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Land Use, Phosphorus Pollution and Risk Assessment for the Bolsena Lake (Italy). An Estimation Using Remote Sensing and Multi Criteria Analysis

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Abstract. This study aims to assess the sustainability of the Land Use (LU) in the water basin of Bolsena Lake (Italy), by measurement of eutrophication status. The total annual phosphorus (P) load was quantified using the simulation model Groundwater Leaching Effects of Agricultural Management Systems (GLEAMS). The Multi-Criteria Analysis (MCA), conducted in accordance to the fuzzy logic, has allowed us to define the Risk Map that shows areas of environmental vulnerability with regards to eutrophication processes. Finally, areas were identified through meta-planning to introduce BMPs (Best Management Practices), that represent a useful tool to reduce nutrients loads, that reach the water body causing eutrophication. The main results obtained show that the total (P) produced in the water basin is 92 tons/year, while four Risk classes were defined according to their vulnerability of the territory to release nutrients. A detailed phytodepuration plan were proposed, that could reduce from 30% to 60% the phosphorus load per year. Both the GLEAMS model and the MCA are found to be essential tools to quantify the factors causing the eutrophication and to identify the most critical areas.

Keywords: Risk assessment · Remote sensing · Multi Criteria Analysis · Bolsena Lake

1 Introduction

Over 75% of Earth's land is substantially degraded, undermining the well-being of 3.2 billion people, according to the report released in 2018 by the Intergovernmental Science-Policy Platform on Land Degradation and Restoration [1]. Soil erosion is a key driver of land degradation process that often cause pollution due to the nutrient's transport with serious consequences, like the loss of soil fertility and eutrophication of water bodies. In these processes, phosphorus (P) and nitrogen (N), commonly used in agriculture can be considered as limiting factors [2–6]. The environmental impacts of non-point source pollution on water quality degradation are of a great concern because produce eutrophication [7]. Non-point source pollutions (NPSs) are caused by two

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essential processes [8]: (i) runoff and infiltration of rainfall or snowmelt, that results in groundwater flow carrying nutrients and pesticides into the water bodies. (P) is rarely transported in this way, only in special cases as organic compounds; (ii) soil erosion, involves phosphorous particulate bound to the sediment [9].

In this context, lakes and ponds are particularly vulnerable to eutrophication [10]. There are several examples worldwide showing the impacts of eutrophication on water bodies, e.g. coastal waters of Black Sea showed this phenomenon since the 1970s.

At the end of the 60^{s} in Europe, the water pollution-point sources were greatly reduced thanks to their relatively easy identification and to the constant development of the purification techniques [11]. The pollution produced by NPS are still cause for concern with respect to the water quality standards [12], especially in the Mediterranean Region where the erosion processes are more frequently caused by changing seasons and climatic patterns: long dry summer periods followed by heavy rainfall periods [13].

NPSs are determined by the land management that can influence the sediment production and the chemical loads, by the hydrology of the water basin and by other processes such as the nutrients detention [14–18].

The Water Framework Directive (2000/60/CE) commits European Union member States to achieve good qualitative and quantitative status of all water bodies. Moreover, it also indicates how to plan mitigation actions, based on the ecological characteristics of water bodies and their variability, in order to secure the water quality. It is therefore necessary to evaluate the effectiveness of the BMPs (Best Management Practices) considering the time difference between the effective and the expected implementation of the improvements in water quality [11, 12].

BMPs are conservation practices in agricultural areas, that represent an effective tool that farmers can utilize to reduce nutrient losses in the watershed, protect water quality while ensuring the economic sustainability.

This paper aims to define the impact of non-point phosphorus sources entering the Bolsena Lake (Italy) and introducing correct BMPs measures for reducing eutrophication. To reach these goals, the following objectives were carried out:

(i.) Application of the GLEAMS model, Groundwater Leaching Effects of Agricultural Management Systems to quantify (P) load at basin scale [19, 20]; (ii.) Update of the Land Use Map (LUM) of Lazio Region with 2018 digital orthophotos; (iii.) Identifying most critical (P) release areas in the watershed by a Multi Criteria Analysis [21–28]; (iv.) Identifying most suitable areas for BMPs introduction and mitigation of P losses at the basin scale; (v.) Preliminary individuation of the location and of the typology of filter bands to reduce the nutrient in-take in the lake.

