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Estimating vulnerability of water body using Sentinel-2 images and environmental modelling: the study case of Bracciano Lake (Italy)

Chiara Giuliani [a], Adrienn Caronte Veisz [a*], Matteo Piccinno [a*] and Fabio Recanatesi [b]

[a]Department of Architecture and Design, Sapienza University of Rome, Rome, Italy; [b]Department of Agriculture and Forest Sciences, Tuscia University, Viterbo, Italy

ABSTRACT

Due to the concomitance of several factors related to progressive climate changes and to increased water management for anthropogenic usage, drastic fall in level of Bracciano Lake, a volcanic lake, 30 km northwest of Rome, was reported. In November 2017 the water level decreased 1.98 m below the hydrometric zero. Vulnerability to eutrophication was investigated by determination of the lake water volume and the related phosphorus concentration. At this purpose, the bathymetry layer of the water body and the application of supervised classification of Sentinel-2 images allowed to quantify the water body and to define the coastline shape. Once calculated the hydrometric reduction in water body after the hydrometric crisis, occurred in 2017, Vollenweider model allowed to estimate nutrient concentration (around 100.93 µg/l) and the relative increase of the eutrophication status (+2.3% per liter). According to the lake water quality classification proposed by the OECD, we classified the lake as a very eutrophic lake with a hypertrophic level in the period of water crisis. The proposed methodology represents an efficient monitoring tool for assessing the vulnerability of water bodies influenced by eutrophication.

Introduction

The Italian Ministry of the Environment and Protection of Land and Sea with the Water Framework Directive (WFD) 2000/60/CE (European Commission, 2000) aims to achieve ambitious goals: avoiding deterioration of freshwater quality and quantity, improving water quality and promoting sustainable water use based on a long-term protection of available water resource.

In Italy, such as the rest of industrialized countries, the main limiting factor in water quality is represented by eutrophication of the water body (Arshad & Martin, 2002; Chislock, Doster, Zitomer, & Wilson, 2013; Oldeman, Hakkeling, & Sombroek, 1991) and it is nowadays considered a problem on a world scale (Chebud, Naja, & Rivero, 2011; Hoorman et al., 2008; Olem & Simpson, 1994).

The eutrophication process, that is considered a limiting factor in water quality, is defined as the phenomenon of trophic enrichment, mainly due to phosphorus and nitrogen, of the water bodies (Anderson et al., 1995).

In this context, the NonPoint Source (NPS) pollution, generally results from land runoff, precipitation, atmospheric deposition, drainage, seepage or hydrologic modification, is the leading remaining cause of water quality problems (Arheimer, Andersson, Larsson, Alsson, & Pers, 2004; Ripa, Leone, Garnier, & Porto, 2006). In many cases, NPS pollution is mainly caused by agriculture (Hoorman et al., 2008; Angima et al., 2002), due not only to the use of fertilizers, pesticides, sludge, compost but also to agricultural practices (Nyakatawa et al., 2001; Morgan, 1992; Brown et al., 1984)that favour the release of these products into the environment (Leone & Marini, 1993; Onori et al., 2006). The water bodies can easily be polluted by nutrients, like Nitrogen and Phosphorus, that are turned out to be the most polluting ones, if they are adjacent to agricultural fields (Chung, Kim, & Kim, 2003). The outflow mechanism and nutrient migration are well known, but these processes are very complex, variable in space and time.

The eutrophication process consequently is widespread in most water bodies, present in industrialized areas or where extensive agriculture is practiced. These water bodies are characterized by a long time turnover, which causes a degenerative state of water quality. This phenomenon therefore affects equally the seas, rivers and lakes that present these conditions everywhere in the World (Recanatesi, Ripa, Leone, Perini, & Salvati, 2013; Wang & Pant, 2011).

For instance, at the case of the Black Sea, since the 70[s], occurs this phenomenon due to the increase of phosphorus and nitrogen caused by human activities, in particular by the use of fertilizers. The effects of eutrophication became evident in 2000 when on 14,000 km^2 of the total surface of the Black Sea,

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CONTACT Chiara Giuliani ✉ chia.giuliani@uniroma1.it ▢ Department of Architecture and Design, Sapienza University of Rome, Rome, Italy
*These authors contributed equally to this work.

brown algae were supplanted by green and red algae controlled by cyanobacteria, that produces potent toxins also to humans.

Others examples in the World are the Lake Okeechobee and the Lake Ontario. The Lake Okeechobee in south-central Florida, is significantly damaged by the increasing levels of nutrients, come from anthropogenic activities that lead to eutrophication. (Chebud et al., 2011).

In the Lake Ontario, according to the Chen and Driscoll (2009) study, there are chemical inputs directly connected to the land use/land cover (LULC) pattern, which in the case of the observed sites along the New York coast corresponded with forests and agricultural land. Agricultural activities mobilize more nutrients than other land uses. In fact, it has been found that the concentration of nutrients increases according to the Spatial Gradient in the rivers, varied with seasonal discharge patterns and agricultural land drainage system: concentrations are generally low during the summer-growing season, increased markedly during fall and decreased during winter and spring.

Also in China, a study conducted on the Yangtze River (also known as Blue River) proved that the total and the inorganic-diluted phosphorus export flows, causing eutrophication processes, are connected to the river outflow and derive mainly from non-agricultural sources and from point sources of industrial waste and residential waste water discharges (Shen, Li, & Miao, 2011).

