HIERARCHICAL MONITORING OF WATER QUALITY: COORDINATING THE SPATIOTEMPORAL RESOLUTION OF MULTILAYER AND MULTISPECTRAL SENSORS TO CHARACTERIZE POLLUTION

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ABSTRACT

Pollutant discharges into the environment can have significant adverse impacts on human health and biodiversity, and the detection of these discharges is hindered by the large spatial and temporal scales across which illicit activities also take place. To assist in environmental monitoring of receiving waters this research developed a hierarchical monitoring program to coordinate the spatiotemporal resolution of multilayer and multispectral sensors. The hierarchical monitoring refers to sensors carried by platforms located at different altitudes, operating at different spatial, temporal and spectral resolutions. The unique combinations of sensors generate information layers characterized by different relationships between several parameters of targeted area, making it possible to focus on specific aspects of the phenomena and to produce novel and complementary results. The proximal sensing instruments, such as drones which can operate closest to the target, often have the highest spatial and temporal resolution, and sufficient multispectral capacity, to provide a link or bridge between in-situ sampling and higher altitude remote sensing. The hierarchical monitoring study was conducted on the Domitia coast in southern Italy, where the Regi Lagni channel discharges. The Regi Lagni is contaminated by discharges from five wastewater plants, and receives illicit discharges in other sections, notably a wide wetland area. The multispectral and multilayer analysis evaluated the impacted area, using multispectral output of the proximal sensing acquisition drone system as a bridge layer to contextualize information coming from satellite acquisition. This operation was able to quantify the spatial impact of pollutant discharges through a classification process related to the anomalies of the multispectral response of coastal waters, using algorithms based on spatial variation of pollutant concentrations. This study, extended over statistically significant time intervals, can provide useful information for the decision-making/technical processes related to the classification and quality control of coastal waters.
Keywords: environmental impact assessment, pollution, coastal waters, multispectral analysis, multilayer analysis, proximal sensing, remote sensing, hierarchical monitoring.

1 INTRODUCTION

The marine coastal zone, like the heart of animals, regulates the circulation of critical ecological, economic and social processes; however, anthropogenic stress poses a serious threat to the coastal environment. Among the phenomena of greatest concern is the pollution of coastal waters via waterways, such as rivers, canals and direct discharges. The substances released in this type of pollution can include: organic matter, synthetic organic compounds (e.g. PCBs and pesticides such as DDT and residues), microorganisms, nutrients (mainly nitrogen and phosphorus), petroleum, waste, heavy metals, radionuclides, and so on. Given the complexity and on-going dynamic evolution of these coastal environments, appropriate coastal management requires data collection whose nature and frequency of space–time acquisition are suitable for the description and the evaluation of the phenomenon of interest.

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Conventional in-situ, low-frequency detection methods are often inadequate to capture the complexity and dynamism of these environments. Advances in environmental monitoring provide suitable techniques and technologies for a more complete description of the investigated phenomenon along coastal zones. Using a combination of remote and proximal sensing allows for hierarchical monitoring [1], [2]. By using sensors transported on platforms located at different altitudes hierarchical monitoring produces information layers characterized by different relationships between the spatial resolution of the image and the size of the area surveyed. Consequently, with the various platforms there is a tendency to focus on different aspects and to produce complementary results [3]–[6].

Recent research utilizing hierarchical monitoring together with bioindicators [7], [8] has emphasized the importance of the proximal sensing information in the study of coastal phenomenon related to algal blooms. The information obtained with proximal sensing are closest to the ground and have high spatial and temporal resolutions, which are generally comparable with the data obtained on the ground by conventional in-situ sampling of water quality concerns such as algal blooms. This proximity allows the information regarding bioindicators derived from remote sensing to be validated with greater certainty [9]–[11], enabling management to respond to potentially harmful exposure to algal blooms.

This paper presents a real application of proximal sensing within hierarchical monitoring with bioindicators as an innovative technology for coastal management and environmental impacts during COVID, September 2021. The study site is of Regi Lagni channel on the coastal area of the Domizia coast, located in southern Italy in the Campania region (Fig. 1). Regi Lagni are essentially a network of canals created to hydraulically reclaim an area that extends for 1095 km^2 in the municipalities of Naples, Caserta, Avellino and Benevento. The canalization and hydraulic reclamation works started in Roman times, and then underwent a major hydraulic reorganization during the Spanish Viceroyalty in the early 1600s. The 1973 cholera infection motivated the start of the sanitary reorganization of the area, so many of the drainage channels were used for the collection and treatment processes of sewage waste. In particular, five large purifiers were built whose treated water discharges directly into the channel of Regi Lagni. These works were supposed to solve the sanitation problem of wastewater and improve the quality of coastal waters.