2 Materials and Methods

2.1 Study Area

The catchment area of the Bolsena Lake (42° 35’41.05” N; 11° 56’11.39” E) is located in the northern part of the Lazio Region, in Central Italy (Fig. 1) and presents an area of 271 km^2. The water body surface is about 114 Km^2 with a maximum depth of 151 m, a mean depth of 81 m. The lake has no tributaries and the only effluent is the Marta River. The water renewal time was estimated in 121 years [29] while the land area (156 Km^2) represents the 58% of the total basin extension [30–32].

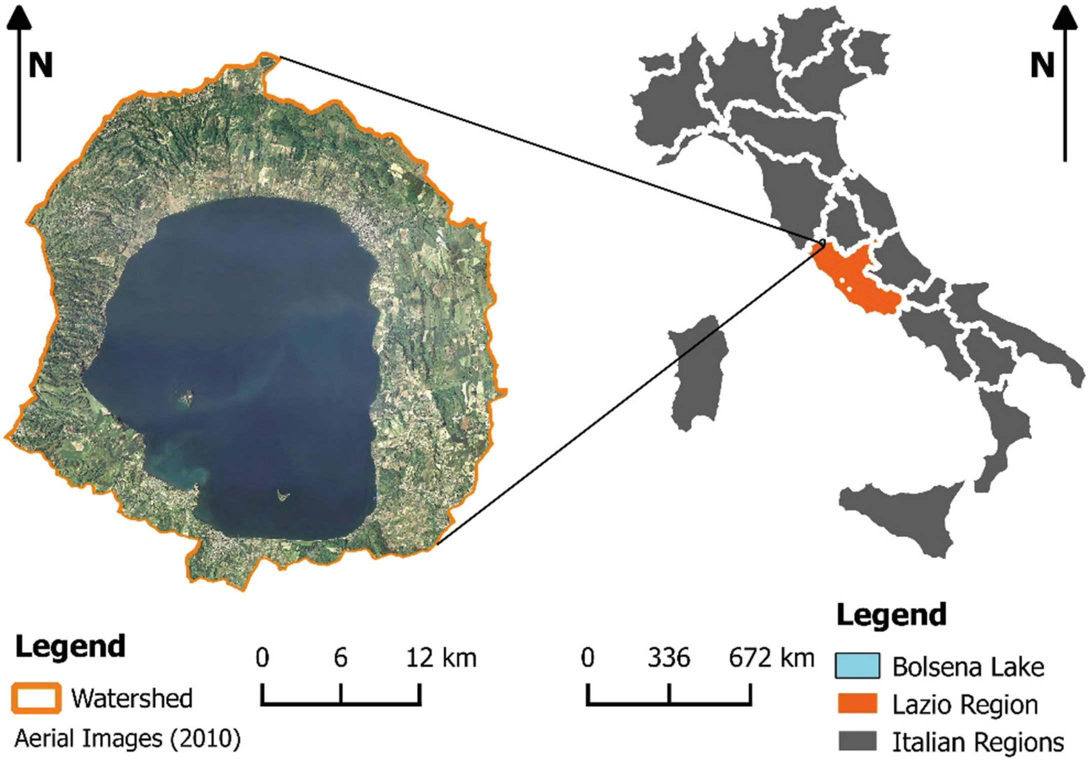

Fig. 1. Geographic location of Bolsena Lake.

On the study area, there is a SPA (Special Protection Area) “Lake Bolsena and Islands Bisentina and Martana” (IT 6010055) and two SCI (Sites of Community Importance) “Bolsena Lake” (IT 6010007) and “Islands Bisentina and Martana” (I 6010041).