In Italy most of the lakes of the central regions are affected by the eutrophication phenomenon: Bolsena Lake, Vico Lake, and Bracciano Lake, that is our studied site (Piccinno et al., 2019).

A long-term monitoring project carried out in the Vico Lake basin demonstrates that land use (LU) and slope represent a limiting factor in phosphorus (P) mobilization consequently to the same climate event (Recanatesi et al., 2013).

Bracciano Lake, that is our studied case, represents one of the many lakes of the central Italy affected by the eutrophication phenomenon.

A long-term monitoring project carried out in the Vico Lake basin, that presents an assessment similar to Bracciano Lake, demonstrates that land use (LU) and slope represent a limiting factor in phosphorus (P) mobilization consequently to the same climate event (Recanatesi et al., 2013).

In this context, the aim of the present study is to quantify for the Bracciano Lake the relative increase of eutrophication status related with the reduction of the water body for the observed period (between 2015 and 2017) and that allows us to define the degree of vulnerability of the lake ecosystem. Another purpose of this study is to arrange a monitoring tool useful for assessing the vulnerability of water bodies exploited for water supply.

The study required to proceed by steps as follows: (i) Georeferencing, digitization and modeling of bathymetric map of the water body; (ii) Creation of a Land Cover Map (LCM) by application of supervised classification of Sentinel-2 images; (iii) Estimation of urban expansion (Sprawl); (iv) Estimation of the total phosphorus (P) load at the basin scale at crisis (2017) and before crisis (2015), using Vollenweider model.

Materials and methods

Study area

Bracciano Lake (42°07′16″N 12°13′55″E) is a lake of volcanic origin, part of the Regional Natural Park complex of Bracciano-Martignano lake, which is included in the Natura 2000 Special Protection Areas (SPAs) and Sites of Community Importance (SCI), Habitat Directive (Council Directive 92/43/EEC of 21 May 1992). The observed lake is located in the Italian region of Lazio, 30 km northwest of Rome.

Concerning the LU of the watershed, it is characterized mainly by natural (30% of the total catchment basin) and agricultural land uses (64% of the total catchment basin), that can negatively influence the freshwater ecosystem while the anthropic settlements represent a small area (7% of the total catchment basin) (Figure 1).

By analysing the trend of the lake's water level, we can observe a continuous decrease, starting from the summer of 2016, with the negative peak reached in the summer of 2017 (ACEA, 2017). Water crisis of Bracciano lake with such intensity has never occurred before. The two key factors that can cause water shortage are the weather conditions and the water demand. According to the rain gauges managed by Acea Ato2 (Acea Ato 2 manages the integrated water supply service for Area No. 2 Central Lazio), the average quantity of rainfall in Rome in 2017 was the lowest recorded since 2009 (ACEA, 2017). It is confirmed also by the archived data of Bracciano Lake's weather station (Table 1), that reported significant decrease of rainfall in 2017. The months in which relevant water scarcity were experienced are: June (2,4 mm of rain), August (0,0 mm of rain), and October (1,6 mm of rain). Comparing the above reported data with the rain data referring to 2015, (June: 20,8 mm of rain, August: 116,9 mm of rain, October: 173,4 mm of rain) we can perceive how significant the decrease of precipitation was in 2017. Moreover, the elevated water consumption for anthropogenic usage was another unfavorable factor, that caused greater water-reduction at Bracciano lake in 2017, when the freshwater withdrawal from the lake by ACEA Ato2
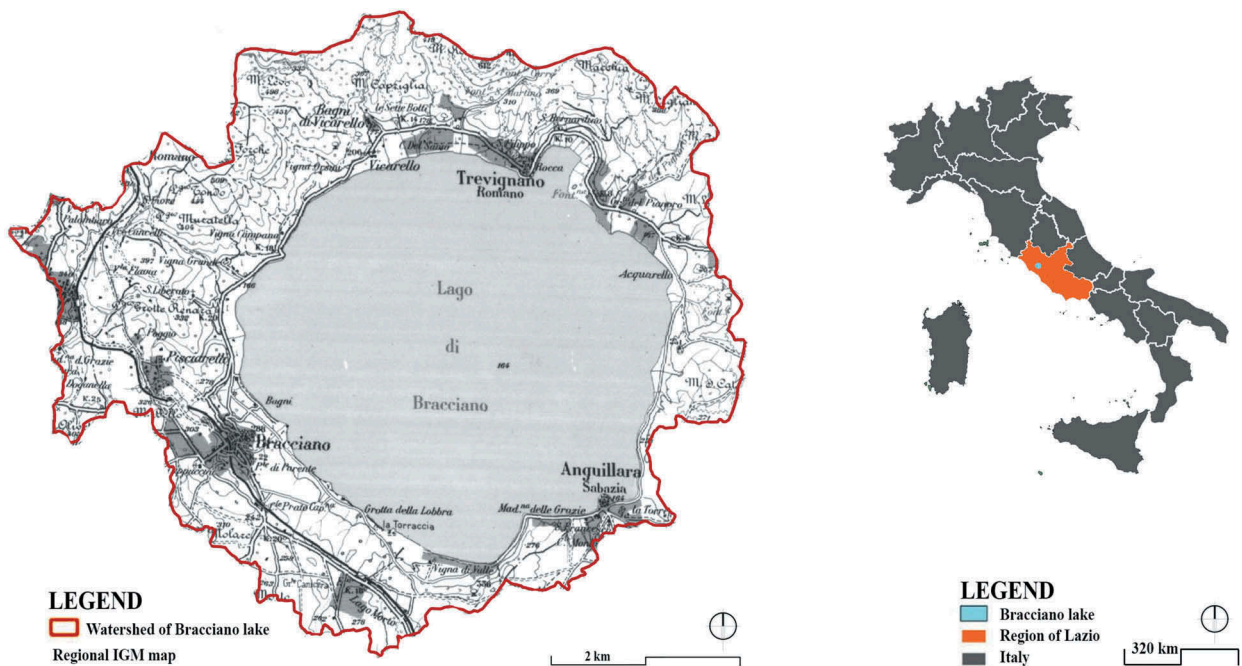
Figure 1. Regional map with the delimited Bracciano lake watershed.