Several environmental studies, including that of ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development), have highlighted various problems concerning the wastewater collection and treatment system and the impact on this Regi Lagni waterway [12]. Furthermore, several police investigations have revealed the direct release of toxic waste (e.g. from companies) and illegal wastewater discharge (e.g. from residential areas, dairy farms and livestock farms) into Regi Lagni [13]. Consequently, for several years, the segment of coast near the mouth of Regi Lagni, located in the Municipality of Castel Volturno, has been one of the most polluted areas of the Domizia coast. The large amount of pollutant discharged into the coastal environment can have significant adverse impacts on human health and biodiversity, and the detection of these discharges is hindered by the large spatial and temporal scales across which illicit activities also take place.

The aim of this study is to reveal hierarchical monitoring methodologies that assist with environmental risk assessment of receiving waters, where monitoring coordinates the spatiotemporal resolution of multilayer and multispectral sensors. The multispectral and multilayer analysis evaluated the impacted area with use of multispectral output from proximal sensing acquisition by a UAV (unmanned aerial vehicle), otherwise known as a drone system. The UAVs are flying platforms characterized by the absence of the pilot on

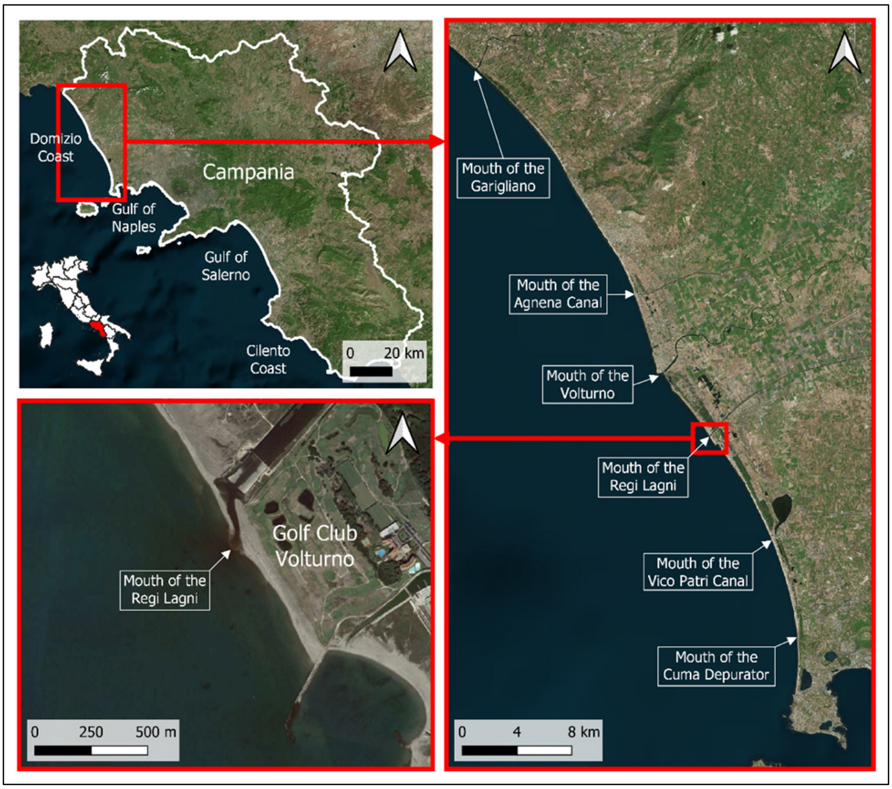

Figure 1: Study sites are to the west of the Italian Gulf of Naples (upper left), along the Domitian Coast (right), and focused about coastal outlet of the Regi Lagni drainage (lower left).

board. The drone system was used as a bridge layer in the multi-layer monitoring to contextualize information coming from satellite acquisition. This study was able to quantify the spatial impact of coastal pollutant discharges through a bioindicator classification process related to the anomalies of the multispectral response of coastal waters, using algorithms based on spatial variation of pollutant concentrations.

2 MATERIALS AND METHODS

2.1 Techniques and technologies

2.1.1 Spectral indices

In the process of remote sensing, the chance of acquiring different bands of the electromagnetic spectrum has allowed the introduction of different spectral indices, which are defined as a simple combination of the reflectance of the spectral bands; spectral indices are generally used to emphasize some elements of the observed scene, which is extremely useful to identify and study "hidden" and complex phenomena. Concerning this study, it was considered appropriate to use two spectral indices, the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Turbidity Index (NDTI), explained below.

