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Evaluation of Aquatic Ecosystem Health Using the Potential Non Point Pollution Index (PNPI) Tool

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1. Introduction

The aquatic ecosystem health is a topic that has been developed by scientific world and local authorities. This study shows numerous aspects of environmental management: one of the most interesting fields is the that investigating the relationships between ecosystem and human health.

An healthy aquatic ecosystem is able to preserve and recovering quickly its structure and functionality against adverse effects due to natural, like floods and landslides, or human causes, like pollution and urbanization.

The degradation of aquatic ecosystems can have important impacts on human health: The ways that water can damage people are different: consumption of contaminated waters and fishes, infections by vectors related to these environments and algal blooms in inland and coastal waters.

The aquatic ecosystem protection come to prominence after the emanation of Water Frame Directive 2000/60/EC (European Union, 2000). The innovative point of WFD is the assessment of water quality entrusted to biological communities and their relationship with human pressures and impacts.

The analysis of four biological elements required, phytobenthos, macrophytes, benthic invertebrates and fishes, describe the ecological status, that represents the functionality of the ecosystems. The concept of "ecological status" is another new point of view in the preservation activities of natural systems, that before took into account only the biodiversity and the preservation of rare species.

Water Frame Directive main objective is to reach a good ecological status for all water bodies until 2015. To achieve this goal, two key steps are needed: the first is the assessment

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of ecological status, then the river management plan in order to preserve healthy ecosystems and restore the damaged ones.

The evaluation of ecological status, as wrote before, required the study of the structures (composition and abundance of species) of the biological elements, giving a global view of different pressures that affect aquatic ecosystem. Main adverse effect are sourced from: nutrients load, organic pollution, hydromorphological alterations.

Biotic communities detect the effect of anthropogenic pressure; evaluate the negative externalities that human activities may have on the water bodies, but cannot be enough for a right management planning of these environments.

The river management plans should include: objectives for each water body; reasons for not achieving objectives where relevant; and the program of actions required to meet the objectives. The restoring actions for the achievement of good ecological status should begin, first of all, by identifying the pressures and the impacts that insist on the water bodies.

Between pressures that affect aquatic communities, eutrophication and organic pollution, generally are not easy to assess. The sources of these pressures could be classified in point pollution sources, and non point pollution sources.

Point pollution sources are linked to those sources "were originally defined as pollutants that enter the transport routes at discrete identifiable locations and that can usually be measured", while nonpoint source pollution was "everything else"(Loague & Corwin, 2005). Point sources of pollution are represented by industrial or municipal wastewater discharges.

Nonpoint pollutants are defined as "contaminants of air, and surface and subsurface soil and water resources that are diffuse in nature and cannot be traced to a point location" (Corwin & Wagenet, 1996). They are linked to agricultural activities (e.g. irrigation and drainage, applications of pesticides and fertilizers, runoff and erosion); urban and industrial runoff; pesticide and fertilizer applications; nitrogen and phosphorus atmospheric deposition; livestock waste; and hydrologic modification e.g. dams, diversions, channelization, over pumping of groundwater, siltation, (Loague & Corwin, 2005, Haycock *et al*., 1993; European Environment Agency, 1999a; Crouzet, 2000; Schilling & Libra, 2000).

Point pollution source are easily identified, and also restoring activities can directly control work on them. Concerning non point pollution sources, they cannot be directly identified, assessed and controlled. One way to evaluate diffuse pollution is by a description of the hydrologic rainfall-runoff transformation processes with attached quality components (Notovny & Chesters, 1981). The useful methods, collecting hydrologic information rainfall-runoff, other environmental parameters are those based on Geographical Information System (Solaimani *et al.,* 2005; Hellweger & Maidment 1999; Olivera & Maidment 1999; Kupcho, 1997).

In this context a Geographical Information System (GIS) based index was developed, the Potential Non-Point Pollution Index (PNPI), in order to describe the global pressure exerted on water bodies by different land uses across the catchment areas (Munafò *et al*., 2005). The chapter showed three case studies of the application of PNPI: the Trasimeno lake (Baiocco *et al.,* 2001) the Tiber River basin (Munafò *et al*., 2005) and the province of Viterbo.

2. Potential Non Point Pollution Index

The Potential Non-Point Pollution Index (PNPI) is a tool designed to assess the global pressure exerted on rivers and other surface water bodies by different land use areas and infrastructures across the catchments. PNPI is a GIS-based watershed scale tool designed to give fast and reliable support to decision makes and public opinion about potential environmental impact of different land management scenarios. PNPI doesn't need a great amount of input data nor highly skilled operators and its high communication potential makes it particularly interesting for a participatory approach to land management. PNPI values is based on land use, geological features and distance from the water body of each land unit (Munafò *et al*., 2005, Cecchi *et al*., 2007). The information required are land use (like Corine Land Cover) maps, geological maps and digital elevation models (DEM).