Table 1. Precipitation data in the analysed period, Weather Station: Bracciano Lake Basin.

YEAR/MOUNTH	Jan.	Febr.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
2015	85.9	172.5	215.3	69.5	43.9	20.8	0.2	116.9	88.9	173.4	17.8	2.8	1007.9
2016	73.5	176.6	54.9	19.8	55.8	65.1	5.6	3.6	211.7	144.9	132	18.6	962.1
2017	61.9	48.9	33.2	38.3	11.7	2.4	1	0	114.4	1.6	127.2	161	601.6

Source: Official website of "Centro Funzionale" of Lazio region.Unit: mm of rain
http://www.idrografico.roma.it/annali/

increased steadily, reaching 1,400 mc/s at the beginning of August 2017 (ACEA, 2017). The average amount of captations from the lake was about 49,5% more between January and July in 2017, than at the same period in 2016. And hence during the summer of 2017, as result of water supply, evaporation and the lack of rainfall, Bracciano Lake experienced serious water deficits with water decrease of 1.81 m below the hydrometric zero established at 163.04 m a.s.l. The water level has continued to decline in November 2017 with a total decrease of 1,98 m a.s.l. (Figure 2). Such a fall in water level has serious consequences for its ecosystem, biodiversity, tourism, while the lake's self-purifying capacities and its degree of eutrophication have also been affected.

Data set and modelling

In order to reach our goals, we applied remote sensing of satellite images and predictive eutrophication models. The
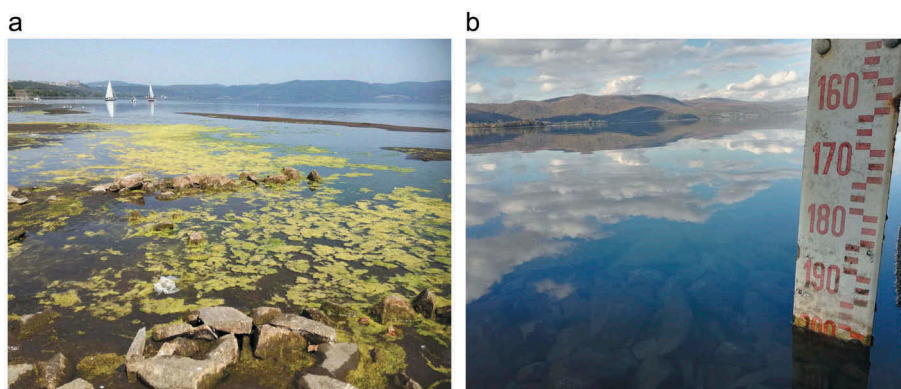
Figure 2. (a) The crisis of Bracciano Lake in pictures (Retrieved from: https://braccianosmartlake.com) a: Algae blooms on Bracciano Lake (Vigna di Valle, 04/08/2017). (b) The crisis of Bracciano Lake in pictures (Retrieved from: https://braccianosmartlake.com) b: The water level of Bracciano Lake on 23 November 2017.

analysis was conducted in two scenarios (2015, 2017) to compare the pre-crisis scenario with the critical one that occurred in 2017. The research process can be overviewed in Figure 3, at the workflow chart, that shows the progress of the data collection, data analysis, and the outputs.

Open access data were collected and analyzed with different Geographic Information System (GIS): ESRI's ArcGIS® for bathymetric modelling, using the "Topo to raster" tool and Quantum GIS® for the production of supervised land use classification.

The Bathymetric layer, collected from the Italian Institute of Hydrobyology (1968) at scale of 1:25 000, was used to model the water body and to estimate the change of the Lake volume between 2015 and 2017.

Supervised Classification of Sentinel-2 satellite images (open access data; European Space Agency; https://scihub.copernicus.eu/; period December 2015 and November 2017) was carried out in Quantum GIS, in order to quantify the surface area of the water body, the coastline, and to create the land cover map referred to 2017 (Darmanto, Varquez, & Kanda, 2017).

