Estimating river pollution from diffuse sources in the Viterbo province using the potential non-point pollution index

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Summary. This paper describes the application of the Index of Potential Non-point Pollution (PNPI) to the territory of the Viterbo Province (Central Italy). PNPI is a GIS tool that allows managers to assess the pressure on surface aquatic ecosystems deriving from diffuse sources of pollution. The index aims to assemble the available environmental datasets and specialists' expertise to set up a user-friendly and informative tool that can support decision-making processes and foster a multi-disciplinary approach. The index calculation is described and results are reported in order to give an overview of PNPI possible applications.

Key words: hydrographic basin, GIS, land use management, surface water bodies.

Riassunto *(Valutazione dell'inquinamento fluviale da sorgenti diffuse nella provincia di Viterbo per mezzo dell'indice di inquinamento diffuso potenziale)*. L'articolo descrive l'applicazione dell'indice di inquinamento diffuso potenziale (IDP) alla Provincia di Viterbo (Italia centrale). L'IDP è uno strumento GIS che permette ai responsabili della gestione ambientale di valutare e controllare la pressione esercitata sugli ecosistemi acquatici superficiali da parte di sorgenti diffuse di inquinamento. L'indice mira a sfruttare i dati ambientali e territoriali disponibili e le conoscenze di esperti del settore delle acque per la definizione di uno strumento semplice da utilizzare e di grande capacità comunicativa ed informativa, il quale possa supportare i processi decisionali e promuovere un approccio multidisciplinare. Nel testo vengono presentate le metodologie per il calcolo dell'indice ed i risultati ottenuti, al fine di fornire una visione generale delle sue possibili applicazioni.

Parole chiave: bacino idrografico, GIS, gestione dell'uso del suolo, corpi idrici superficiali.

INTRODUCTION

Sound policies for the management of water resources must be grounded in a deep knowledge of the environment and of the affected ecosystems. An integrated approach is essential to reach a multidisciplinary and comprehensive knowledge. Coordinated contributions from a variety of specialized technicians and scientists (biologists, naturalists, chemists, engineers, economists) can be highly beneficial. The National Institute of Health (Istituto Superiore di Sanità, ISS) and the councillorship for the environment of the Viterbo Province implemented a project with the goal of putting such an integrated approach into practice [1]. The main objective of the project was the application of the index of potential non-point pollution (PNPI) for the assessment of the pressure exerted by diffuse sources on surface water ecosystems. Within the project, many other aspects of the management and protection of water resources were addressed; among the project activities we mention the application of the fluvial functioning index (FFI) to estimate the integrity and identify alterations in fluvial ecosystems [2, 3], the use of the model SWAT (soil and water assessment tool) [4] on a pilot river basin for a different perspective on diffuse pollution assessment, and the study of the ornithic community, that contributed to the research on biodiversity. Last, guidelines for an economic analysis were defined in order to foster the achievement of restoration objectives by means of a "costs-benefits" analysis.

The method applied within the project "Development and deployment of a GIS based decisions support system for the control of water bodies' pollution from non-point sources" is in line with the ecosystem health approach to environmental management, which is in turn a keystone of all activities of the ISS Department of Environment and Primary Prevention [5, 6].

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The present paper describes in detail the line of activity concerning the assessment of pollution from diffuse sources. It aims at providing a novel insight into the complex interactions between fluvial ecosystems, land use management and environmental health; it also tries to show how readily available tools and datasets can be exploited with a view to fostering a more informed and knowledge-based decision making process.

MATERIALS AND METHODS

Assessment of water bodies' pollution from non-point sources is a complex, data-intensive and time-consuming task. 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 practices across the watershed [7, 8]. One key feature of PNPI is the ready availability of the input data needed to run the model. Highly detailed input maps, often lacking for many areas, are not required for the calculation of the PNPI. As a consequence of the input data chosen, the modelling of physical processes is simplified. The model applies an "expert system" approach; it bypasses the accurate representation of the physical reality to assess globally the pollution potential of different land uses, as estimated by scientists dealing with different aspects of watershed management. PNPI is a GIS-based, river basin-scale tool designed to inform decision makers and public opinion about the potential environmental impacts of different land management scenarios. PNPI calculation applies the multi-criteria approach to the description of pollutants dynamic and assessment of water bodies' health. It broadly follows the approach used in the environmental impact assessment. Diffuse pressure on water bodies deriving from different land units is expressed as a function of three indicators: land use (LCI), run-off (ROI) and distance from the river network (DI). They are calculated from land cover/land use datasets, geological maps and a digital elevation models (DEM). The meaning of each Indicator is explained below:

1) LCI (land cover indicator): refers to the potential generation of non-point pollution, as determined by the land use of the different parcels;
2) ROI (run-off indicator): takes into account pollutants mobility and possible filtering due to terrain slope, land cover/land use and geology/pedology;
3) DI (distance indicator): permits to account for the effect of the hydraulic distance between the source of pollution and the receiving water body.

