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Phosphorus export from agricultural land: a simple approach

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In the last few decades, increased inputs of nutrients (mostly nitrogen and phosphorus) to agricultural land have led to runoff transporting an ever growing portion of these nutrients from non-point (diffuse) pollution sources into rivers and lakes, thus threatening freshwater quality.

Phosphorus (P), the focus of the present paper, is principally transported from agricultural land bound to sediments and can accelerate freshwater eutrophication. Two fundamental problems face land managers when dealing with the problem of non-point P pollution. The first is posed by the quantitative evaluation of P loads at basin scale, which is essential in assessing areas of higher export risk and transport pathways. The second is finding a satisfactory compromise between two opposing needs: simplicity, to satisfy management, and complexity, to interpret real processes and their related uncertainty. Uncertainty is not merely the uncertainty that is intrinsic to model simulations, but also that deriving from the inherent stochastic variability of real systems.

In the present study, an attempt to maximise the advantages of both approaches was made. The Lake Vico basin, Central Italy, was selected as a suitable site, since the P concentration of the lake increased dramatically at the beginning of the 1990s, due to P non-point pollution source loads.

The simulation model (Groundwater Leaching Effects of Agricultural Management Systems, GLEAMS) was used to evaluate field scale P losses in two different scenarios: conventional and conservative agricultural practices. A regression model for each of these two scenarios was then fitted, to find the best relation between slope, on the one hand, and P losses. This regression allowed the GLEAMS results to be extended to basin scale, by a digital terrain model and a geographic information system (GIS), making it possible to evaluate P export into the lake, thus meeting management needs. The accuracy of this type of approach was evaluated by comparing model predictions with monitored results of P concentration in water.

The suggested approach offers solutions to several problems regarding land management sustainability, including: (i) a quantitative evaluation of different land management scenarios; (ii) the possibility of zoning landscape according to risk level, comparing

Abbrevations: BMPs, best management practices; CAP, Common Agriculture Policy; CN, Curve Number; GIS, geographic information system; GLEAMS, Groundwater Leaching Effects of Agricultural Management Systems; L/R, Length Ratio; LU/LC, land use/land cover; NPS, non-point pollution sources; P, Phosphorus; PDR, phosphorus delivery ratio; SCS, Soil Conservation Service; SDR, sediment delivery ratio.

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different scenarios and related environmental efficiency; (iii) an integrated evaluation of land cover, in terms of its impact on freshwater ecological status and the long-term water body condition, as a consequence of land use.

1. Introduction

There is a worldwide, growing consensus for the need to reconcile agricultural policies and the environment. Intensification of land use has created environmental problems through the increased use of fertilisers, pesticides, water resources, equipment, and additional feeds for livestock. In Europe, there has been progress towards integrating the EU agriculture and environmental policies since 1992, when a reform of the Common Agriculture Policy (CAP) was agreed on and the Fifth Action Programme was adopted.

Water pollution is probably the main threat to agricultural environmental sustainability. It mainly derives from diffuse, non-point pollution sources (NPS), where pollution results from sources that are dispersed across a watershed (sediments, animal wastes, plant nutrients, crop residues, inorganic salts and minerals, pesticides) and arise from land use/land cover (LU/LC), and not from a pipe (White and Howe, 2004).

In the last 50 years, there has been a major shift in the agricultural sector from family subsistence farming, to large commercial, mostly mono-cultural agro-businesses. This change has led to excessive diffuse pollution and an unsustainable adverse impact on the environment, above all on water bodies, due to the loss of fertilisers from fields and related export into surface and ground water (Novotny, 2005). In this context, freshwater eutrophication is one of the most pressing concerns (Arheimer *et al.*, 2004).

Non-point sources originate from storm water runoff or percolation, which carries pollutants into receiving water. Hence, they depend on the complex interaction among many factors: input quantities to the land; climate; drainage net characteristics: soil kind; topography; presence in the landscape of buffer systems (riparian vegetation, hedges and wetlands, that intercept sediments and runoff or denitrify water or uptake nutrients *etc.*). Hence, change in water quality due to NPS indicates a change in some aspects of the climatic, terrestrial, riparian or in-channel ecosystem and in LU/LC.