The phosphorus export coefficients from each land use class (De Paz & Ramos, 2002; Garnier, Porto, Marini, & Leone., 1998, 1993; Knisel, Leonard, Davis, & Sheridan, 1991; Leone, Ripa, Uricchio, Deak, & Vargay, 2009; Reyes, Raczkowski, Gayle, & Reddy, 2004; Sarmah, Close, Pang, Lee, & Green, 2005; Stallings, Huffman, Khorram, & Guo, 1992), were determined using the Ground water Loading Effects of Agricultural Management Systems (GLEAMS) simulation model. GLEAMS allows to simulate and then evaluate the effects of agricultural practices on the chemical compounds movement in the root zone, the leaching of the same, the percolation and the soil erosion determined by the various cultivation techniques.

The final step was the Vollenweider model, applied to quantify P load and, consequentially, to calculate the vulnerability of the lake ecosystem in terms of eutrophication status (Milstead, Hollister, Moore, &

Walker, 2013; Rana Magar & Khatry, 2017). This model, proposed by the Austrian limnologist in 1976 (Vollenweider, 1976), is very useful for territorial analysis, as it correlates, with considerable simplicity, the P export from a lake basin caused by land use and the lake trophic state. The analysis was conducted in two scenarios, with the estimation of the total P load at crisis (2017) and before crisis (2015).

Bathymetry and edge of Bracciano Lake

The official Bathymetric Layer of Bracciano Lake, provided by the Italian Institute of Hydrobiology and published in 1968, was realized at scale of 1:25,000. In order to quantify the volume of the water body for the two considered scenarios, bathymetric information, and edge shape were conducted in the Geographic Information System (GIS) environment. The scanned Bathymetric map (600 dpi) was georeferenced in WGS 84 coordinate system and digitized. Overall, the digitization process produced: 7,650 points and 20 polylines (Figure 4).

Water body modelling

The bathymetric data and shape edge have allowed us to gain a model with the bottom of the water body (Figure 5). The model was obtained by using the "Topo to raster" tool in ArcGIS 10.3 environment, which allows the creation of hydrologically correct digital elevation models (DEMs). As such, it is the only ArcGIS interpolator specifically designed to work intelligently with edge inputs. The modeling of the bathymetry of the water body was implemented with the digital elevation model (DEM) with spatial resolution of 10 m, Figure 6 shows six different perspectives of the union of the two information layers.
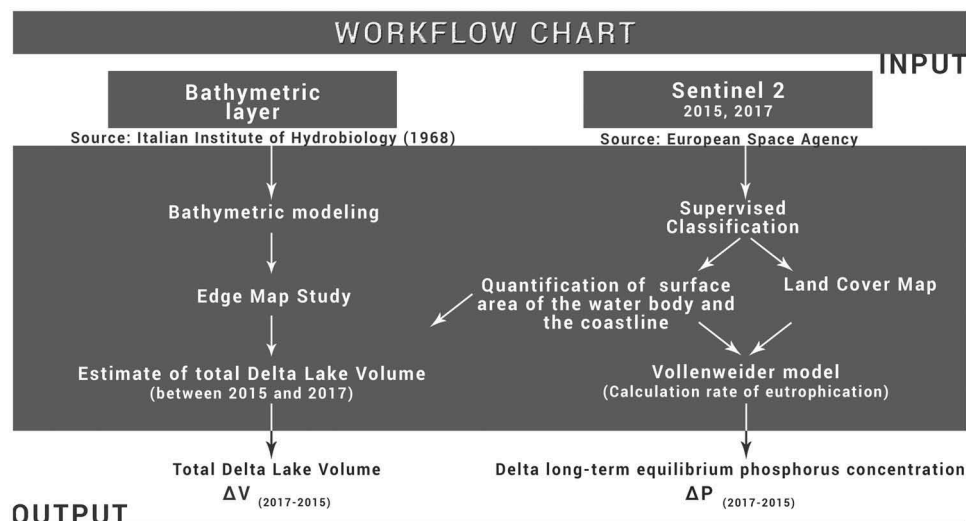

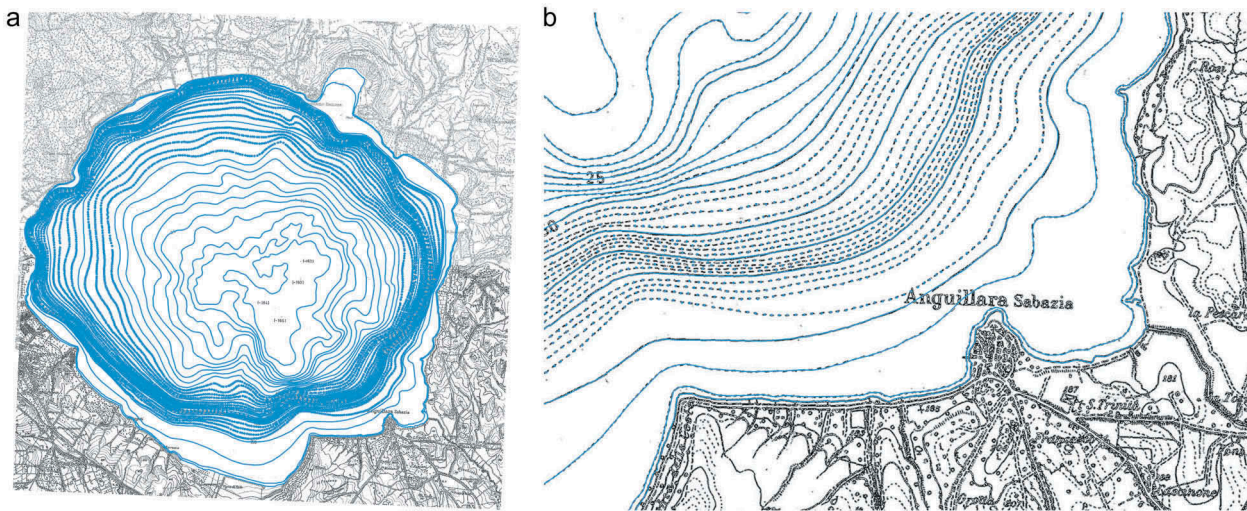**Figure 3.** Workflow chart of the research.