The NDVI, used for the first time by Rouse et al. [14], allows to identify the vegetation areas and their vigour (linked to the photosynthetic activity of the plant). NDVI can also provide useful information on possible pollution phenomena, in fact, this index is sensitive to the presence of algal blooms and bacteria (e.g. cyanobacteria), inside coastal waters, which are generally triggered by eutrophic conditions due to supply of nutrients contained in waste or contaminated water. The NDVI combines the reflectance of the red (RED) and near infrared (NIR) spectral bands and is defined with the following expression:

$$\text{NDVI} = (R_{\text{NIR}} - R_{\text{RED}})/(R_{\text{NIR}} + R_{\text{RED}}). \tag{1}$$

The NDTI provides information on the turbidity of the water. Because the turbidity of the water is due to the dispersion and absorption of light caused by the presence of suspended particles, high values of the NDTI indicate cloudy water, while low values indicate clear water. Generally, this index tends to emphasize the presence of plumes that water courses form when they meet coastal waters; the greater turbidity of the inlet waters is generally due to suspended particles, such as clay, silt, microorganisms and various substances, deriving from water courses. The NDTI index combines the reflectance of the red (RED) and green (GREEN) spectral bands:

$$\text{NDTI} = (R_{\text{RED}} - R_{\text{GREEN}})/(R_{\text{RED}} + R_{\text{GREEN}}). \tag{2}$$

2.1.2 Platforms and sensors for proximal and remote sensing

In environmental studies, hierarchical monitoring represents an important source of information provided by sensors carried on platforms located at different altitudes. These sensors provide information layers characterized by different ratios between the spatial resolution of the image and the size of the detected area. Consequently, through hierarchical monitoring thanks to the various platforms it is possible to focus on different aspects of a phenomenon and to produce complementary results.

This study applied hierarchical monitoring with two types of platforms, each with specific sensors. The higher layer was monitored by satellite platforms of the Copernicus Sentinel 2 mission. The lower, proximal layer was monitored by the DJI Mavic 2 Pro drone. Through the sensors carried onboard these platforms, remote and proximal information levels to the surface of interest were obtained respectively.

The Copernicus Sentinel 2 mission includes a constellation of two satellites located in the same polar orbit with 180° out of phase distance. These twin satellites (2A and 2B) make it possible to obtain broad spectrum and high-resolution multispectral images using an optical instrument that samples 13 spectral bands (see Table 1). The Sentinel 2 products included a collection of orthophotos, each spanning 100x100 km^2 in UTM/WGS84 projection, containing the 13 spectral bands previously listed. In particular, only bands 3, 4 and 8 were used for the calculation of the indices of interest, which makes it possible to obtain elaborations with a pixel spatial resolution of 10 m.

The DJI Mavic 2 Pro drone was equipped with an RGB camera fully stabilized by a three-axis gimbal, with a 1-inch CMOS sensor (developed in collaboration with Hasselblad) to record videos in 4K and to acquire 20-megapixel pictures. In addition to the sensor equipment provided by the Mavic 2 Pro manufacturer, the drone was equipped with a multispectral camera Survey 3 with wide-angle lens (Survey3W) produced by MAPIR. The Survey3 used a Sony Exmor R IMX117 12 MP (Bayer RGB) sensor that was customized with an OCN (orange, cyan, near-infrared) filter to allow detection of the spectral bands of orange, cyan and near infrared (Fig. 2). To use the measurements acquired by the Survey3, they were

Table 1: Spectral bands for the SENTINEL-2 sensors (S2A and S2B) showing spatial resolution (m), central wavelength (nm), bandwidth (nm) and a description, where VNIR is very near infrared and SWIR is shortwave infrared. *(Source: Sentinel-2 MSI Technical Guide – Sentinel Online – esa.int.)*

Band number	Spatial resolution (m)	Central wavelength (nm)		Bandwidth (nm)		Description
		S2A	S2B	S2A	S2B	
1	60	442.7	442.3	21	21	Ultra blue
2	10	492.4	492.1	66	66	Blue
3	10	559.8	559.0	36	36	Green
4	10	664.6	665.0	31	31	Red
5	20	704.1	703.8	15	16	VNIR
6	20	740.5	739.1	15	15	VNIR
7	20	782.8	779.7	20	20	VNIR
8	10	832.8	833.0	106	106	VNIR
8a	20	864.7	864.0	21	22	VNIR
9	60	945.1	943.2	20	21	SWIR
10	60	1,373.5	1,376.9	31	30	SWIR
11	20	1,613.7	1,610.4	91	94	SWIR
12	20	2,202.4	2,185.7	175	185	SWIR