The potential pollution is the expression of three indicators:

Land Cover Indicator, LCI: refers to the potential generation of non-point pollution due to the land uses of the parcel; it depends on the pollution potential load of the single cell mainly due to management practices (i.e. fertilizers and manure application for agricultural areas).

Run-Off Indicator, ROI,: takes into account pollutant mobility and possible filtering with respect to terrain slope, land cover and geology, it depends on the physical features of the entire path from cell to drainage network, features that affect flow velocity and subsequently pollution filtering.

Distance Indicator, DI, is the distance from the water body into a pollution dumping coefficient.

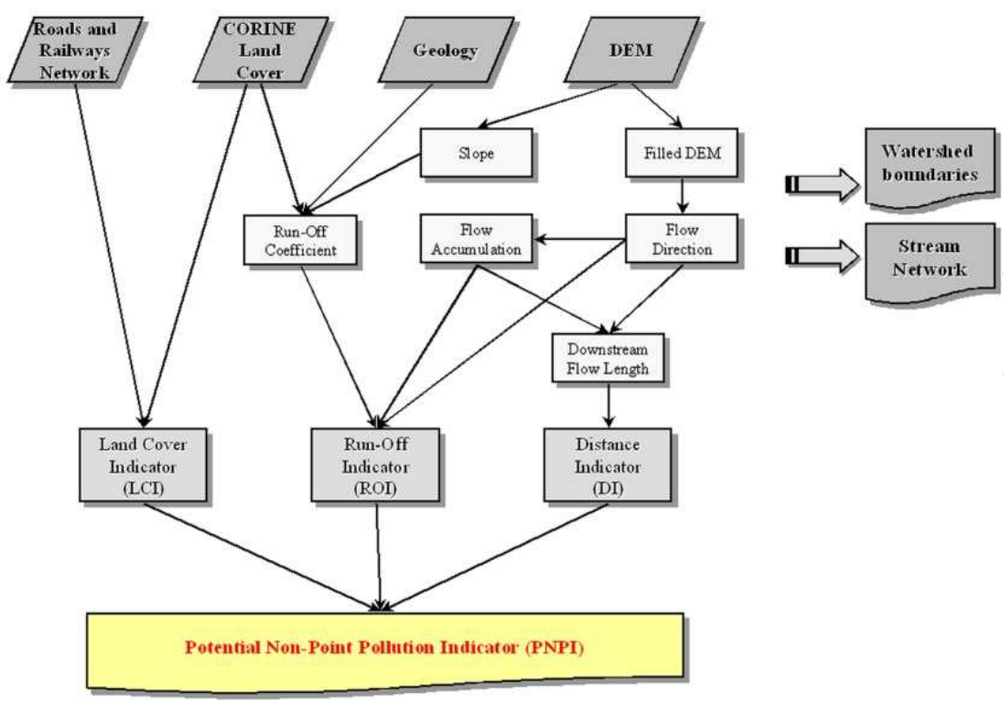

Fig. 1. Calculation pathway of PNPI (Munafò *et al*.,2005).

PNPI gives the potential contribution of each cell of the DEM (as land unit) to the non-point pollution of the studied aquatic ecosystem. PNPI values can then be used to build up five quality classes: natural and unaltered zones gave the lowest values and represented the first class (Munafò *et al*., 2005), whereas densely populated areas and intensively cultivated crop lands highest values and corresponded to the fifth class. The output of the calculation can be presented in the form of maps showing areas that are more likely to produce pollution and the aquatic ecosystem section that is more affected by these areas.

2.1 Calculation of PNPI

The PNPI for every cell of the river basin is then calculated as a combination of the three indicators described above (LCI, ROI, DI) following the formula:

$$PNPI = 5 * LCI * 3 * DI * 2 * ROI$$

Most important of the three indicator is the LCI. For its values, experts, provided to each land use a coefficient depending on the polluting potential Land use types and their geographic distribution were taken from CORINE land cover (CLC) digital maps. Densely built areas and intensively cultivated fields were given the highest coefficients whereas natural and unaltered zones were placed at the opposite end of the scale (Munafò *et al*., 2005; Cecchi *et al*., 2007). Experts such as biologists, engineers, naturalists assessed for each land use type a score from 0, minimum pollution, to 10, maximum pollution (Fig. 2).