Figure 4. (a) The elaboration process of the digital bathymetric map. Digitalization process: the positioning of points and polyline. (b) The elaboration process of the digital bathymetric map. Digitalization process: the positioning of points and polylines.
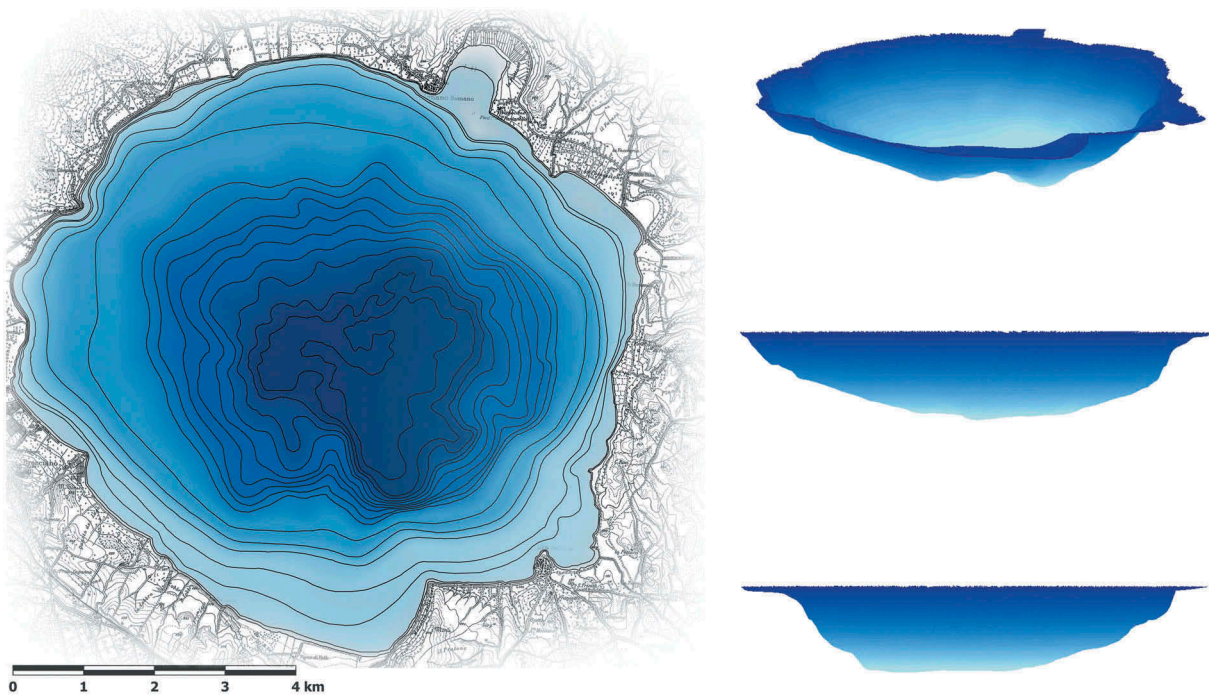

Figure 5. Bathymetry and Edge Map Study, GIS model of the water body.

Supervised classification of Sentinel-2 multispectral images

We applied supervised classification of remote sensing data (Sentinel-2 multispectral images) for mapping land cover (LC) in Bracciano water basin; an image classification technic, that allows to group areas with homogeneous physical characteristics (coverage classes), to create a thematic map showing the main land covers categorized in four main classes: (i) the anthropic area consisting of the whole impermeable surfaces, (ii) the agricultural land, (iii) the water body, (iv) forests and uncultivated areas. We used Sentinel-2 multispectral images, which were processed through the Sen2cor program. Sen2Cor is a processor for

Sentinel-2 Level 2A product generation and formatting; it performs the atmospheric-, terrain and cirrus correction of Top-Of- Atmosphere Level 1C input data. The multi-temporal image datasets, selected for the study area through Sentinel-2 Multi Spectral Instrument (MSI), report a pre-crisis situation referred to December 2015 and a crisis scenario referred to November 2017.