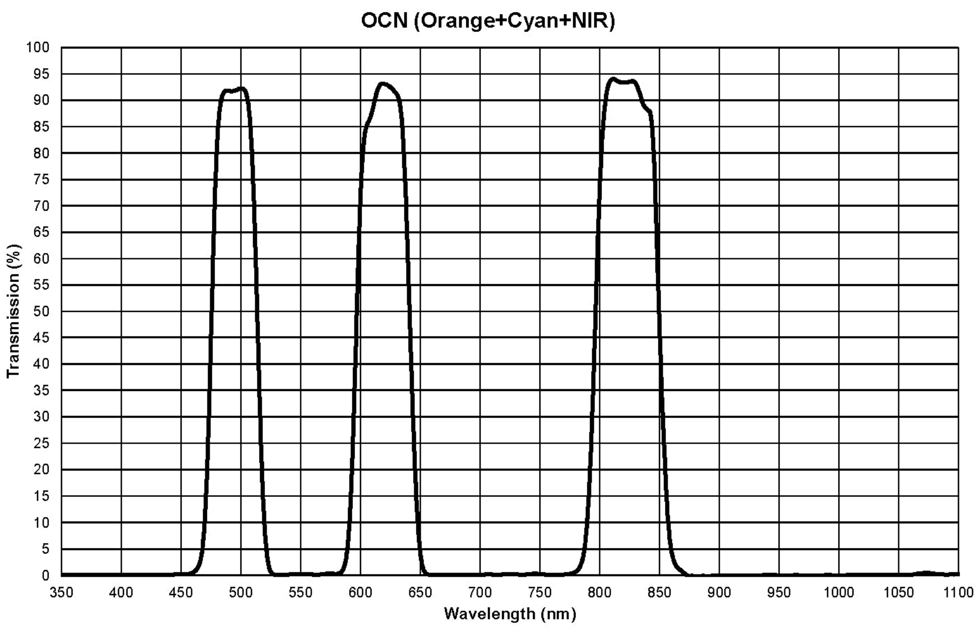

Figure 2: Characteristics of the spectral bands transmitted by the OCN (orange, cyan, near-infrared) filter on the Survey3 sensor carried by the proximal sensing DJI Mavic 2 Pro drone within this mission.

calibrated using a specialized software coupled with a calibrated reflectance target; the latter consists of four surfaces, each of which has known reflectance curves. Prior to an acquisition mission, the target must also be acquired in the same light conditions, taking care not to cover the targets with shadows or debris.

The proximal acquisition phases of the study used two cameras: RGB (red, green, blue) and multispectral combination with detection of six spectral bands. The NDTI index was calculated with the RGB camera bands, while the NDVI index was calculated with the multispectral camera bands. The spatial resolution of the proximal acquisitions used in this study, relative to a maximum altitude of about 350 m, is of the order of 10 cm.

2.1.3 Software

The Sentinel 2 mission orthophotos relating to the area of interest were selected and downloaded from the ESA Copernicus Open Access Hub. For processing of the Survey3 images, two software programs were used in this study. Pre-processing was performed with the Mapir Camera Control (MCC) where this program allowed conversion of RAW + JPG files into TIFF along with calibration of the images. In-depth processing was performed with QGIS software, which enabled calculation of indices using the raster calculator. QGIS allowed customized classes of index values and the false colour scale, as well as a whole series of features that help to visually enhance, through thematic maps, certain aspects of a phenomenon.

2.2 Procedure

The study was conducted following a top-down approach, that is, using first remote platforms and then those proximal to the surface of interest; this strategy allowed to initially have a global view of the anomalies of the multispectral response of the coastal waters of a stretch of the Domizia coastline; after that, using the Mavic 2 Pro, it was decided to accurately analyse the mouth of Regi Lagni, located in the territory of Castel Volturno (Caserta). To optimize the use of the drone, the date of the flight mission was chosen to make it coincident with one of the dates of passage of the Sentinel 2 satellites at the place of interest; at the same time, among the various available dates, the one that presented favourable weather conditions was chosen; in essence, the day that satisfied these conditions was 24 September 2021. A flight plan was programmed through the DJI Ground Station Pro (DJI GS PRO) application, and before take-off a series of checks were carried out. The mission was complemented by a series of supporting information channels, including the weather conditions obtained from the Grazzanise airport meteorological station (Table 2).

Table 2: Weather data provided by the Meteorological Station of Grazzanise Airport (CE) in the southern coast of Italy.