For the calculation of both the ROI (run off indicator) and DI (distance indicator), data on terrain elevation are needed. DEM is used to draw the basin shape and drainage network.

A 75-meter grid DEM but higher or lower resolution can be used. 75-meter resolution was chosen to keep computing time under control and because it is congruent with the reference scale of other layers (ex. 1:100.000 for Corine Land Cover maps). As a consequence of this choice, the grid size of PNPI computation is 75 m.

The method used to model the outflow area (Jenson & Domingue, 1988) consisted of:

- Filling of the depressions
- Calculation of the flow directions
- Calculation of flow accumulation
- Definition of the boundary of the river basins and the hydrographical network

The filling of the depressions is essential since DEM always contains some cells working as accumulation areas, which are at a lower level than surrounding ones. The goal of this phase is to produce a modified DEM in which any cell is part of a decreasing monotone route, leading to the outlet of the watershed. A route is made up of adjacent hydraulically linked cells, the assumption being that the route is always downhill or flat. The second step is to recognize the directions of flow coming out from any cell, assuming that the water leaving a cell enters only one of the eight adjacent cells; the receiving cell is the one on the steepest slope. Such information is used to draw a new grid where every cell is assigned a value (flow accumulation, FA) corresponding to the number of cells that flow into it. Since all the cells are part of a route always leading to the outlet of the study area, by selecting the cells exceeding a given FA, a river network is obtained. Similarly the boundaries of the drainage basins are easily identified. Additional information such as a vector river network can be used to refine the automatic delineation (Munafò *et al.,* 2005).

The DI (distance indicator) can be calculated from the hydraulic distance between each point of the basin and the receiving water body. Distances are calculated along the theoretical route taken by water on ground. DI is such that longer distances from the river give lower DI values to take into account the pollution dumping effect of the distance.

Corine land cover class	Score - Average value (0 - 10)	Score - standard deviation
Continuous urban fabric	8.22	2.22
Discontinuous urban fabric	6.89	1.36
Industrial or commercial units	7.78	2.49
Road and rail networks and associated land	5.67	2.55
Port areas	7.00	3.10
Airports	5.56	1.67
Mineral extraction sites	7.78	1.72
Dump sites	8.11	2.32
Construction sites	7.22	2.54
Green urban areas	2.33	1.66
Sport and leisure facilities	3.00	1.66
Non-irrigated arable land	6.33	2.50
Permanently irrigated land	8.89	2.03
Rice fields	7.67	1.80
Vineyards	7.00	2.24
Fruit trees and berry plantations	7.89	2.26
Olive groves	5.22	1.99
Pastures	4.00	2.35
Annual crops associated with permanent crops	7.44	2.24
Complex cultivation patterns	6.89	1.96
Land principally occupied by agriculture. with significant areas of natural vegetation	5.67	1.94
Agro-forestry areas	2.89	2.03
Broad-leaved forest	0.56	1.13
Coniferous forest	0.56	0.88
Mixed forest	0.44	0.88
Natural grasslands	1.94	2.27
Moors and heathland	0.56	1.01
Sclerophyllous vegetation	0.22	0.44
Transitional woodland-shrub	0.78	1.09
Beaches, dunes, sands	0.78	1.64
Bare rocks	0.00	0.00
Sparsely vegetated areas	0.89	1.96
Burnt areas	2.67	2.24
Glaciers and perpetual snow	0.11	0.33
Inland marshes	0.89	1.17
Peat bogs	1.00	1.50
Salt marshes	0.44	0.88
Salines	0.43	1.13
Intertidal flats	0.43	1.13
Water courses	0.14	0.38
Water bodies	0.88	1.81
Coastal lagoons	0.14	0.38
Estuaries	0.43	1.13
Sea and ocean	0.14	0.38

Fig. 2. Estimated diffuse pollution generation of Corine land cover classes as resulted from an experts' consultation. The table reports the average values of the consultation and the relevant standard deviations (Cecchi *et al.,* 2007).

The ROI (run off indicator) is calculated as the average of the run-off coefficient along the entire path from cell to river. The run-off coefficient for every cell is a function of soil permeability, land use and slope (Fig. 3). In this way, the effects of velocity and flow rate on pollution can be taken into account (Fig 4). Before using the LCI, ROI and DI for the calculation of the PNPI, they are normalized between their maximum and minimum values in order to have indicators ranging between 0 and 1.