The Land Cover Map (LCM) was created in QGIS, an open-source software, using the semi-automatic classification plugin (Congedo, 2016). Both image datasets (the one, referred to pre-crisis, in December 2015, and the other, to crisis in November 2017) were elaborated. It allowed us not just to produce an LCM,
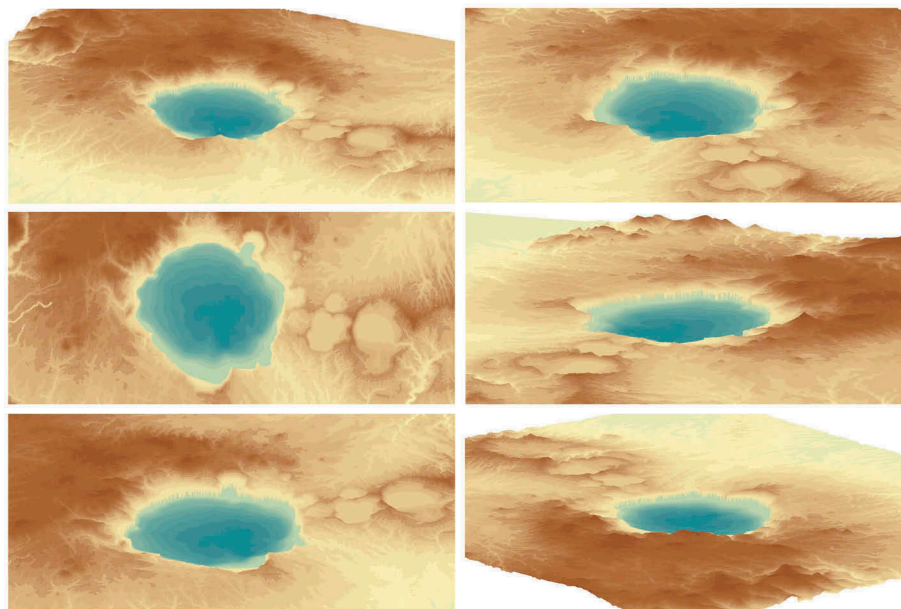
Figure 6. Digital Elevation Model of Bracciano basin.

updated to 2018, but also to isolate the water body from the rest of the basin area and to quantify the land cover classes of the water area and the variation of the coastline (Figure 7).

Having a detailed bathymetric map and the lake area in the 2 years, the volume of water (3) was calculated for the two scenarios (2015, 2017).

Supervised classification was elaborated through the Spectral Angle Mapper (SAM) algorithm that quantifies the spectral angle between the spectral signatures of the image pixels and the spectral signatures of the training polygons.

According to (Congalton, 1991), the validation process was based on the random distribution (for each land cover class) of 50 control points for each identified land cover class if the cover card reports less than 12 classes of coverage. The control points were checked with information layers with higher spatial resolution and a confusing matrix was constructed.

The land cover map, updated to 2018, and the Vollenweider model allowed us to estimate the phosphorus concentrations that contribute to the eutrophication of the water body.

Phosphorus load – vollenweider model

The Vollenweider model (1) correlates the trophic state of a lake with the long-term equilibrium phosphorus [P] concentration, [µg/l] (2) with anthropic activity and with the morphology of the relevant catchment basin.
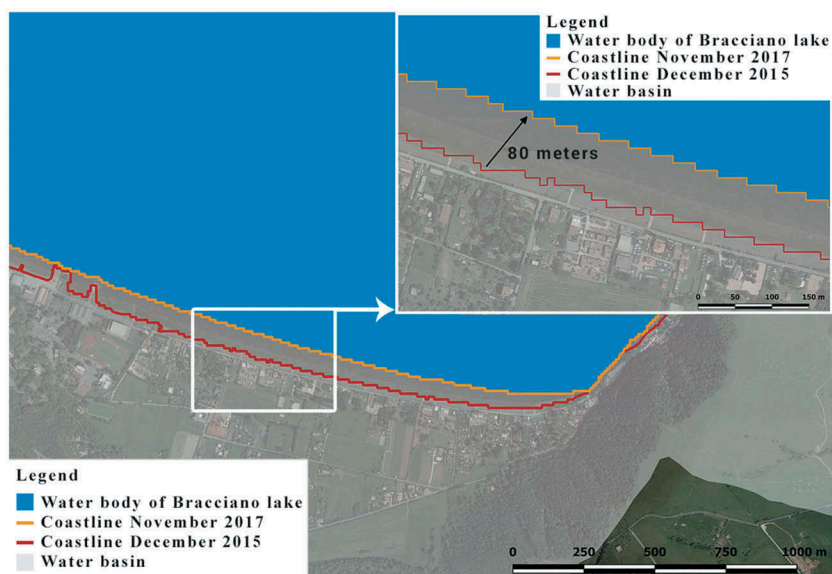

Figure 7. Coastline and the surface area determination.

$$[P]\infty = \frac{L(P)tw}{Z(1 + tw)} \qquad (1)$$

where

[P] = long-term equilibrium R

Z = average depth of the lake, [m];

tw = theoretical renewal time of lake water, [years].

L(P) = specific surface load, [hg/km^2]

$$L(P) = CfAf + CagAag + CuAu + CaA0 + Cst * Na \\ * (1 - SR) \qquad (2)$$

where

Cf = export coefficient for the forest territory;

Cag = export coefficient for the agricultural territory;

Cu = export coefficient for urbanized areas;

Ca = export coefficient from atmospheric contributions

Cst = export coefficient related to the impact on the lake of the urban waste system;

Af = forest area (ha);

Aag = agricultural area (ha);

Au = urbanized area (ha);

Ao = area of the lake (ha);

Na = number of inhabitants served by septic tanks (leaking);

SR = coefficient linked to soil retention factors.