Medium temperature	Minimum temperature	Maximum temperature	Dew point	Average humidity
20°C	13°C	27°C	13°C	68%
Minimum humidity	Maximum humidity	Average pressure above sea level	Phenomena	Weather conditions
34%	100%	1020 mb	Nothing	Clear

Figure 3: Mouth of Regi Lagni drainage entering the Italian coastal area, as seen from the DJI MAVIC 2 Pro drone with the RGB (red, green, blue) image.

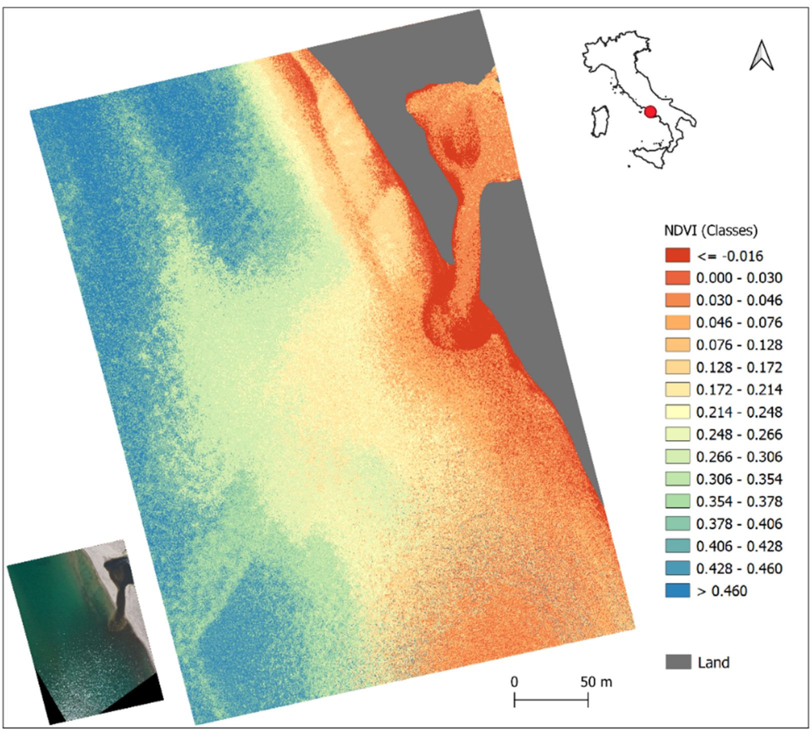

Figure 4: Mouth of Regi Lagni drainage entering the Italian coastal waters, shown in colour with the modified normalized difference vegetation index (NDVI) of the image acquired by DJI Mavic 2 Pro drone Survey3 sensor.

3 RESULTS AND DISCUSSION

The pollution plume discharging into the coastal waters from the Regi Lagni drainage was first sighted through the RGB image captured with the 20 Megapixel camera of the drone (Fig. 3). Even without the use of any spectral index, the Regi Lagni canal waters discharging at the coast were clearly distinguishable from that of the sea, due to the different colour, which was the first clue of the pollutant plume.

The initial visible, e.g., RGB, proximal imagery of the plume (Fig. 3) alone would suggest the impact was spatially limited in extent, however its plume extent was larger. Processing the image obtained from the multispectral camera with the NDVI index shed light on the real impacted zone, a much larger area (Fig. 4) than the one detected in the field of visible. Once the plume was characterized at its full extent with NDVI, the monitoring could consider a potential diffusion of pollutants to a much larger area than characterized by the RGB image.

By applying the NDTI index to the image obtained with the drone camera, it was possible to observe a different, yet also very extensive plume (Fig. 5). In particular, the NDTI in this case provided a very detailed delimitation of the possible zones of the plume.