Land use class (Corine land cover)	Permeability Classes			
	A	B	C	D
Continuous urban fabric	0.77	0.85	0.90	0.92
Discontinuous urban fabric	0.57	0.72	0.81	0.86
Industrial or commercial units	0.89	0.90	0.94	0.94
Road and rail networks and associated land	0.98	0.98	0.98	0.98
Port areas	0.89	0.92	0.94	0.94
Airports	0.81	0.88	0.91	0.93
Mineral extraction sites	0.46	0.69	0.79	0.84
Dump sites	0.46	0.69	0.79	0.84
Construction sites	0.46	0.69	0.79	0.84
Green urban areas	0.39	0.61	0.74	0.80
Sport and leisure facilities	0.39	0.61	0.74	0.80
Non-irrigated arable land	0.70	0.80	0.86	0.90
Permanently irrigated land	0.70	0.80	0.86	0.90
Rice fields	0.90	0.90	0.90	0.90
Vineyards	0.45	0.66	0.77	0.83
Fruit trees and berry plantations	0.45	0.66	0.77	0.83
Olive groves	0.45	0.66	0.77	0.83
Pastures	0.30	0.58	0.71	0.78
Annual crops associated with permanent crops	0.58	0.73	0.82	0.87
Complex cultivation patterns	0.58	0.73	0.82	0.87
Land principally occupied by agriculture with significant areas of natural vegetation	0.52	0.70	0.80	0.85
Agro-forestry areas	0.45	0.66	0.77	0.83
Broad-leaved forest	0.36	0.60	0.73	0.79
Coniferous forest	0.36	0.60	0.73	0.79
Mixed forest	0.36	0.60	0.73	0.79
Natural grasslands	0.49	0.69	0.79	0.84
Moors and heathland	0.49	0.69	0.79	0.84
Sclerophyllous vegetation	0.49	0.69	0.79	0.84
Transitional woodland-shrub	0.36	0.60	0.73	0.79
Beaches. dunes. sands	0.76	0.85	0.89	0.91
Bare rocks	0.77	0.86	0.91	0.94
Sparsely vegetated areas	0.49	0.69	0.79	0.84
Burnt areas	0.77	0.86	0.91	0.94
Glaciers and perpetual snow	1.00	1.00	1.00	1.00
Inland marshes	1.00	1.00	1.00	1.00
Peat bogs	1.00	1.00	1.00	1.00
Salt marshes	1.00	1.00	1.00	1.00
Salines	1.00	1.00	1.00	1.00
Intertidal flats	1.00	1.00	1.00	1.00
Water courses	1.00	1.00	1.00	1.00
Water bodies	1.00	1.00	1.00	1.00
Coastal lagoons	1.00	1.00	1.00	1.00
Estuaries	1.00	1.00	1.00	1.00
Sea and ocean	1.00	1.00	1.00	1.00

Fig. 3. Run-off coefficients by land use class (Corine Land Cover) and by permeability class: A: high permeability, D: low permeability (Cecchi *et al.,* 2007).

Slope classes (degrees)	Correction coefficient
< 2°50'	0
2°50'-3°41'	0.1
3°41'-4°32'	0.2
4°32'-5°23'	0.3
5°23'-6°14'	0.4
6°14'-7°05'	0.5
7°05'-7°56'	0.6
7°56'-8°47'	0.7
8°47'-9°38'	0.8
9°38'-10°29'	0.9
> 10°29'	1.0

Fig. 4. Slope correction coefficients for the calculation of the Run-off indicator(Cecchi *et al 2007*). The coefficient is added to the Run-off coefficient as derived from Figure 3.

LCI, ROI and DI might not seem completely independent. For example both LCI and ROI depend on land cover. Nevertheless there is no double counting because different features of the land cover are taken into account. Input to the DB comes from the processing of basic maps performed by ESRI ArcView GIS 3.2 (Environmental System Research Institute, 1999b), together with its extensions 3D Analyst (Environmental System Research Institute, 1999a), Spatial Analyst (Environmental System Research Institute, 1999c) and Hydrologic Modelling (Environmental System Research Institute , 1999d).

3. Potential Non Point Pollution Index case studies

Potential Non Point Pollution Index (PNPI) has been evaluated on the aquatic ecosystems of Central Italy, at three different scales. It was applied on the Trasimeno lake, Tiber river basin, on all water bodies of Viterbo Province (Fig. 5).

