# ATTRIBUTION OF POLLUTION DISCHARGES IN COASTAL WATERS DURING THE COVID-19 LOCKDOWN USING REMOTE SENSING AND BIOINDICATORS

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## ABSTRACT

Attribution of environmental pollution phenomena and their causes represents a real challenge due to the complexity of the scenarios to be examined and the multiple sources to be considered. Furthermore, the definition of the parameters to be monitored, considering the specific phenomenon, becomes very difficult, especially in relation to the available technological solutions and operational needs. Various elements, naturally present in the scenario under examination, can be used as perfect sensors/indicators to detect the status of the environment and effectively reveal the relationships between specific sources of pollution and target areas. This study demonstrates how pollution attribution is achieved using remote sensing of cyanobacteria, which are excellent bioindicators due to their sensitivity to multiple stressors and rapid response to habitat changes throughout the event. The study was conducted in the coastal waters of the Campania region (southern Italy) for the period before, during and after the COVID-19 lockdown. Along the coastal area examined, a special focus was dedicated to Lake Avernus. This program detected the presence of specific cyanobacteria species, some toxic, and revealed the relationship between their presence and anthropic pollution activities. This paper demonstrates how deployment of multidisciplinary analysis with choreographed use of remote/proximal sensing and in situ sampling across space and time utilized the cyanobacteria to characterize the impact of human activities. The study allowed environmental forensic teams to identify and confirm the anthropogenic origin of the environmental variations that stimulate the cyanobacterial blooming.

*Keywords: environmental impact assessment, pollution, coastal waters, multispectral analysis, multilayer analysis, proximal sensing, remote sensing, hierarchical monitoring.*

## 1 INTRODUCTION

Identifying a polluted site is an important action for safeguarding health, however often the process of analysing pollution phenomena is limited to verifying the effects and not the causes. Attribution of environmental pollution phenomena and their causes represents a real challenge due to the complexity of the scenarios to be examined and the multiple sources to be considered. Furthermore, the definition of the parameters to be monitored, considering the specific phenomenon, becomes very difficult, especially in relation to the available technological solutions and operational needs.

Understanding a pollution phenomenon often requires a multidisciplinary approach and a multi-temporal analysis, but, unfortunately, sometimes also these types of approaches do not reveal the cause–effect relationships; environmental issues are often faced where there is the evidence of concomitant changes and effects in a specific location and time without immediately understanding the phenomena relationships. An example of these flaws occurred during the COVID-19 lockdown in Italy, when the environment was affected by important changes and the only certainty is that they happened in that particular period and not before and not after. Many people and the media in general have interpreted the environmental changes detected during the lockdown as a consequence of the change of

WIT Transactions on Ecology and the Environment, Vol 257, 
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/WMEI220151

habits of the communities and therefore hypothesizing them as the causes of the changes. However, much of this news does not arise from real scientific studies and has been disseminated by the media as "sensationalism".

Our previous research studies [1] have already analyzed pollution phenomena along the coasts of the Campania region (Southern Italy) using combined techniques and technologies (remote sensing, proximal sensing and in situ surveys). In particular, a specific approach was developed with a hierarchical monitoring approach called multi-level and multi-parametric monitoring framework (MuM3 hereafter) [2], [3] proved to be particularly effective and efficient in the analysis of source–path–target route of pollution phenomena. When available technologies do not allow to observe some parameters directly, bioindication takes on a fundamental role. Indeed, various elements, naturally present in the scenario under examination, can be used as perfect sensors/indicators to detect the status of the environment and effectively reveal the relationships between specific sources of pollution and target areas; in particular, our research group has investigated the use of cyanobacteria as bioindicators of anthropic pollution [4], [5].

There are several spots of the coastal areas in Campania where cyanobacteria blooms have been detected [6] and in many cases their presence was associated with the eutrophication and, more generically, pollution. Furthermore, we have discovered that cyanobacteria blooms in some lakes along the Campania coasts were linked to anthropogenic pressure and the environmental stress conditions meant that the cyanobacteria also produced toxins dangerous for human health [7].