In the last fifty years the increased tourism and anthropic pressures caused a greater transport of nutrients into the lake. The present phosphorus concentrations show that the deepest zone of the lake is in a mesotrophic condition [29].

2.2 Total Phosphorus Load

The total (P) load was determined using the simulation model: GLEAMS [12, 33–37]. The photo interpretation of aerial images referred 2018, field surveys and the interviews with the landowners allowed to determine the type of fertilizer used, the tillage performed, and the crops currently cultivated in the catchment area. Therefore, eight land use (LU) classes were determined according to Corine Land Cover project (https://www.copernicus.eu/it) (Table 1).

Table 1. Land use classes

Land use GLEAMS	Corine land cover class
Forest	Forests 3.1.
Uncultivated	Pastures 2.3.1.
Ryegrass-corn	Permanently irrigated land 2.1.2.
Medical	Non-irrigated arable land 2.1.1.
Conventional hazel	Fruit trees 2.2.2.
Grassy hazel	Fruit trees 2.2.2.
Cropping vegetables	Permanent crops 2.2

The LU and the slope gradient represent the main limiting factor in the transport of nutrients and in the calculation of the removal coefficients within the GLEAMS model [38–41]. For this reason, the Land Use Map (Fig. 2) was updated in the Esri ArcMap® environment, obtaining the total area and number of patches for the year 2018. The LU map was implemented also with the streets network and sprawl layers realized *ad hoc* for the present study.

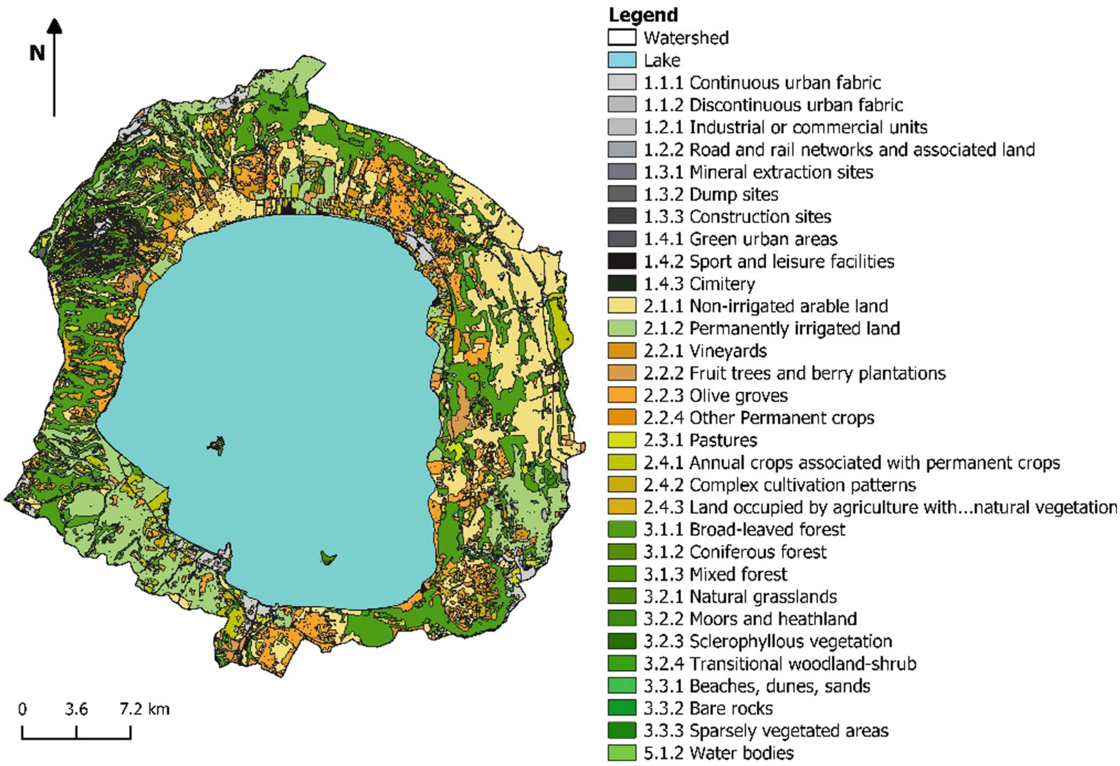

Fig. 2. Land use map 2018.