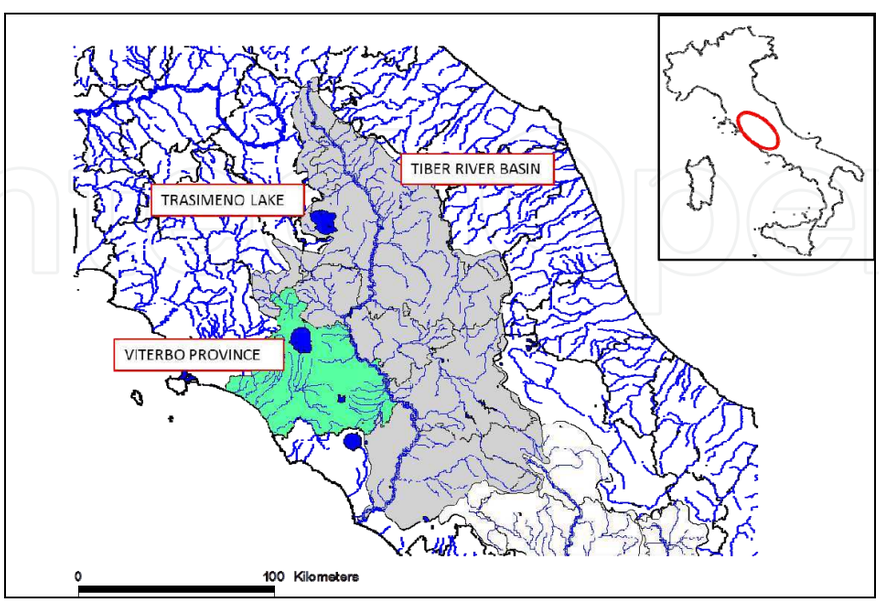

Fig. 5. Localization of PNPI three case studies.

3.1 Trasimeno Lake

3.1.1 Study area

The first study case of Non Point Pollution Index reported is on a volcanic lake ecosystem in Central of Italy, Trasimeno Lake (Baiocco *et al*., 2001). It has a catchment area is 309 km², the surface area is 128 km² The main tributary is Fosso Anguillara, and the effluent is the Emissario of Trasimeno, an artificial waterbody.

3.1.2 Potential Non Point Pollution Index of Trasimeno Lake

Potential non Point Pollution Index was applied on the Trasimeno lake catchment area

The PNPI application described the potential contribution of each land unit to the non-point pollution on Trasimeno lake (Fig. 6). This basin, mainly, resulted affected by slightly or moderate pollution (second and third class of PNPI) due to agricultural and farm activities. The most critical areas resulted, those near the banks of the lake, characterized by urban areas.

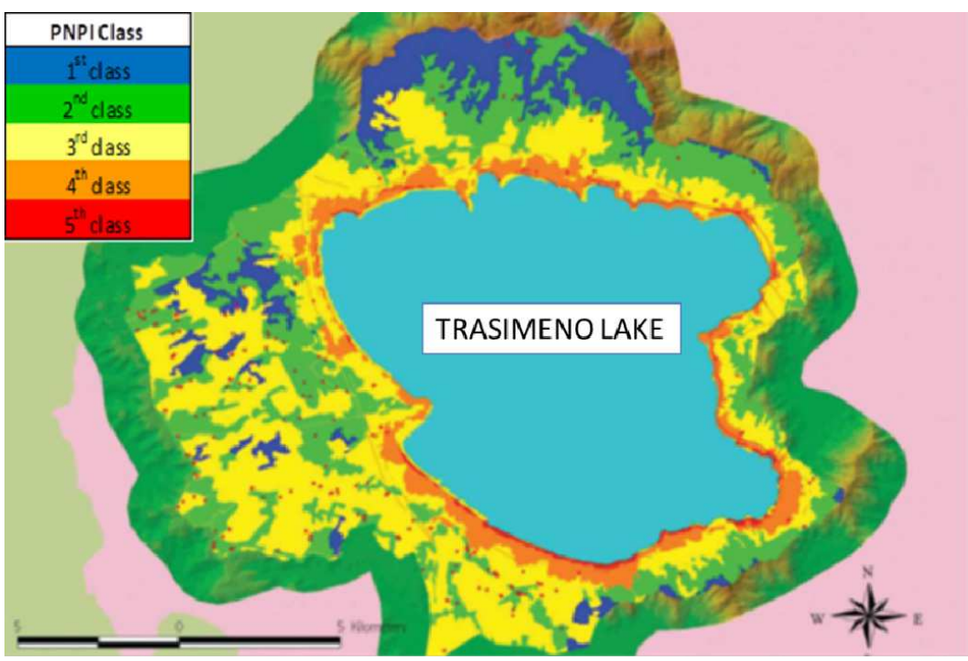

Fig. 6. Potential non Point Pollution Index on Trasimeno Lake (Ciambella *et al*., 2005).