The aim of this work is to combine and implement the MuM3 and the fast detection strategy (FDS) [8], previously tested and validated, with a top-down approach applied to a real "test bed". Consequently, using both remote and proximal data, beginning at the satellite level and scaling-down at different spatial–temporal resolutions, the validity of the added value of such a method is explored.

The study was conducted in the coastal waters of the Campania region (southern Italy) (Fig. 1) for the period before, during and after the COVID-19 lockdown. In a first step the entire coastal area located in north of Naples was examined, then a special focus was dedicated to Lake Avernus, a volcanic coastal lake, that due to its funnel shape collects rainwater as well as waters of different origins washed out from the surrounding area; as perfect "test bed", Lake Avernus experienced several cyanobacterial blooms in different years, alternating different species and associated toxins; in all cases, the blooming event started in association with stress condition defined from specific environmental status. This study shed light on causes and consequences of the environmental status at the turn of COVID-19 lockdown and deepened the relationship between the variation of anthropic pressure and cyanobacterial bloom events.

## 2 METHODS

To detect discharges in coastal waters and in general pollution phenomena along the coasts of Campania, in southern Italy, we used a hierarchical monitoring that includes acquisition and analysis of remote data acquired by satellite, proximal data acquired by drone, and in-situ sampling. Consequently, using both remote and proximal data, beginning at the satellite level and scaling-down at different spatial–temporal resolutions, the validity of the added value of such a method was explored. In particular, the combination of two platforms/sensors was used: remote (satellites of the Copernicus Sentinel 2 mission) and proximal (DJI Mavic 2 Pro drone). The twin satellites (2A and 2B) of the Copernicus Sentinel 2 mission are equipped with an optical instrument that samples 13 spectral bands (see Table 1).


Figure 1: Study sites are to the west of the Italian Gulf of Naples (upper left), along the Domitian Coast (right), and include Lake Avernus (lower left).

The first activity was the satellite-based multispectral analysis of the coastal area over a wide time interval, spanning pre and during the COVID-19 period, from 2019 to 2021.We used the Sentinel 2 data to calculate two multispectral indexes to transform the data into useful information: NDVI (normalized difference vegetation index) and SABI (surface algal bloom index). The calculation of the indices was carried out using the radiometrically corrected Sentinel 2 data, subsequently a classification was performed aimed at highlighting the areas with the plumes of discharges and the inlets of rivers into the sea.

The NDVI is one of the best-known spectral indices and was used for the first time by Rouse et al (1973); it allows to identify the vegetated areas and their vigor by exploiting the reflectance of red (RED) and near infrared (NIR).However, this index is also sensitive to chlorophyll present in algal and bacterial blooms (e.g. cyanobacteria) within coastal waters; therefore, it can be used, with the necessary precautions, also to analyze eutrophic conditions due to the supply of nutrients contained in waste or contaminated water. The NDVI is defined with the following formula:

$$NDVI = (R_{NIR} - R_{RED})/(R_{NIR} + R_{RED}) \quad (1)$$

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: MSI Instrument – 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 | 1373.5 | 1376.9 | 31 | 30 | SWIR |
| 11 | 20 | 1613.7 | 1610.4 | 91 | 94 | SWIR |
| 12 | 20 | 2202.4 | 2185.7 | 175 | 185 | SWIR |

The SABI allows the detection of biomass floating on water and is therefore particularly sensitive to algal and bacterial blooms. The SABI combines the reflectance of the red (RED), green (GREEN), blue (BLUE) and near infrared (NIR) spectral bands:

$$SABI = (R_{NIR} - R_{RED})/(R_{BLUE} + R_{GREEN}) \quad (2)$$

Thanks to the data acquisitions of the sensors transported aboard platforms located at different altitudes, the study was conducted on the basis of different relationships between the spatial resolution of the image and the size of the detected area.

The Copernicus Sentinel 2 mission provides the user segment with a collection of orthophotos, 100 × 100 km$^2$ in UTM / WGS84 projection, relating to the 13 spectral bands listed above. In particular, bands 2, 3, 4 and 8 were used to calculate the NDVI and SABI indices, consequently the spatial resolution of the satellite data is 10 m.