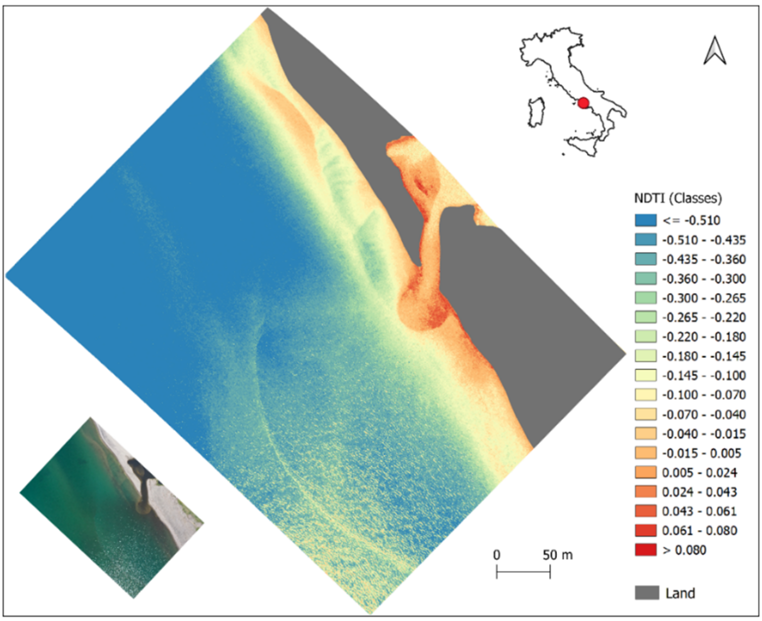

Figure 5: Mouth of the Regi Lagni drainage entering the Italian coastal waters, shown in colour with the modified normalized difference turbidity index (NDTI) of the image acquired by the DJI Mavic 2 Pro drone Survey3 sensor.

Satellite multispectral imagery for 24 September 2021 was then used to elaborate on the spatial extent of the pollution plume, which the drone was unable to fully capture given its proximal distance from the target. The satellite acquisition was processed into the NDTI and provided a spatially broader but coarser 10 m pixel resolution view of the plume (Fig. 6). Data fusion by overlap was then used to merge the two hierarchical monitoring levels, combining the 10 m resolution satellite NDTI with the cm resolution drone NDTI, to obtain enhanced information (Fig. 7).

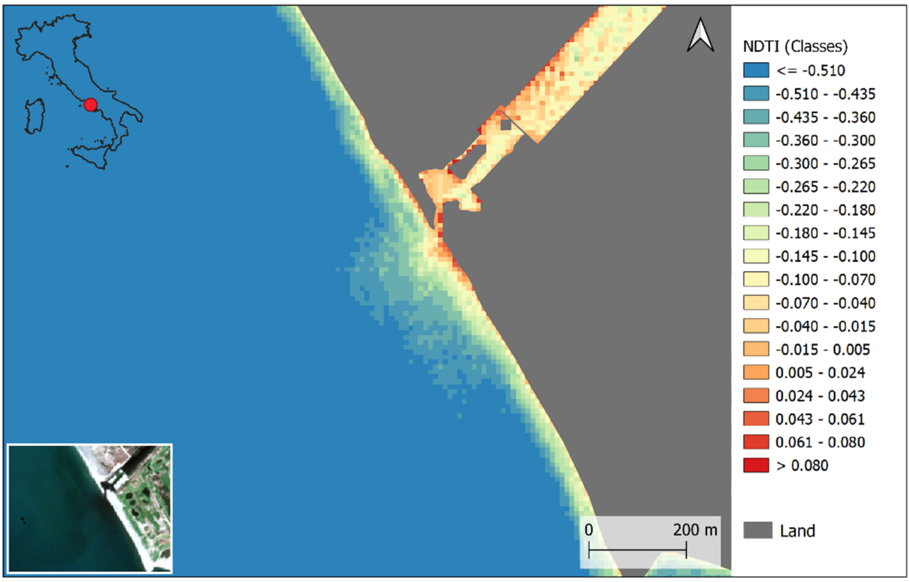

Figure 6: Mouth of the Regi Lagni drainage entering the Italian coastal waters, shown in colour with the modified normalized difference turbidity index (NDTI) of the image acquired by the Sentinel 2 mission. Scale used for comparison.