3.2 Tiber River

3.2.1 Study area

The Tiber river is the third-longest river in Italy, rising in the Apennine Mountains, in Monte Fumaiolo, and flowing 406 kilometres through six region Emilia Romagna Toscana

Marche, Umbria Abruzzi, Lazio. It flows into the Tyrrhenian Sea near the City of Rome. The Tiber River basin covers a territory of 17.156 km² and the length is 409 km. The Tiber River basin's population accounts for 4 344 000 inhabitants (population census from 2001), of which 70% lives in the metropolitan area of Rome, about 10% in five of the main cities (Rieti, Perugia, Terni, Tivoli, Spoleto), and the remaining in the other small municipalities.

The Tiber River Basin is identified as Pilot Basin for testing of the implementation of the Water Framework Directive 2000/60/EC by the Italian Government.

3.2.2 Potential Non Point Pollution Index on the Tiber River basin

Potential Non Point Pollution index was applied on the whole catchement area of Tiber River and on the rivers (Figs.7-8).

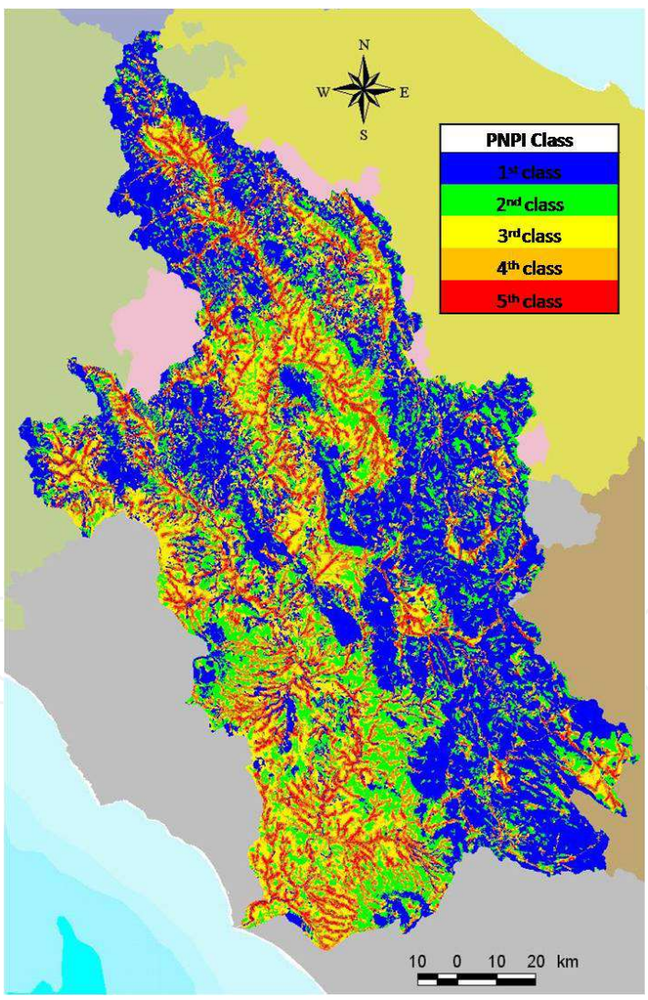

Fig. 7. Potential non Point Pollution Index results on Tiber River Basin.

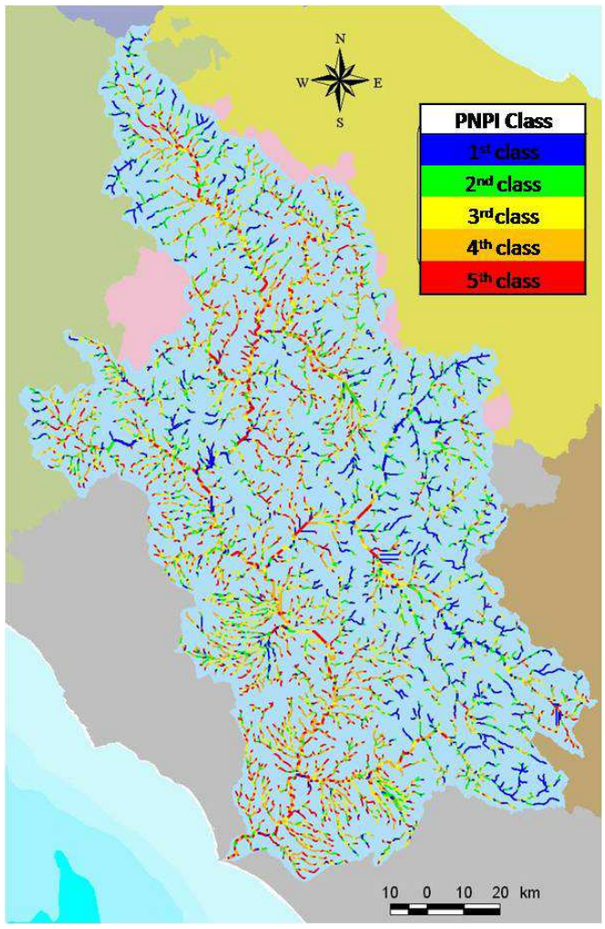

Fig. 8. Potential non Point Pollution Index results on Tiber River Basin, applied on watercourses.