2.3 The Multi Criterial Analysis

The LU map was classified in order to obtain a sustainability map. This map allowed us to define five sustainability classes, expressed in percentage values, considering the specific land use trend to release phosphorus into the environment: the class 0 represents urban areas, so not a P source, while the class 75-100 represents the least sustainable one (Fig. 3).

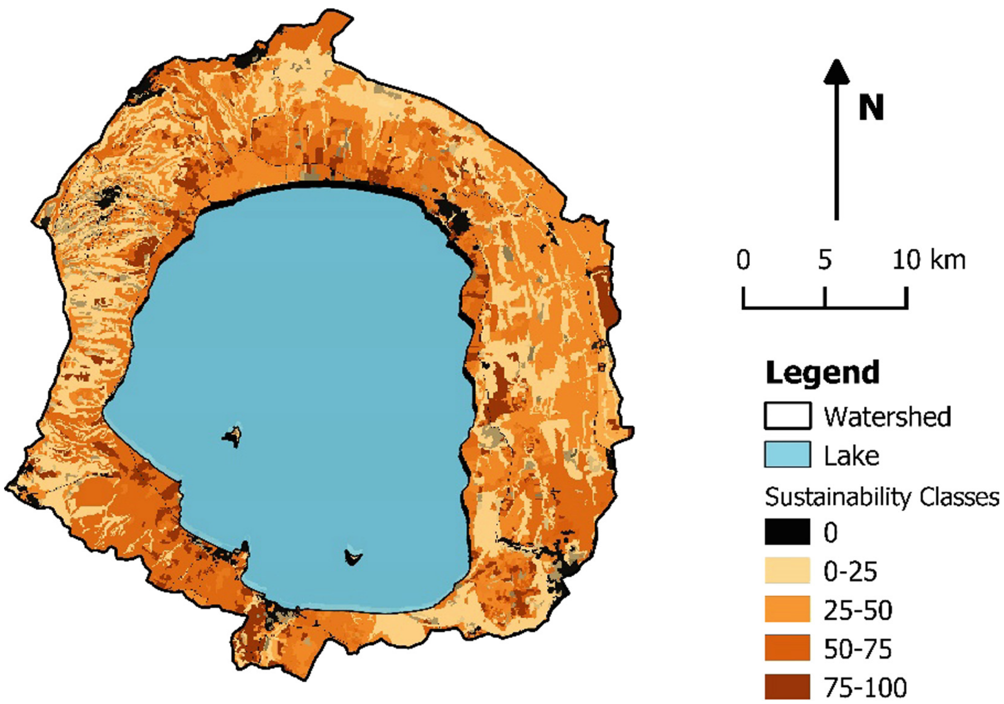

Fig. 3. Sustainability map.

At the basin scale, the LU classes less sustainable (Class 75-100) are:

- Annual crops associated with permanent crops (2.4.1.).
- Fruit trees and berry plantations (2.2.2.). In our case Fruit trees are represented by Hazel trees.
- Complex cultivation patterns (2.4.2.).

To define how the nutrients are released and moved in the water basin, considering the LU Sustainability, a Multi Criteria Analysis (MCA) [21–25] in GIS environment was conducted. This investigation method applies the fuzzy logic, theorized by Lotfi Zadeh in 1965. This calculation includes five steps: fuzzification of attributes, generation of joint membership values, generation of fuzzy rules, aggregation of the fuzzy rules, and defuzzification to find the crisp suitability index [42–44].

In this analysis, restricted to the water basin boundaries, the layers used are:

1. Sustainability Map
2. Slope Map (%), obtained using the Digital Elevation Model (DEM) (40×40 m) provided by the Lazio Region;
3. Maps obtained with the classification based on the extension of the polygons included in each LU layer for the three classes less sustainable:
    - Annual crops associated with permanent crops

- Fruit trees and berry plantations
- Complex cultivation patterns.