The weights assigned to the three indicators and to the different land uses allow to calculate the value of the PNPI on each node of a grid representing the watershed: the higher the PNPI of the cell the heavier the potential impact on the river network.

LCI indicator is the most important of the set (in this regard, see also the weights given to the indicators as reported in *Table 1*); it allows to estimate the environmental consequences of different planning scenarios. Part of the research activities presented in this paper deal with the definition of the weights for the three indicators and for the land uses classes. To this purpose, several specialists with different backgrounds were consulted; the experts are biologists, natural scientists, ecologists and environmental engineers. The outcomes of the consultation are presented in the section "Results".

The calculation of the ROI on the cell *i* requires the preliminary definition of the Run-off coefficient for each cell along the hydraulic path between the cell *i* and the river network. The values for the Run-off coefficients are found in *Table 2*. The coefficient depends on the land use and permeability classes. Permeability ranges from A (high permeability) to D (low permeability). If permeability maps are not available, estimates of this parameter can be made through geological, lithological or pedological maps. For the present work, the permeability levels were retrieved from the lithological map of Lazio on a scale of 1:50 000 (which includes the Viterbo province); within the lithological map permeability classes had already been determined. The values in *Table 2* must be corrected for the effect of slope. This is done by adding the values in *Table 3* [9] (if the corrected value is higher than 1, the Run-off coefficient is set at 1). Once the Run-off coefficient for each cell is set, the Run-off indicator of the cell *i* can be calculated as the average of the Run-off coefficients of all cells between the cell *i* and the river network (along the hydraulic path).

The DI is calculated as the normalized distance between the cell *i* and the river network. The normalization was done by means of an exponential function expressed by the formula $DI_i = Exp(-([D_i]*k)$, where D_i is the distance of the cell *i* from the river measured in number of cells, and k is a constant value set at 0.090533.

Table 1 | *Indicators used to measure three key aspects shaping the land-based, diffuse pressure on surface water bodies [7]. The indicators, weighted according to the outcome of an experts' consultation, are combined to calculate the potential non-point pollution index (PNPI). The average values that resulted from of the consultation were normalized, therefore their sum is 10*

Indicator	Weight of the indicator (average)	Weight of the indicator (standard deviation)
LCI (Land cover indicator)	4.8	0.71
ROI (Run-off indicator)	2.6	0.52
DI (Distance indicator)	2.6	0.71

Table 2 | *Run-off coefficients by land use class (Corine land cover) and by permeability class (A: high permeability, D: low permeability). For the present study, the permeability levels were retrieved from the lithological map of Lazio (scale 1:50 000)*

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

If $D_i = 0$ then $DI_i = 1$, while if $D_i = \infty$ then $DI_i = 0$.

For the Viterbo Province the PNPI [7] was adapted to match the characteristics of the available datasets. For the purpose of watershed delineation, a 75 meters resolution DEM was used together with the hydrological network on the scale of 1:250 000 produced APAT (Italian Agency for Environmental Protection and Technical Services) [10]. The permeability was derived from a lithological map on a scale of 1:50 000. The land use map derives from the "Corine land cover 2000" project [11].

In order to define protection or restoration policies

Table 3 | *Slope correction coefficients for the calculation of the Run-off indicator [9]. The coefficient is added to the Run-off coefficient as derived from* Table 2*; if the total is bigger than 1 it is nonetheless equalized to 1*

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

it can be very useful to know which river stretches suffer the highest pressure from diffuse sources. While the PNPI as it is shown in *Figure 1* describes how diffuse sources are scattered across the watersheds, it is possible to focus on one single basin and estimate the pressure affecting the different parts of its river network. To do so, the river network can be divided into segments and for each segment the sum of all related pressures can be calculated. This allows the creation of a map that can support studies of hydrological network vulnerability. In *Figure 2* it is shown this type of output for the Mignone river basin, which is partly within the Viterbo Province. For this exercise, the river network was divided into portions 5 kilometres long and the relative quality classes were depicted using the usual representation (darker segments correspond to higher pressure).