For each LU classes, the phosphorus export coefficients (Table 2) were determined using the GLEAMS simulation model, Ground water Loading Effects of Agricultural Management Systems (De Paz & Ramos, 2002; Garnier et al., 1998; Knisel, 1993; Knisel et al., 1991; Leone et al., 2009; Reyes et al., 2004; Sarmah et al., 2005; Stallings et al., 1992).

The (SR) coefficient, linked to soil retention factors, has been defined equal to 0, assuming that all the nutrient produced reaches the lake because of the morphology of the basin and the shape of the volcanic caldera.

We obtained the land use areas (Table 2) considered in the Vollenweider model using Supervised Classification of the land cover map, the total Urban Area (697.76 ha) was divided between the building served by the sewer service and the sprawl, within a distance of 300 m from the urban area, that could leak nutrients by the septic tanks.

The (Na) coefficient was obtained photo-interpreting Google Earth aerial images of the year

2018 and was quantified in 8,763 sprawl units and considering an average of 2 residents per unit (17,526 habitants estimated).

Results

The conducted bathymetry and the water shape (coastline) edge map in Geographic Information System (GIS) environment allowed us to quantify the volume of the water body for the two considered scenarios (pre-crisis situation in December 2015 and crisis in November 2017).

The coastline and the surface area analysis (Figure 7), correlated to the modelled bathymetry data, lead us to assess the volume of the water resources and its delta between the two periods (3). The above-mentioned maps (reported in Figures 7 and 8) were produced at high-level accuracy (approaching 100%). This particularly high degree of accuracy is mainly due to the homogeneity of the water body coverage class during spectral signature evaluation and its uniqueness in the watershed area (it is hard to be confused with any other class of land cover).

The aggregated data concerning the morphometric characters of Bracciano Lake (volume, surface, average depth, theoretical renewal time of lake water) in the two scenarios (in 2015 and in 2017) are reported in Table 3.

$$\Delta \text{WATER BODY SURFACE} (2015 - 2017) = 88.44 \text{ ha}$$
$$2015: \quad V(m3) = 41.9 * 10^8$$
$$2017: \quad V(m3) = 40.5 * 10^8$$
$$\Delta V(m3) = 1.3 * 10^8$$

$$(3)$$

where V = volume of water (m3)

The Land Cover Map (Figure 8), produced by the supervised classification of Sentinel-2 satellite imagery, referred to the most recent time scenario of 2018, shows the natural and semi-natural classes, respectively, of: 30% and 64%. The anthropic surface corresponds to 916.84 ha, is about 7% of the total area of the Bracciano water basin. The graphs below summarize the extent of land cover classes (Table 2).

The accuracy of LCM, produced for the 2018 time scenario is equal to 91%. Specifically, the class that reports the highest degree of precision is the class that identifies the body of water (100%), followed by the forest with 94% while those that have reported lower levels of reliability are: the urban class and the one that identifies the agricultural area, both with accuracy values of 84%.

The accuracy of the three above mentioned maps, produced in this research (two that determined the water body and one that reported the land cover data for the entire water basin) was calculated according to the confusion matrix (Story & Congalton, 1986). The realization of the matrix made it possible to verify the

Table 2. Land cover classes surface and export coefficients.

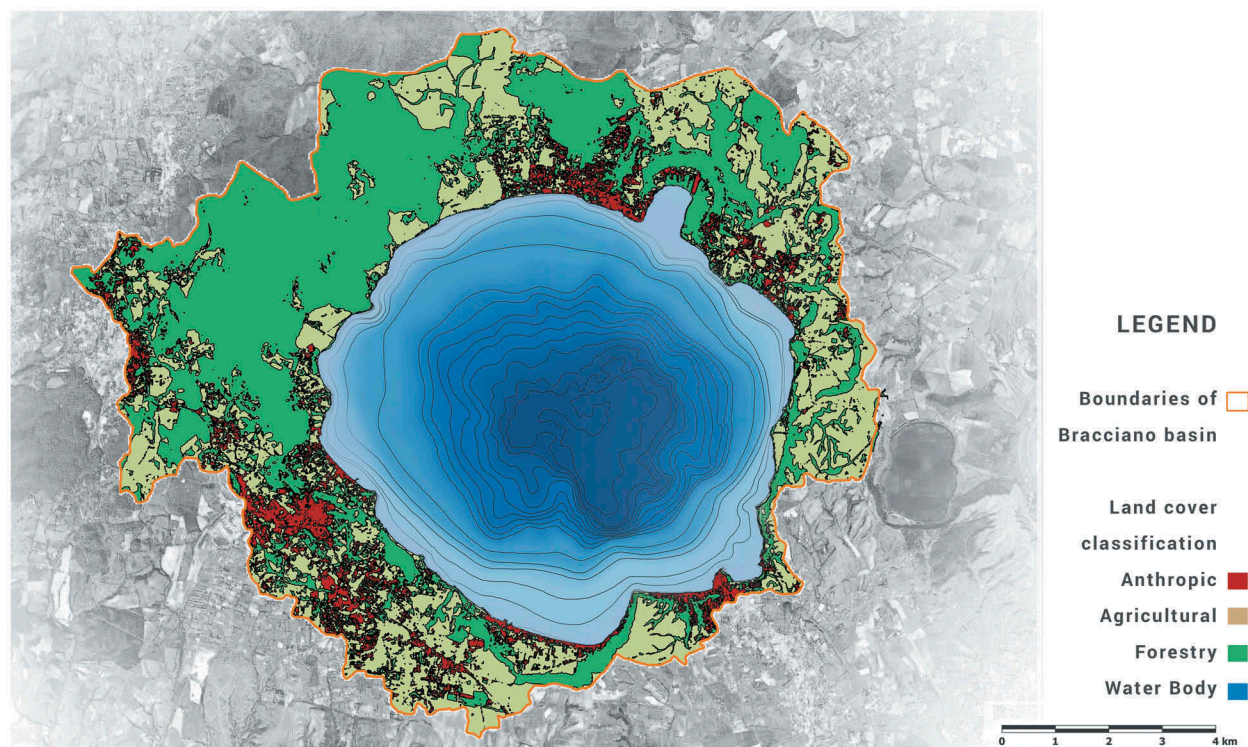| Land Cover Surfaces	(ha)	Export coefficients (GLEAMS)
Sprawl	219.08	0.1
Urban Area	697.76	0.6
Agricultural area	8596.24	0.27
Forest/uncultivated	4109.69	0.05
Total Basin Area	**13,403.69**	0.165