The result of this MCA is a Risk Map that allowed us to fix four Risk Classes (%) and to create the High-Risk Class layer showing the highest values (Fig. 4).

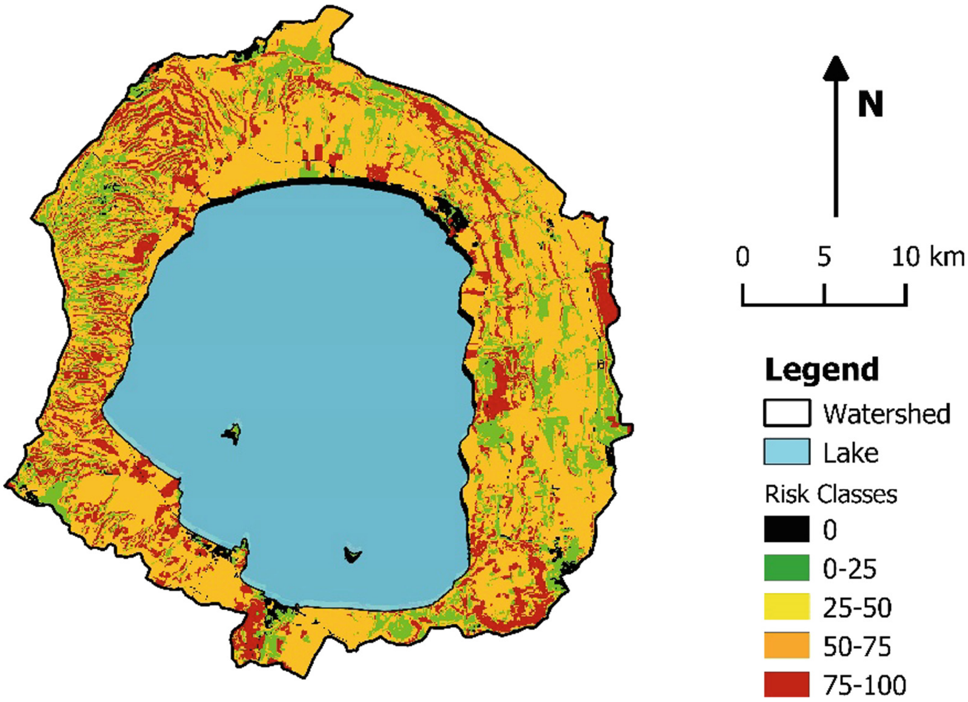

Fig. 4. Risk map classes (%).

Using the MCA, we identified the better sites where BMPs could reduce the nutrients that would be transported to the lake. For the layers included in the analysis we defined the direct or inverse proportionality with the suitability to host BMPs solutions:

1. Risk Map: growing trend;
2. Slope Map, obtained through the Digital Elevation Model (DEM) (40×40 m) of the Lazio Region: decreasing trend;
3. Urban Centers Map: constraints to exclude them in the analysis, because they could not host phytodepuration systems;
4. Five Zoning Maps, with a decreasing trend, obtained with the classification of the watershed based on the distance from the considered layer, for the following maps:

   - Hight Risk;
   - Lake;
   - Hydrographic network;
   - Road network;
   - Sprawl.

The resulting map (Fig. 5) presents higher values for areas where the risk of release nutrient is high, where they would be transported but also where the orographic conditions are compatible with a BMP installation. This map was finally classified to define the areas with an extension greater than 5000 m^2, in which is possible to realize a BMP system of phytodepuration.