The application of PNPI of Tiber River Basin described the non-point pollution of the Tiber river main course and its tributaries.

As described in figure (Fig. 7), it is possible to recognize slightly non point pollution only in the northern part of the basin, near the spring and in the left part of river basin. The natural habitats of the Apennines obtained the highest class of PNPI. Upstream to downstream there is a progressively increasing of impact and pressures, such as agricultural activities and urban areas (Fig. 8).

All the cities showed high level of pollution. A critical situation was described for the flood plain around Rome showing that only can be classified as low pollution driver (Cecchi *et al.*, 2005).

3.3 Viterbo Province

3.3.1 Study area

Viterbo Province is characterized by two groups of rivers: one that flows directly into the Tyrrhenian Sea and the second right tributaries of Tiber river. The main sub-basins of the

first group are represented by Arrone , Fiora River, Mignone River; and for the second group Treja River, right tributary of the Tiber.

The geology of the area is volcanic due to the activity of the Vulsini, the Vicano and the Cimino.

3.3.2 Potential Non Point Pollution Index of Viterbo Province

The data obtained on PNPI of river basin of, Arrone, Fiora, Mignone e Treja, were merged in order to describe the non point pollution of the study area within Viterbo Province (Fig 9).

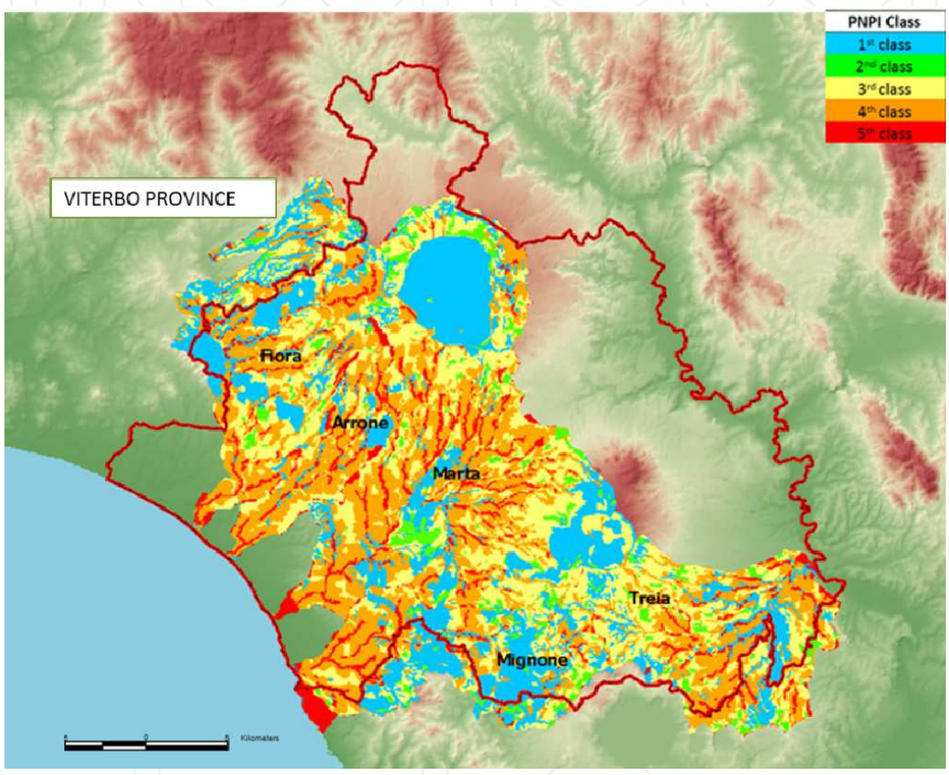

Fig. 9. Potential non Point Pollution Index of Viterbo Province.

The natural areas, where are located the river springs, are represented by non polluted or minimum polluted land units. Significant pollution was detected for the large part of the Province (Fig. 8). Strong impacts are located near the urban areas, and near the mouths of these rivers.

Fiora River basin has natural and less impact areas around its watercourse at the boundary between Tuscany and Latium; this basin is affected by significant diffuse pollution due to agricultural activities. The most critical area resulted the city of Montalto di Castro, where the river flows into the sea. The fourth class of PNPI is due to the presence of hydroelectric power plant and to the urban areas.