The drone DJI Mavic 2 Pro, on the other hand, is UAV (unmanned aerial vehicle) equipped with a fully stabilized three-axis gimbal RGB camera and capable of taking 20 megapixel photos. In addition, we have added to the standard payload a multispectral camera (MAPIR Survey 3) to permit acquisition of other three bands (“Orange”, “Ciano”, “Near Infrared”). Using the RGB camera bands it was possible to have a proximity confirmation, in the visible range, of what was observed remotely. In our study the proximal acquisitions have a high spatial resolution that range from a few cm/px, depending from the altitude of flight path (e.g., we acquired a large part of images at spatial resolutions of 5–10 cm).

The data acquired were processed using the QGIS software; with this program the various spectral indices were calculated and, through the classification of the index values, thematic maps were created in order to visually enhance certain aspects of the phenomenon of interest. Particular attention was paid to maintaining constant the subdivision into classes for all the elaborations carried out to make the results and, above all, the relative representations in the form of thematic maps, comparable.

## 3 RESULTS AND DISCUSSION

The multispectral analyses on the coasts of Campania, in particular the Gulf of Naples and the Domitian coast, were carried out using satellite data over the time interval 2019–2021, divided into years and months (Fig. 2). The definition of classes and colours represented the crucial step in terms of efforts and time, as in the case of all such analyses, in that only a correct classification allows to bring out the areas of interest.

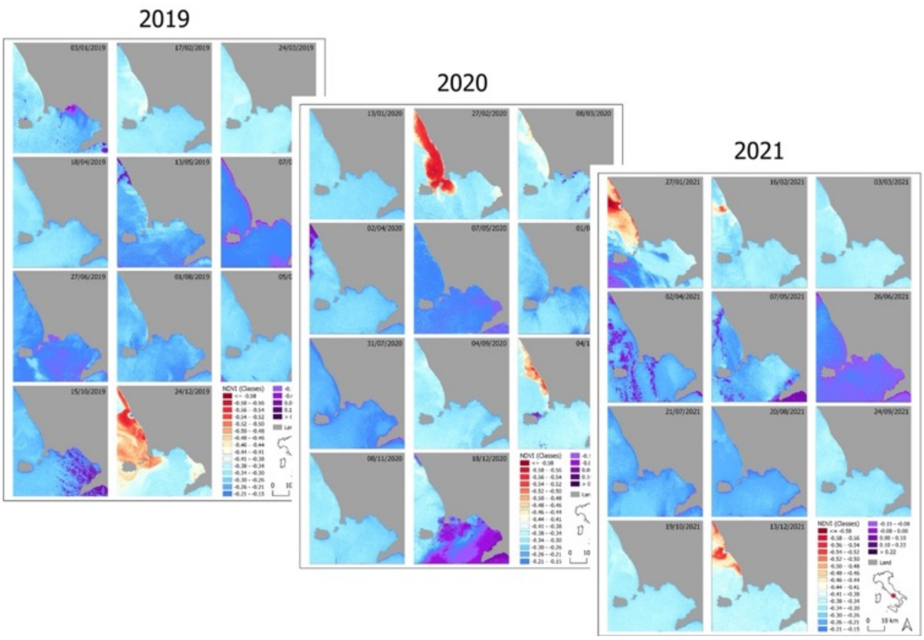


Figure 2: Thematic maps (grey is land area, color is water area) obtained from the calculation of the NDVI (normalized difference vegetation index) and subsequent classification of the results in 20 classes for years 2019 to 2021. The purple and red colors identify the waters of greatest interest; in particular, those in purple identify a potential presence of chlorophyll a (not to be confused with spectral response of atmospheric disturbances, i.e. clouds), those in red adjacent to the coast are near the mouths of rivers and canals and are related to the plumes deriving from periods of intense rain.