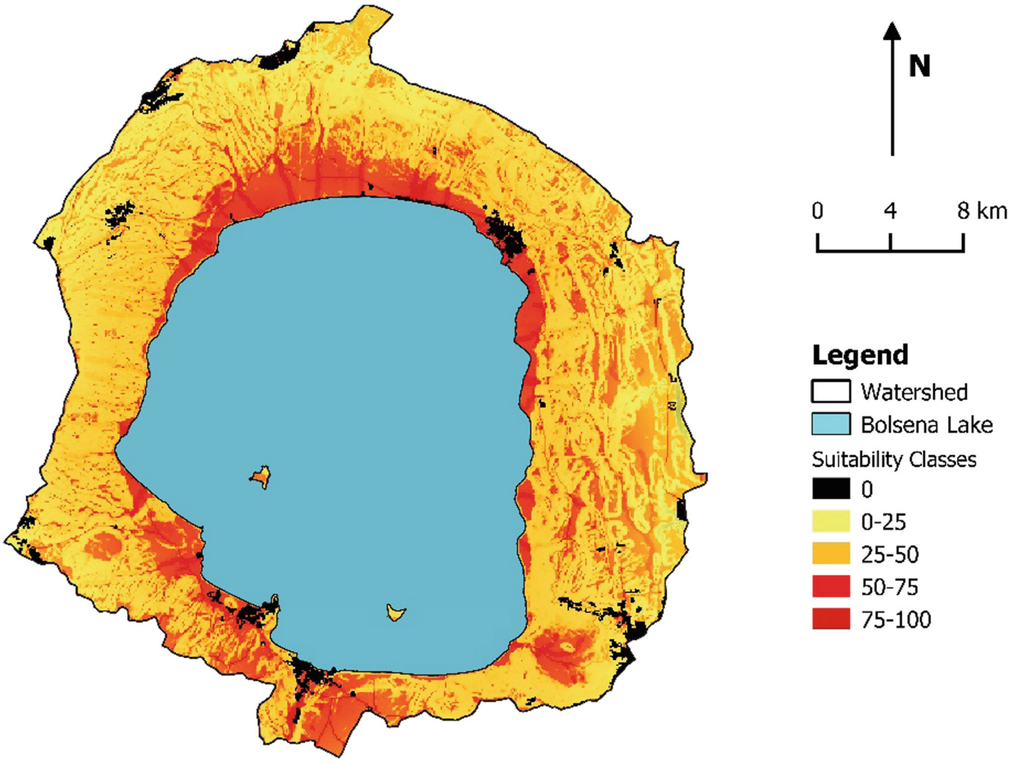

Fig. 5. BMPs suitable map.

3 Results

The Land Use Map, updated to 2018, was used in the simulation model GLEAMS to determine the load of nutrient (kg/ha) produced by each land use class in 2018, and therefore quantify the total P produced in the water basin every year, that is 92 tons/year (Table 2).

Table 2. Phosphorus load at watershed scale

Land use GLEAMS	Corine land cover class	TOT. P (Kg)
Forest	Forests 3.1.	10263.55
Uncultivated	Pastures 2.3.1.	10014.20
Ryegrass-corn	Permanently irrigated land 2.1.2.	8510.48
Alfalfa	Non-irrigated arable land 2.1.1.	32530.42
Conventional hazel	Fruit trees 2.2.2.	1410.027
Grassy hazel	Fruit trees 2.2.2.	20275.36
Cropping vegetables	Permanent crops 2.2	9234.07
TOT. P/watershed		92238.12

The Multi Criterial Analysis allowed to define in the basin area four risk classes according to the vulnerability of the territory to release nutrients.

In order to reduce the risk, some of BMPs were suggested:

- Planting hazel groves, that protecting the soil, reduces the erosion and the consequent transport of nutrients;
- Fertilization closed to the roots area, proportional to the quantity assimilated by the plant in the short term and possibly after a rainfall event.

In detail, we suggested (Fig. 6):

- 69 bumps or dips for the correspondent road section with an average length of 358.04 m and a total length of 24.7 km.
- 7 filter bands with an average length of 757.5 m and a total length of 5.3 km.
- 12 wet ponds with an average area of 23.3 ha and a total extension of 280 ha.

We have excluded the urban areas (*Contraints*) from the analysis because they do not contribute to the introduction of phosphorus into the water body.

The realization of these BMPs solutions, as reported in several studies, will potentially reduce by 30 to 60% the phosphorus load per year [45].