Figure 8. Supervised classification, LCM of Bracciano basin.

Table 3. Morphometric characters of Bracciano Lake in 2015 and in 2017.

Year	Volume (m3)	A_0 Surface (ha)	Z Average depth (m)	Tw Theoretical renewal time of lake water (year)
2015 (pre-crisis)	$41.9 *10^8$	5702.33	88.6	137
2017 (post-crisis)	$40.5 *10^8$	5613.89	86.6	137

real correspondence of the randomly distributed control points for each investigated class of land cover (Nguyen, 2015).

Considering the area of each land cover classes, obtained with the supervised classification (Table 2), we achieved the phosphorus amount stems from land use infiltration and urban system (Table 4).

Using the Vollenweider model we obtained the phosphorus load L(P) of 2015 and considering the different depth of the lake in the two scenarios (88.6 m in the 2015; 86.6 m in the 2017) we calculated the P concentration (4).

$$P\infty 2015 = 98.66 \; \mu g/l \; P\infty 2017 = 100.93 \mu g/l \; \Delta P\infty \\ = 2.28 \; \mu g/l$$

$$(4)$$

In 2015 (98.66 μg/l), we estimated in 13.78 tons the P which caused an increase of the total trophic level in 2017.

Table 4. The phosphorus level.

P origin	P kg/year 2015	P kg/year 2017
Forest/uncultivated	410.97	410.97
Agricultural area	5157.74	5157.74
Sprawl	59.15	59.15
Atmospheric contributions	285.12	280.69
Urban waste system	2891.79	2891.79
Total L(P)	8804.77	8800.34

The results of this study show the eutrophic state of the water basin in 2015 that recorded a deterioration in the scenario referred to November 2017, motivated mainly by the reduction of the water volume. A reduction of 3.33% of the water volume was observed, with an increase in the amount of phosphorus of 2.3% per liter. The decrease in rainfall has certainly contributed to increasing the trophic load of the water body but what has most affected was the improperly managed anthropic sampling. This study allows us to affirm that the level of eutrophication of the water body would have been less in the absence of anthropogenic pressure. The increased eutrophication level can be justified also by the reduction of the surface in the first part of the coast where the major Phytodepuration processes take place.

According to the lake water quality classification proposed by the OECD (OECD, 1982), currently, the lake is classifiable as a very eutrophic lake that has reached a slightly hypertrophic level in the period of water crisis.

Conclusions and discussion

In order to respond to the researchers and managers' necessity to understand freshwater ecosystem vulnerability (Angeler et al., 2014), the present research was

carried out with mixed method analysis to develop an effective and reliable conceptual model for long-term monitoring of freshwater ecosystems. The data modelling, related to the bathymetry of Bracciano lake water body, allows to provide high quality information to evaluate the volume of water resources. The application of Remote Sensing data and the Vollenweider model have allowed us to estimate the critical nutrient load that affects Bracciano Lake and to define its trophic status according to the trophic classification scheme for lake waters proposed by the O.E.C.D. (OECD, 1982).

Remote Sensing data have allowed us to empirically study vulnerability patterns in ecosystems at the case study of Bracciano Lake that helped us to set up a long-term monitoring approach. The methodology used in this study is easily replicable to monitor other basins, demonstrates excellent process reliability, while it offers a low-cost approach for assessing and managing freshwater ecosystem vulnerable to environmental changes. That is why the proposed method represents an efficient monitoring tool for assessing the vulnerability of water bodies influenced by eutrophication. However, being a tool for long-term monitoring, it cannot predict sudden regime shifts or unexpected changes in ecosystems. Nonetheless, this cognitive tool improves our knowledge of ecosystem responses to environmental changes, so could provide support for decision making in the future.

Acknowledgments

Disclosure statement

ORCID

Chiara Giuliani 🔟 http://orcid.org/0000-0001-7521-5442
Adrienn Caronte Veisz 🔟 http://orcid.org/0000-0002-0373-6377
Matteo Piccinno 🔟 http://orcid.org/0000-0002-9012-4204
Fabio Recanatesi 🔟 http://orcid.org/0000-0002-1173-4240

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