Arrone basin is characterized generally by significant non point pollution. The catchment of this River is set in an area with predominantly agricultural activities , which are uncommon

civilian settlements, and fewer still industrial (Andreani *et al.*, 2003; Ciambella *et al.*, 2005; Mancini *et al.*, 2008). Near the mouths, except for a small area, represented by a pinewood, there are presence of significant pollution effects.

Marta River presented two different pollution degrees: the northern part of its basin has moderate diffuse pollution and the southern part, no or slightly pollution. The fourth class of PNPI is due to the presence of industrial activities, farms and from urban areas near its course and the fifth class, near the mouth of the river is due to the city of Tarquinia (Mancini *et al.*, 2008). The first and the second class of PNPI in the southern part are due to Tuscania Regional protected area and the surrounding areas.

Mignone River basin, by application of PNPI, resulted without pollution or shligtly pollution in the upper part of the basin (first and second class of PNPI), indicating natural areas around the water courses. It worst downstream, when the water course is surrounded by agricultural activities and urban areas (third and fourth class). In critical situation of pollution resulted the area near the mouth, due to the presence of the harbour, industries of the city of Civitavecchia.

River Treja is the major tributary of the right side of Tiber river; its course is characterized by slightly or moderate impact come from non pollution sources. Its quality could be influenced by urban areas and agricultural activities near its flow in the Tiber River (Andreani *et al.*, 2005).

4. Conclusion

Potential Non Point Pollution Index was set up with the view to give a reading of the diffuse pollution, using the Geographic Information Systems and the knowledge on the biological communities and their relationship with environmental parameters.

This index, as others systems based on GIS describes complex environmental phenomena, using a large amount of parameters and their results can be easily interpreted.

The results of three case studies showed the application of Non potential Point Index at three different scales: the aquatic ecosystem of Trasimeno Lake, the Tiber River basin and the river basins of Viterbo Province.

The information obtained in the first study case are obviously more detailed than those achieved in the others, and useful to identify where are the vulnerable areas. On the other hand, the Tiber River case study showed a global view of diffuse pollution at interregional level, indicating the main pressures that damage the whole catchment area. The analyses of PNPI values of Viterbo Province described the first experimental approach of the assessment of non point pollution, done by a local authority. PNPI was resulted able to give useful information at all three scales.

Compared with other models (Di Luzio *et al.*, 2002), the PNPI approach showed some advantages: a low need for input data, simplicity of use and a direct reference to the pollution driving forces. The strength point of this index, is the combination of environmental data and expert judgment of biologists, naturalists, and engineers, giving a qualitative ecological component.

The evaluation of each land use type could be improved with the more information achieved from biological communities researches. The implementation activities of Water Frame Directive at Italian level have focused the attention of scientific world to improve the knowledge of the biological indicators and their response to environmental parameters.

In particular the acquired knowledge about the four biological elements, phytobenthos, macrophytes, benthic invertebrates and fishes will improve the evaluation of land use type making the PNPI more suitable for the achieving a good ecological status, after restoring activities of the river management plans, as required at national and European level (Italy, 2006; European Union, 2000).

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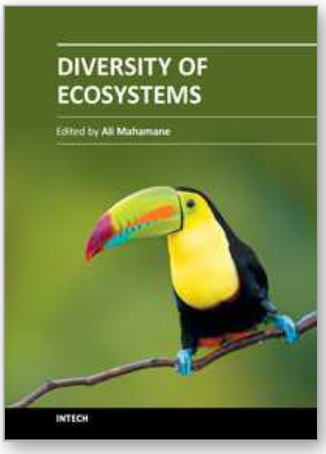

Diversity of Ecosystems

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The ecosystems present a great diversity worldwide and use various functionalities according to ecologic regions. In this new context of variability and climatic changes, these ecosystems undergo notable modifications amplified by domestic uses of which it was subjected to. Indeed the ecosystems render diverse services to humanity from their composition and structure but the tolerable levels are unknown. The preservation of these ecosystemic services needs a clear understanding of their complexity. The role of research is not only to characterise the ecosystems but also to clearly define the tolerable usage levels. Their characterisation proves to be important not only for the local populations that use it but also for the conservation of biodiversity. Hence, the measurement, management and protection of ecosystems need innovative and diverse methods. For all these reasons, the aim of this book is to bring out a general view on the function of ecosystems, modelling, sampling strategies, invading species, the response of organisms to modifications, the carbon dynamics, the mathematical models and theories that can be applied in diverse conditions.

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