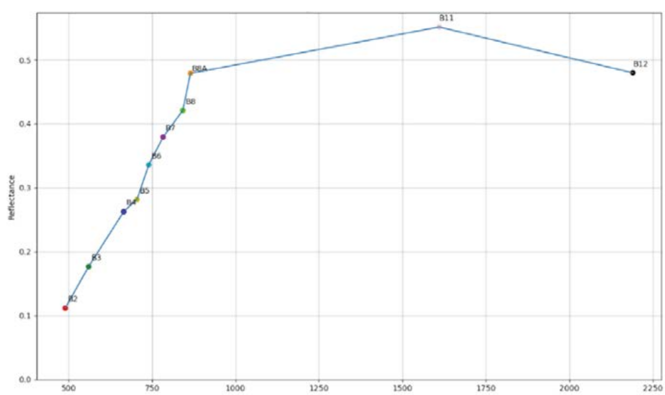


Figure 6b – Mean sand spectra. The spectra have been collected averaging pixel values within three square areas of 5x5 pixel size located along the sandy beach of Lignano town in the FVG Region. It has been verified by on-field proofs that the selected polygons where free of anthropic objects as umbrellas or deckchairs.

Model results have highlighted several marine litter hot spots along the North Adriatic Basin, so in applying the methodology we have selected one of such accumulation points to presents the catalogue of spectra that can be extracted when investigating an *open scenario* case study.

The beach we choose to study is part of the *"Tagliamento river mouth beaches"*. Here below in Figure 7 we report the 10 m spatial resolution RGB image of the study area and the corresponding Google Maps view.

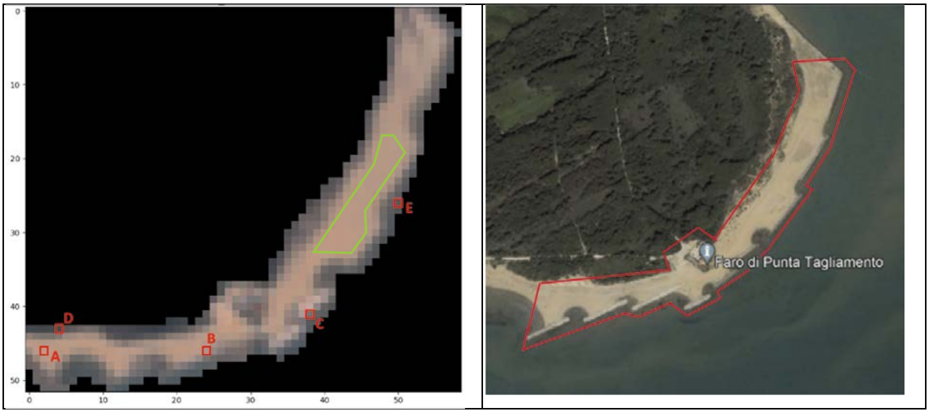
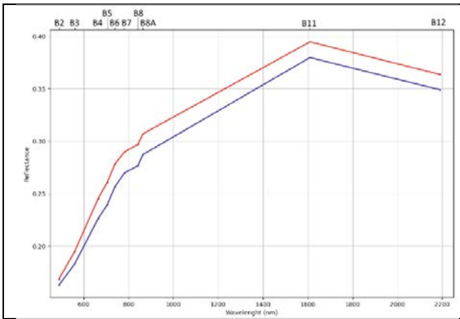


Figure 7 – The image on the left shows the RGB band composition of the study area we selected. The green polygon delimits the area chosen to calculate the average sand spectra; the red squares show the location of the sample of the selected spectra. The right picture is a screenshot from Google Maps of the same area of study.

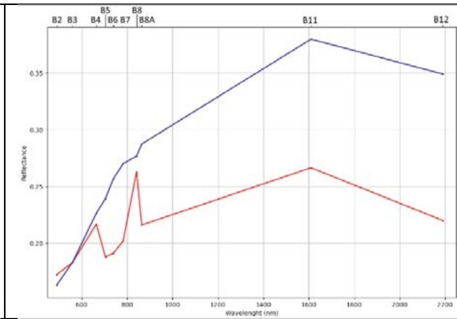
The sequence of figures 8 presents a sample of the most representative spectra we have found in this polygon. All the spectra are compared with the *local* average sand spectra, Figure 6b, which is computed using pixels inside the green sub-polygon shown in Figure 7.