In the NDVI thematic maps of Campania coasts, the purple and red zones identify specific characteristics of the areas. Those map areas in purple highlight the greater concentration of chlorophyll *a* and, therefore, delimit water potentially impacted by environmental issues due to the input of nutrients (for example sewage drains, collection channels of irrigation water from agricultural fields, etc.), which give rise to eutrophication phenomena. Those map areas in red highlight the water impacted by the introduction of waters deriving from intense periods of rain and often with even greater turbidity. Since the observed area were very large while the extension of the above issues was limited in size and sometimes hidden by atmospheric phenomena, we decided to focus on a specific target area that had best showed the relationships between anthropogenic pressure conditions and the environmental response, the Lake Avernus (Fig. 3).

 
www.witpress.com, ISSN 1743-3541 (on-line)

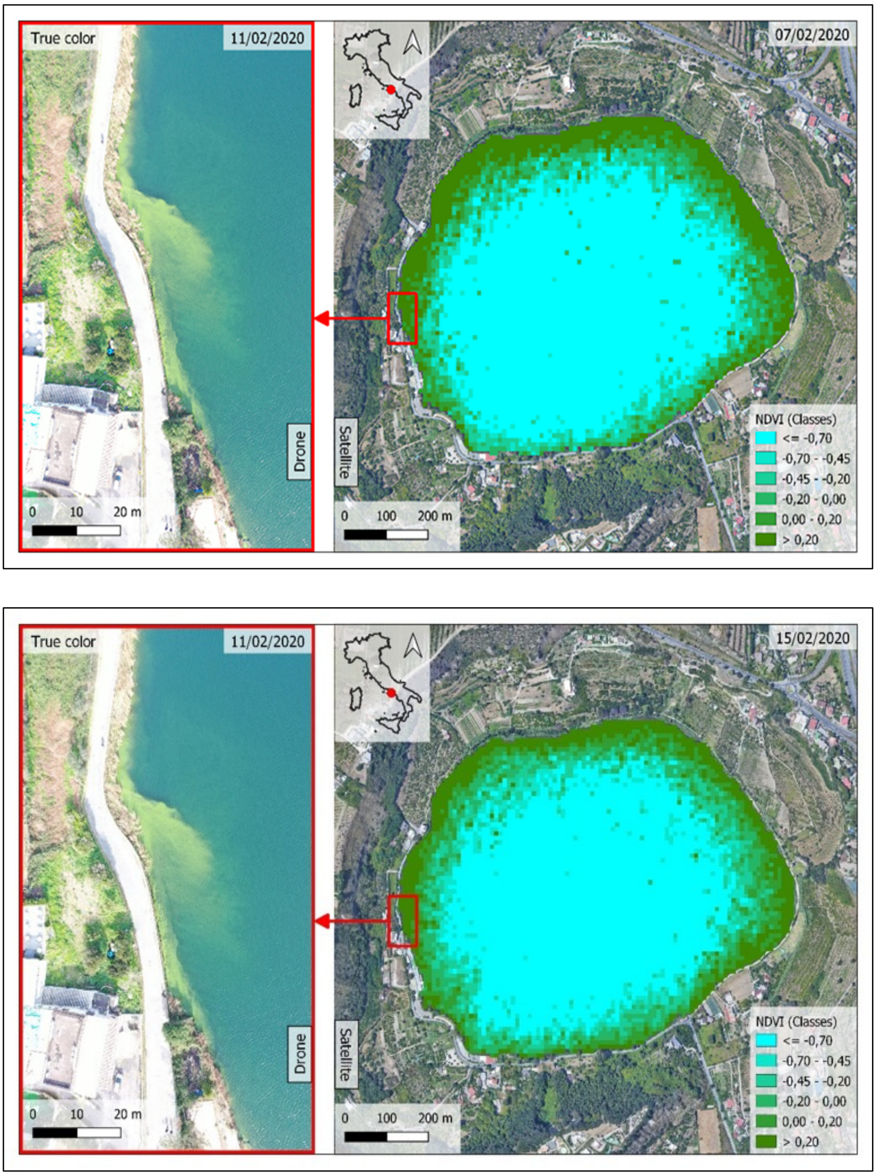


Figure 3: Drone (left) and satellite (right) thematic maps of the Lake Avernus study site for NDVI (normalized difference vegetation index) triggered attribution. The multispectral satellite images were obtained 7 February 2020 (top right) and 8 days later (bottom right) and used to calculate the NDVI and subsequent classification of the results in VI classes. A higher NDVI (dark green) corresponds to higher chlorophyll a content. The drone image in true color has the spatial resolution to reveal the plume discharge, and was obtained on 11 February 2020, after the NDVI analysis of the 7 February 2020 image revealed pollution concern; the drone can attribute the green plume to the cyanobacterial bloom.