RESULTS

An extremely important part of the project dealt with the experts’ consultation through which the core of the knowledge base was created. Some of the experts selected had a specific knowledge of the study area while some others had not. In addition to the authors of the paper, seven experts were consulted (see acknowledgements below). They expressed their opinion on the weights for the three indicators (LCI, ROI, DI) and they also estimated the potential pollution generated by the different land uses.

In *Table 1* we present the average weights given to the three indicators by the experts and the relevant standard deviations. It is clearly shown that land use is considered to be the most important indicator among the three and the relatively low values of the standard deviations are proof of the substantial agreement among the consulted experts.

In *Table 4* it is shown the potential generation of pollution for different land use classes as evaluated by the experts; the potential ranges from 0 to 10. We should stress that densely built areas and intensively cultivated fields score the highest coefficients whereas natural and unaltered zones are, not unexpectedly, placed at the opposite end of the scale.

The output of the calculation can be presented in the form of maps depicting areas that are more likely to produce pollution (darker areas in *Figure 1*). PNPI works at watershed level, in this case results from adjacent basins were put together on a GIS system for display purposes. One clear feature in *Figure 1* is the concentration of high pressure areas (black areas in the Figure) along the river network. This is due to the relatively high weight assigned by experts to the Distance Indicator; in the map it is made evident to land use planners and decision makers that the territory in the vicinity of the rivers plays a key role in generating diffuse pollution.

As proof of concept, in *Figure 2* it is shown how it is possible to aggregate the PNPI index so as to identify the segments of the river network that undergo the highest pressure in terms of diffuse pollution. In this representation, darker areas are more at risk of diffuse pollution. This does not directly entails that they are more vulnerable; if a continuous and substantial riverine vegetation is present, the pressure can be largely absorbed and the impact may be limited.

DISCUSSION

The use of land cover maps to monitor and control sources of diffuse pollution appear very promising. Other sources of diffuse pollution such as atmospheric depositions can play a significant role in the overall nutrient budget of a watershed, but such sources are more homogeneous in space than the land-based ones; in addition, the spatial resolution of the available datasets of atmospheric depositions is normally very coarse (*e.g.*, in Italy the resolution is 50 km) which makes them unfit for an accurate GIS-based analysis. Besides, the authors decided to concentrate on the land based sources because they are much more dependent on local policies and therefore they can be more easily integrated in decision making processes.

In the calculation of the PNPI the experts’ judgment is highly critical. This work and the related experts’ consultation substantially confirmed the weights originally assigned by the index developers in a previous work on the Tevere river basin [7, 8] thus testifying to the soundness of the assumptions. However, the weights remain eminently subjective in nature and there is a need to assess the sensitivity of the index to the weights used. Some tests, not presented in this paper, were made for the Viterbo Province by using the values assigned by individual experts. On the whole, it appeared that the macro-pattern of the pollution sources remained unchanged, differences being very limited in space. It seems reasonable to assume that decisions on which areas to tackle first to reduce diffuse pollution would not be affected to a large extent by the use of weights given by different experts.

In the results section it is also underlined the close association between hydrological network used as input and the PNPI map. This implies that the use of GIS-layers for the river network at a differed resolution (and detail) would give different results. PNPI users are encouraged to adopt the hydrological network that is more relevant at the scale of the intervention: if the objective of the study is to identify

Table 4 | *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. Experts were asked to assign a score ranging from 0 (minimum pollution) to 10 (maximum pollution)*