Discussion

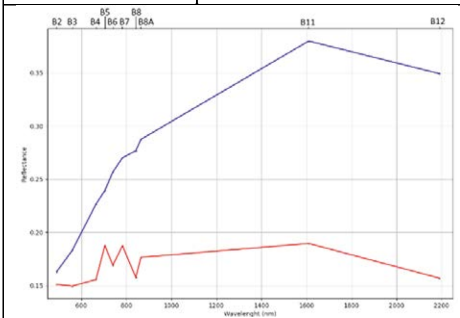
The twofold approach to the marine litter hot spot identification is promising even if there are several weak points that are going to be considered to remove the uncertainties affecting the hot spots identification. So far, some fundamental results are already available. From summaries presented in Figure 4 and Figure 5, the greatest contributions are given by the nearest sources to the studied. Moreover, it can be noticed that the accumulation contributes follow the anticyclonic mean pattern of the Adriatic basin currents: i.e, the major contributes come from the eastward sources with respect to the target beach, in particular, this can be seen from the example of the Tagliamento's mouth beach. As far as the Reno's case is concerned, it can be noticed that the Grado source contribute is comparable to the Po source that is nearer to the point in study.



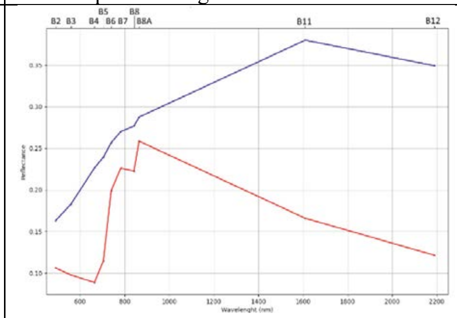
This pixel exhibits a spectra with a shape very close to the sand one, thus it can be easily classified as a sand pixel.



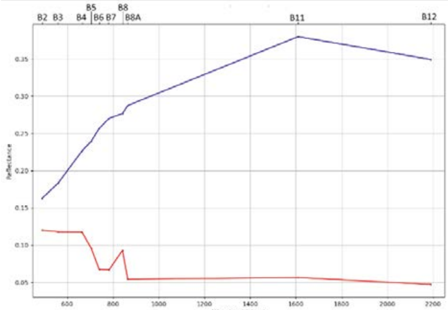
This spectra is an example of a *rafted log* signature, as can be deduced by comparison with the red spectra in Figure 3.



This spectra is an example of a *rock* signature, as can be deduced by comparison with the grey spectra in Figure 3. Moreover, visual comparison with the Google Maps image suggests this pixel could be mostly occupied by a breackwater.



Example of an unclear specral signature. Visual comparison with the Google Maps image suggests the pixel surface should be covered with vegetations, but the spectra doesn't seem to resemble the shape expected from the literature.



Example of unclear signature with potential trend similar to plastics, however, the leak of in-situ formation of the beach at this lat/lon doesn't allow to confrim the true nature of this spectral signature.

Figure 8 – We present a selection of pixel spectra that depicts the variety of shapes that can be found in an *open scenario* case of study class. In red is reported the average local sand spectra.

The dispersion simulation approach presents some not negligible limits: the most important is the low spatial resolution of the sea surface currents that led the LEs to be moved only by the wind field near the shorelines and in the lagoon waters. Moreover, there is the need to associate the correct refloat half-life parameter to the specific marine litter and to set the windage parameter according to the litter buoyancy; furthermore, the coast morphology has to be included, in order to better simulate the beaching behaviour. The above mentioned limits require another simulation code to applied and we consider suitable the PARCELS model [17]. Furthermore, to increase the sea currents availability and their resolution at the shore line and into the lagoons, a first attempt for the Friuli Venezia Giulia coasts is going to be done thanks to the oceanographic fields simulated by the ARPA FVG – SHYFEM hydrodynamic model. That improvement will allow to leverage the back trajectories to find shaded sources.

The huge and systematic amount of work required by satellite imagery post processing together with the complexity of the spectra signature identification, has put in evidence the need for an automatic algorithm to identify potential hotspot pixels, in Sentinel 2 imagery. To this end, a neural network framework is considered to work as a filter that will catch the suspicious pixels only, giving them a probability to be a polluted area. The training of the neural network is going to be based on the set of signatures collected thanks to the high and medium confidence analyses. Due to the trivial level of development of the spectra database, we are not still able to provide an interpretation of most of the potential signatures embedded in the available satellite imagery, although some relevant features can be identified thanks to the comparison with the literature.

Conclusion

The coupled approach to marine litter hot spots identification, that join information coming from the dynamic feature of the floating debris, which are moving in the sea due to sea currents and surface wind, and the remote sensing spectral signature for each pixel of the Earth surface satellite imagery has been proved to give good results.

The low spatial resolution of the satellite imagery and the limited number of bands, nowadays available from operational satellites, pose an important limit in the level of confidence of hot spot identification, Furthermore, there details of the marine litter journey that depends on physical effects poorly represented in most of the lagrangian numerical models that could be applied to the problem.

Anyway the experience presented in this paper stimulates improvements of the above described tools and in the use of the presented materials. Those improvements, which are going to be applied in the frame of the INTERREG IT-HR MARLESS project and beyond are promising.

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