The analysis was carried out on the lake using the NDVI and SABI indices in February 2020, when the lake was interested from a *Microcystis aeruginosa* bloom event [7]. The multispectral data refer to the dates closest to the sampling campaign (see below for details). During the sampling, a drone mission was also performed to survey proximal data.

As evident, there is a significant correspondence of blooming peak along the shores of the lake between satellite thematic map and drone RGB images. Driven by the positive results, the satellite data analysis was extended to the years 2018, 2019, 2020 and 2021 and for each year to at least once a month, choosing from the available dates those with the lowest cloud cover. A synoptic table that brings together all the thematic maps is shown in Fig. 4.

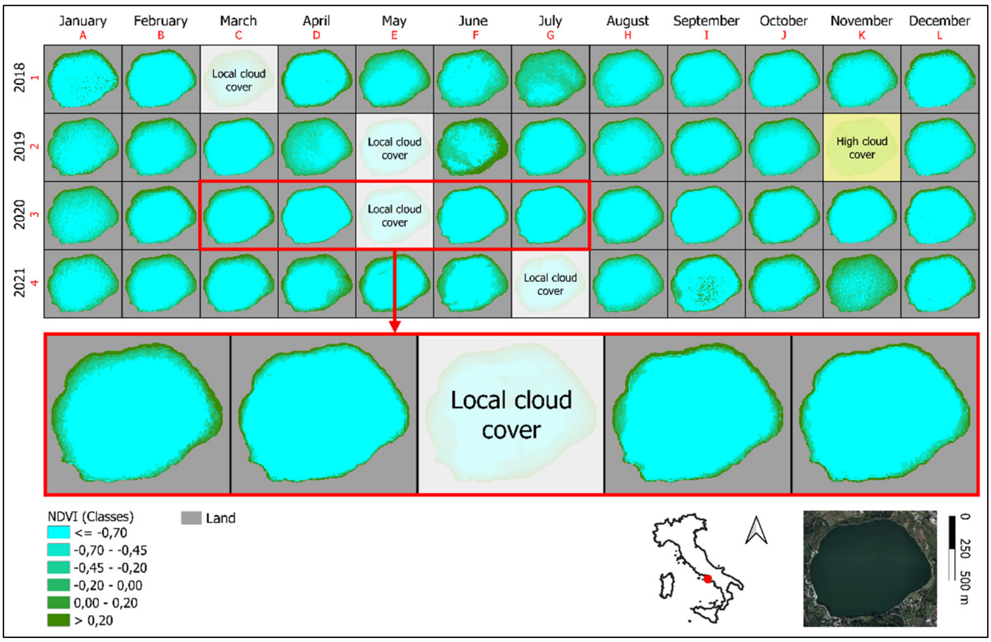


Figure 4: Time series as a synoptic table of the NDVI (normalized difference vegetation index) thematic maps of the Lake Avernus study site for all months in the years 2018–2021, where grey is land, magenta is water with no detected algal bloom concern, and dark green is maximum algal bloom concern.

The periodicity of blooming is certainly evident and reflects aspects of seasonality both connected to the climate and to the human activities of the areas around the lake.

The study of cyanobacterial species throughout the parallel analysis of samples taken in situ revealed the presence of two prevalent species: *Microcystis aeruginosa* and *Planktothrix rubescens* (Fig. 5). Studies on the reasons why one species or the other one blooms are still ongoing. Both species are potentially toxic. The link between toxin production and environmental stress has been previously ascertained [7].