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

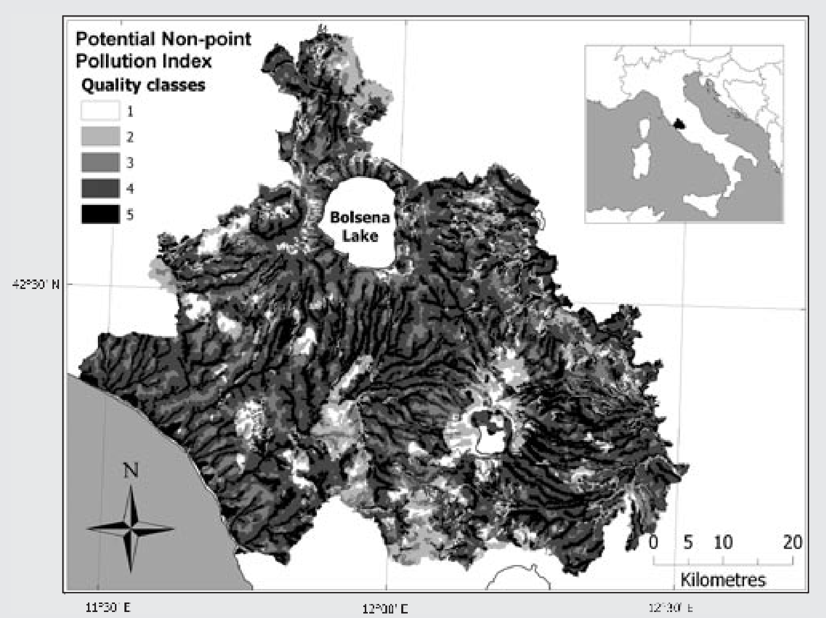

Fig. 1 | *Spatial distribution of the diffuse sources of pollution across the province of Viterbo. Darker areas are characterized by a higher potential for diffuse pollution. In this figure, the results of all watersheds in the province of Viterbo are combined.*

the watersheds more at risk, a coarse river map can be sufficient; on the contrary, a more detailed layer could help select the river stretches or small tributaries that need a wider and more continuous riparian vegetation to balance the higher pollution input.

CONCLUSIONS

Both national and continental legislation on surface water management recently pushed environmental protection authorities toward a deeper commitment to diffuse pollution defence. Nevertheless, tools and skills currently available within mandated control and planning authorities are very often insufficient. Data availability is also a serious constraint to the application of sophisticated models. In this context, PNPI is believed to be a valid support to the monitoring of the aquatic environments and related restoration programmes in accordance with the targets set by the Italian regulations and the European directives [12-14]. A major advantage of such a tool is the capability to investigate the pollution drivers and their spatial distribution, thus making it possible to depict current situation and assess the likely impact of alterative intervention options. The index emphasises the indissoluble link between the river

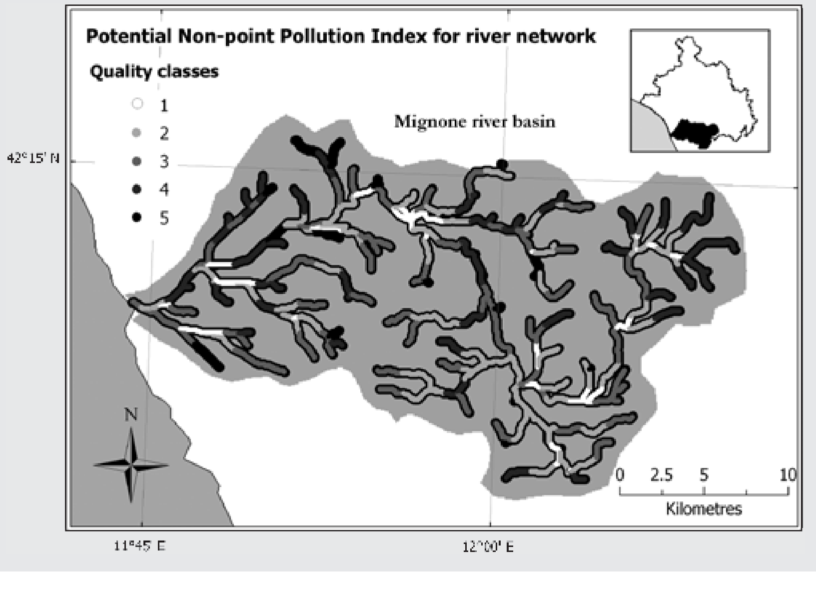

Fig. 2 | *River network vulnerability classes (Mignone basin). Darker stretches are estimated to suffer a more severe pressure from diffuse sources of pollution.*

and its territory and it is meant to facilitate the integration of waterbodies protection into the decision making process and land planning activities. Local authorities such as Viterbo Province could use the PNPI as a synthetic tool for sounder management of river diversions and wells exploitation.

While PNPI as it is displayed in *Figure 1* is more directly concerned with land planning and the strategic environmental assessment, *Figure 2* brings back the focus on the riverine ecosystem and provides an example of how the index can be used to assist the river management and the related monitoring activities; river stretches that undergo a major pressure from diffuse pollution can be identified so that targeted control and protection actions can be taken. In conclusion, it seems that PNPI can effectively support the development of new multidisciplinary methods for riverine ecosystem assessment and it can complement the results of well-established methods such as FFI [2, 3].

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