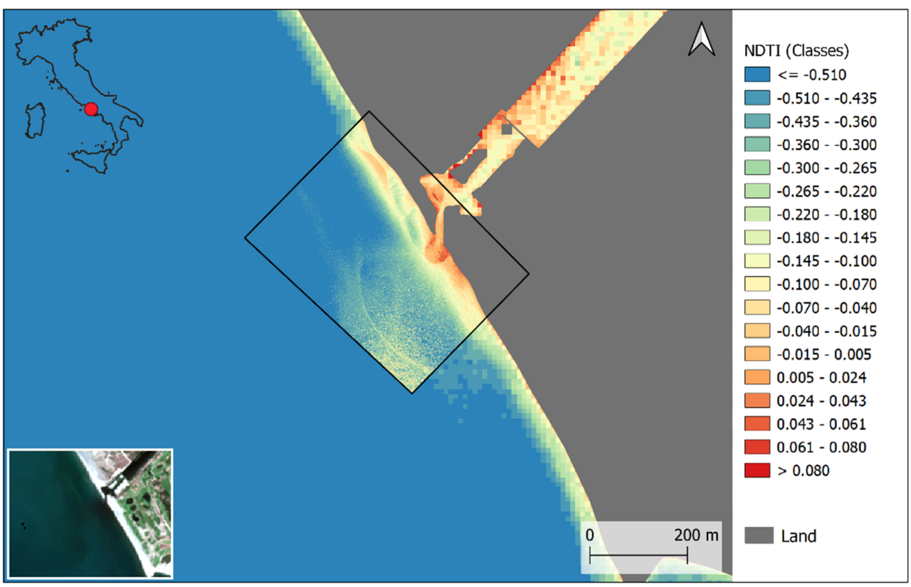

Figure 7: Mouth of the Regi Lagni drainage entering the Italian coastal waters, shown in colour with the modified normalized difference turbidity index (NDTI) data fusion of the satellite Sentinel 2 mission and DJI Mavic 2 Pro drone mission.

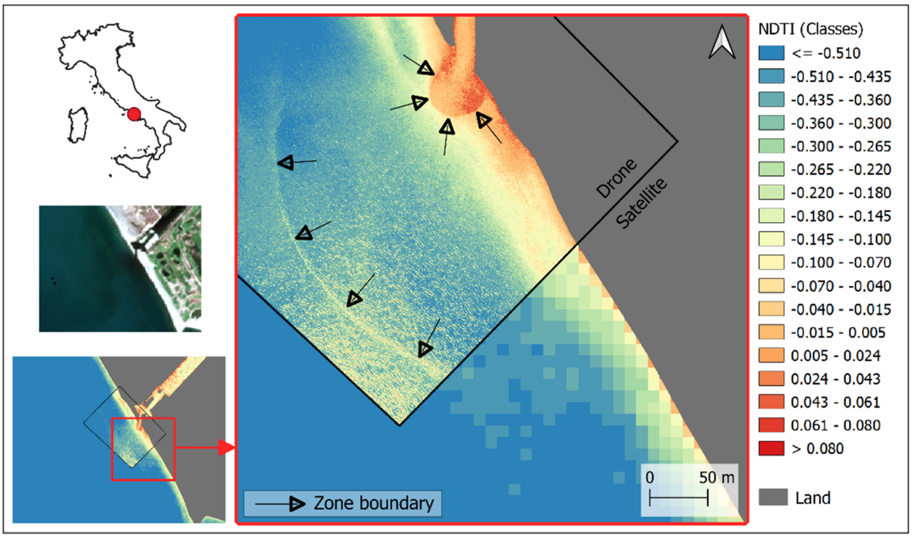

Figure 8: Mouth of the Regi Lagni drainage entering the Italian coastal waters with delimitation of the hierarchical monitoring zones by satellite and drone.

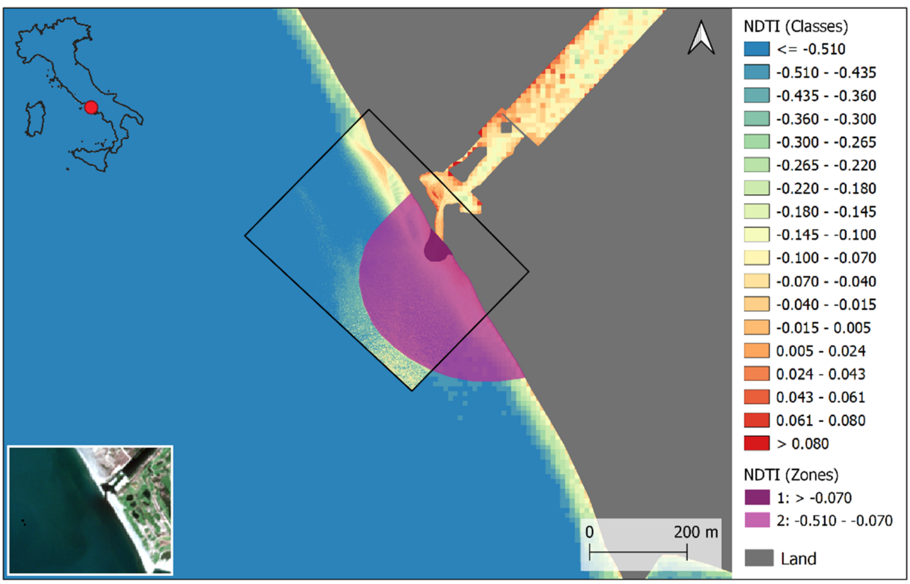

Figure 9: Mouth of Regi Lagni drainage entering the Italian coastal waters with geometric characterization of two zones of the plume based on normalized difference turbidity index (NDTI) with data from the drone.