In the period March to July 2020, the magnitude of the blooming was not comparable to the homologous periods of the other annuities; the extent of the perimeter bloom was remarkably reduced in that period corresponding to the first and most severe Italian COVID-19 lockdown.

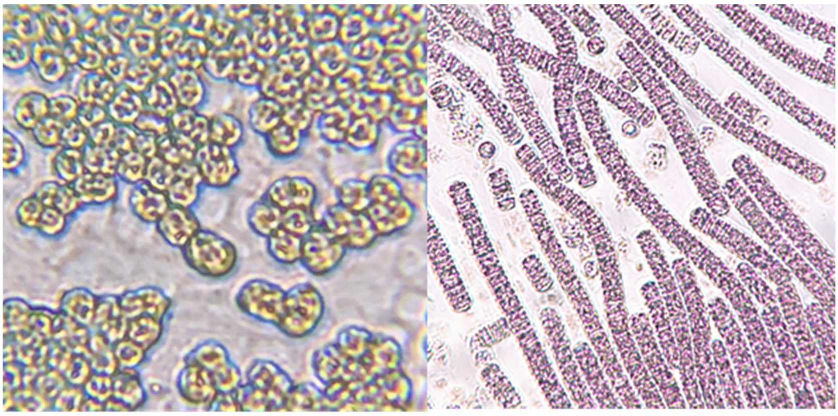


Figure 5: Laboratory images of water samples taken from algal blooms in the Lake Avernus study site, showing the two prevalent cyanobacterial species, *Microcystis aeruginosa* and *Planktothrix rubescens*.

This condition is justified by the reduced anthropogenic pressure in that period on the specific area of the lake. In fact, it should be pointed out that the area around the lake has a prevalent use in cultivation and recreation, both of which were very limited during COVID-19 lockdown. For a complete and in-depth analysis, the use of SABI multispectral index, specific for the study of algal bloom was also investigated. Fig. 6 shows the results obtained from the application of SABI index to the satellite images of Lake Avernus in the same dates used for NDVI index for comparison. As clearly visible no differences are observed between the two sets of multispectral data, confirming the previous results and also the presence of cyanobacteria.

## 4 CONCLUSIONS

This paper demonstrates how the deployment of multidisciplinary analysis with composed use of remote/proximal sensing and in situ sampling across space and time, makes possible to utilize cyanobacteria to characterize the impact of human activities.

This study confirms definitely how pollution attribution can be achieved using remote sensing of cyanobacteria, which are excellent bioindicators due to their sensitivity to multiple stressors and rapid response to habitat changes throughout the event.

This study allowed also to identify and confirm the anthropogenic origin of the environmental variations occurred during COVID-19 lockdown in Italy, that stimulate the cyanobacterial blooming.