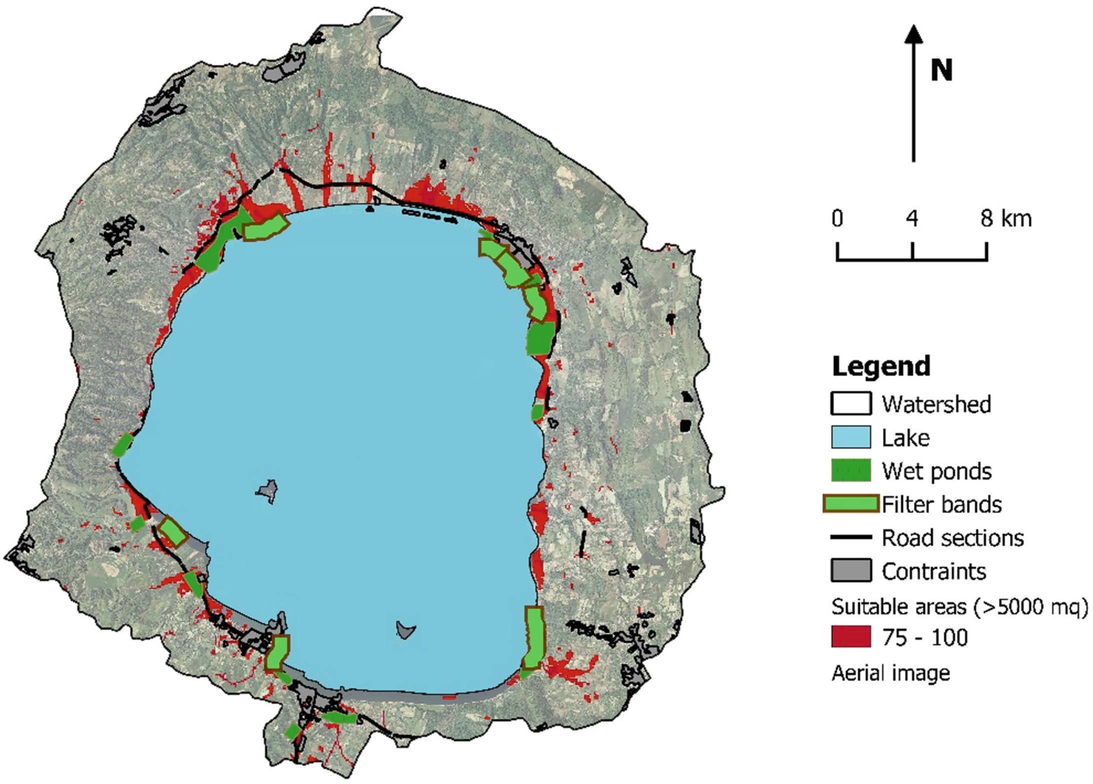

Fig. 6. Sites suggested to install BMPs.

4 Discussion and Conclusions

The degenerative status of Bolsena Lake's water quality is due to the excessive trophic load, in particular to the P. The sewage had a central role in the eutrophication processes in the seventies and eighties, when the water quality was deteriorated. In the 1996 the lake water was prevented by a sewage collector from the main population centres to a treatment plant located about three km from the lake. Therefore, the NP sources are the most important sources of pollution and they are caused by the agricultural activities. The analysis on the sustainability of the land use identified the main limiting factors in relation to these processes with the land use and the morphology.

The model used (GLEAMS), as well as the Multi Criterial Analysis (MCA), resulted both essential tools to quantify the factors causing the eutrophication and to identify the most critical areas.

In the last point, the study identified the better BMPs, mainly phytodepuration plans, and their location in a meta-project. The BMPs are necessary, in the general river basin management, to preserve and protect the most important SPA and the two SCI sites involved.

This study calls attention to obtain analytical instruments to plan actions at basin-scale with a focus on the correct planning. The adoption of less polluting management practices is driven by farmers' perception of their effect on profitability, but public incentives and environmental legislations could also promote the adoption of these practices.

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