The data fusion overlap emphasized the substantial differences in spatial resolution between the products of different information levels, and allowed interpretation of the relationships between hierarchical monitoring. From the high spatial resolution drone image it was possible to accurately identify at least two zones of the plume, but the lower spatial resolution satellite image of the outermost plume along the coast cannot be fully defined (Fig. 8).

Geometric processing was used to clarify the intensity of the NDTI values, as sections of the plume and concentration of pollutant. The proximal sensing allowed for a limited spatial extent of two NDTI zones near the drainage outlet to the coast (see Fig. 9). The data fusion between drone and satellite sensing allowed for greater spatial extent and characterization of four NDTI zones (see Fig. 10).

The characterization of the plume zones based on NDTI, with two from the drone (Fig. 9) and four with the data fusion of drone and satellite (Fig. 10) relied on the coordination of hierarchical monitoring. The reconstruction of these two additional zones of the plume by use of satellite data was characterized by less spatial precision and accuracy. This reconstruction performed in QGIS allowed, through polygonal shapefiles, to quantify the extent of the plume surface in square meters (Table 3).

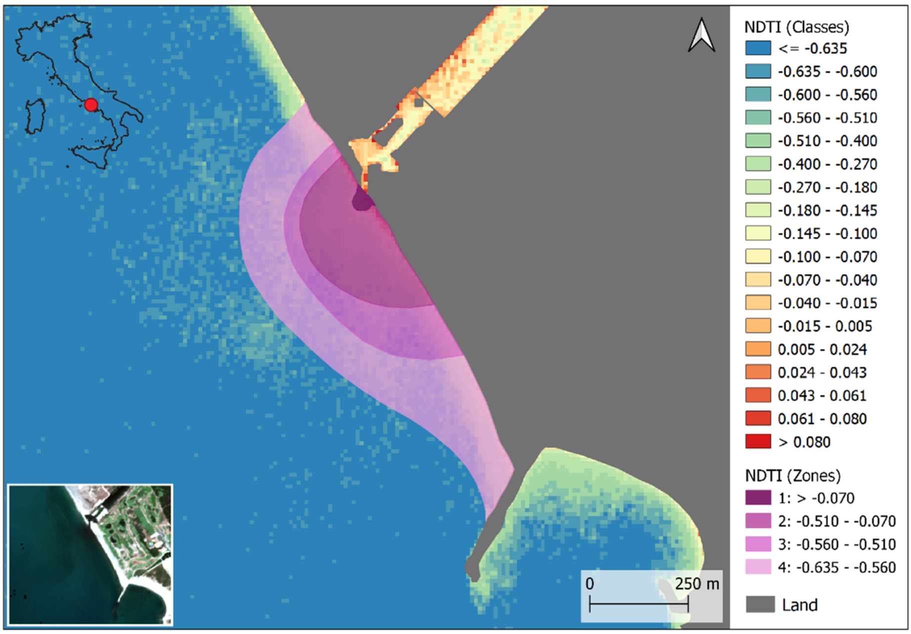

Figure 10: Mouth of Regi Lagni drainage entering the Italian coastal waters with geometric characterization of four zones of the plume based on normalized difference turbidity index (NDTI) with data from the drone and satellite.

Table 3: Areal extension of the plume extent (m^2) in the Italian coastal waters near Regi Lagni, as calculated through the QGIS software analysis.

Extension of the plume surface (m^2)				
Zone 1	Zone 2	Zone 3	Zone 4	total
2087	66774	53360	155329	277550

4 CONCLUSIONS

This study reports how a hierarchical monitoring with specialized sensors and bioindicator indices characterized the pollutant plume for a large, dynamic coastal area. This approach facilitated the focus on specific aspects of the pollution phenomena, and enabled novel and complementary results. Specifically, through this approach it was possible to (a) detect and identify the plume impacting the coastal area near the Regi Lagni drainage, and (b) to define the plume extent and quantify its area in different concentrations of potential pollution.

The proximal sensing instruments, such as drones which can operate closest to the target, often have the highest spatial and temporal resolution, and sufficient multispectral capacity, to provide a link or bridge between in-situ sampling and higher altitude remote sensing. This paper demonstrates how multidisciplinary analysis with coordinated use of remote and proximal sensing was able to quantify the spatial impact of pollutant discharges through a classification process related to the anomalies of the multispectral response of coastal waters, using algorithms based on spatial variation of pollutant concentrations.

This study, when extended over statistically significant time intervals, can provide useful information for the decision-making and technical processes related to the classification and quality control of coastal waters.

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