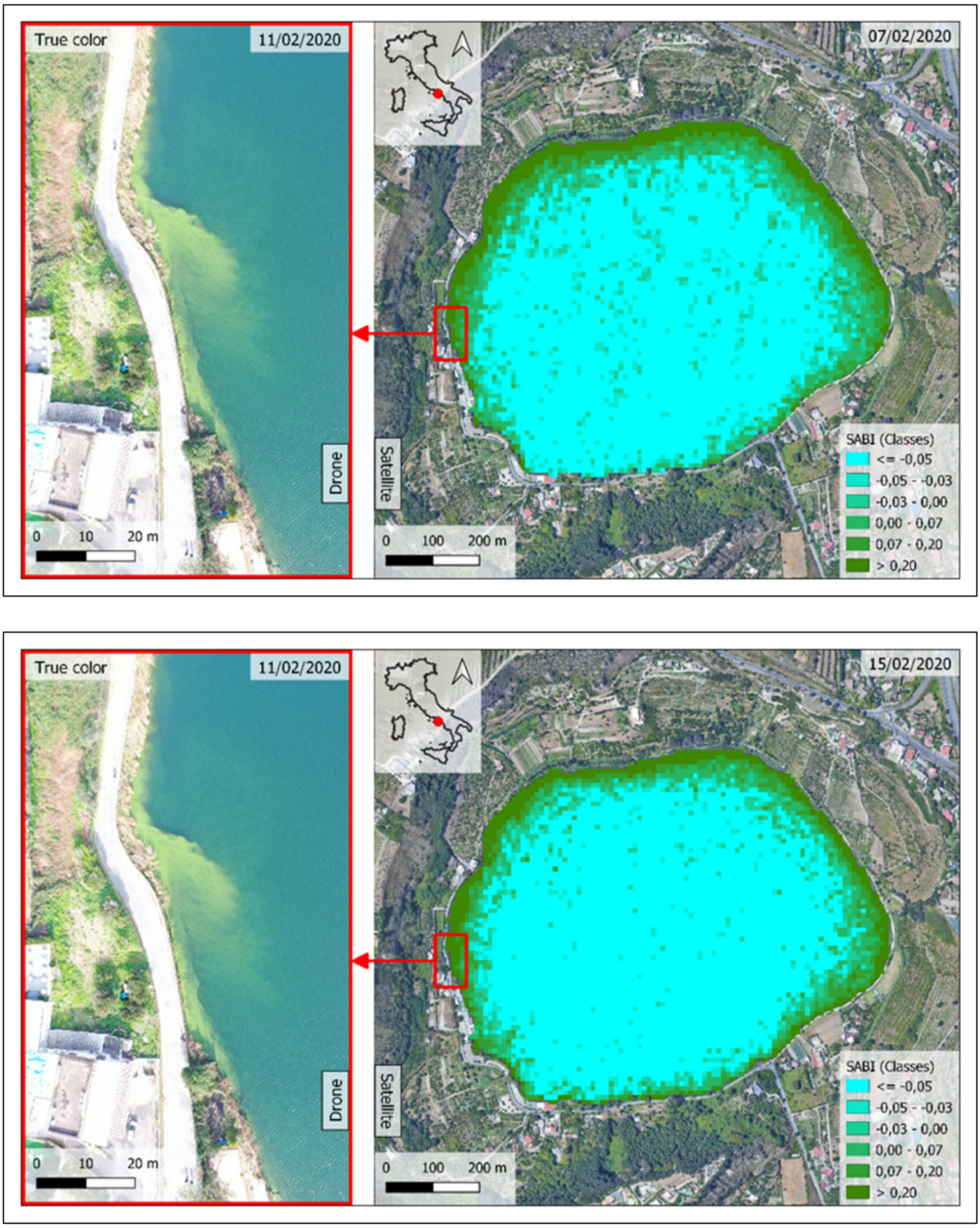


Figure 6: Drone (left) and satellite (right) thematic maps of the Lake Avernus study site for SABI (surface algal bloom index) triggered attribution. The SABI analysis and subsequent classification resulted in VI classes, and no differences with NDVI (normalized difference vegetation index) were noted (see Fig. 3). The satellite image of 7 February 2020 (top right) allowed calculation of the SABI, which identified a potential algal bloom, and triggered the drone flight and true color picture (left images) showing the green discharge associated with the cyanobacterial bloom.

## ACKNOWLEDGEMENTS

The data presented in this work are derived from the project “Attivita pilota di Monitoraggio di Cianobatteri nella fascia costiera della regione Campania” funded by the “Centro di Riferimento Regionale per la Sicurezza Sanitaria del Pescato (CRiSSaP)” and performed in cooperation with the Agency for the Environmental Protection of Campania region in Italy (ARPAC), University of Naples “Federico II” (Department of Pharmacy, ref. V. Costantino and Department of Veterinary Medicine and Animal Production, ref. A. Anastasio), University of Naples “Parthenope” (Department of Engineering, ref. M. Lega). This project was supported in part by the University of Naples “Parthenope” (Italy) under “Bando di sostegno alla ricerca individuale” and by Department of Pharmacy, University of Naples Federico II under “Bando contributo alla ricercar—Anno 2021” for the project “CyaAq—I cianobatteri come promettente risorsa di antimicrobici non convenzionali”.

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