The relevance of NPS to water quality and the role of agriculture as a major source of NPS pollutants are confirmed by both scientific literature and technical reports (Omernick *et al.*, 1981; Sharpley *et al.*, 1994; Heathwaite and Sharpley, 1999; Heathwaite, 2003; Novotny, 2005).

Reliable estimations of diffuse pollutant exports at basin scale are fundamental to an understanding of possible hazard for the aquatic systems and, thus, are critical to the development of strategies to limit negative effects on freshwater. The principal challenge lies in the fact that diffuse pollution effectively operates outside 'traditional' mechanisms of structural control; until recently almost all water pollution abatement efforts were aimed at water treatment plants in order to control point sources flowing into receiving waters. The focus for NPS is on land management that affects water quality by influencing sediment yield, chemical loads, watershed hydrology and other processes, such as nutrient detention and transformation zones, dissolved or suspended nutrients or sediment mobilisation zones, *i.e.* areas where sediments move downstream (Basnyat *et al.*, 1999).

Thus, although landscape 'controls' NPS production, there is always potential for improving water quality with proper landscape management (Haycock and Muscutt, 1995; Garnier *et al.*, 1998; US-EPA, 2000; White and Howe, 2004), whose main tool consists in the promotion of best management practices (BMPs) (Turpin *et al.*, 2005). It is also necessary to manage the many aspects of LU/LC, topography, climate, soils and the related complex interactions that regulate NPS production and consequent pollutant input–output. For instance, the study by Pote *et al.* (1996, referred by Sharpley *et al.*, 2002), who measured very variable total P losses (from 0.05 to 0.35 kg [P]ha^{-1}), from three sites with very low soil P content (285–295 ppm), showed that erosion, rather than soil P content, accounted for relevant differences in P losses between sites, revealing just how chaotic NPS behaviour can be.

It is therefore necessary to make another shift in perspective towards a more integrated approach, analysing the joint contribution of multiple land use activities, their environmental context and related consequences on receiving waters. Little has been done in this sense, despite numerous studies on the effects of individual LU/LC types.

Investigating the export into water bodies of phosphorus (P), whose role in freshwater eutrophication is well known (Sharpley *et al.*, 1994; Correll, 1998), involves evaluating the coincidence of both source and transport factors. In order to produce satisfactory models that could be used to manage the environmental impact of P non-point source water pollution, would require very long detailed and expensive monitoring. However, it is not at all certain that the processes can be 'deterministically' described by models, considering their chaotic behaviour. In fact, it is not clear whether large, over parameterised, deterministic models can be satisfactory because it is almost impossible to validate them (Heathwaite, 2003).

Land managers should be aware of these limitations when deciding which kind of model and what consequent method to adopt (Lewis and McGechan, 2002). Scientific literature offers very different approaches, aimed at estimating the watershed nutrient losses of water. But in each case, planning land use and modelling its consequences (both at field and basin scale) are the key factors in control strategies.

The methods of evaluating phosphorus export into freshwater can be summarised as follows:

(1) Methods that consider simple export coefficients. These coefficients depend only on land use (Dillon and Kirchner,

1975; Beaulac and Reckhow, 1982) or methods based on some synthetic indices of hydrological or soil characteristics (Frink 1991; Mattikalli and Richards, 1996).

In this category, the most complete analysis, is probably the USDA-Natural Resources Conservation Service NRCS P index (Lemunyon and Gilbert, 1993; Gburek *et al.*, 2000), which incorporates source characteristics (soil test P, fertilisers and manure inputs) and transport characteristics (runoff and erosion), at field scale.

This approach has the advantage of simple and immediate application, but of necessity it cannot interpret complex environment–anthropogenic interactions. Hence, it satisfies the management requirement of a 'simple and easy to apply' method. On the other hand, it is neither able to interpret complexity, nor the effectiveness of the best management practice (BMP) choice in the specific context.

(2) Running field scale, dynamic, physics based management models, such as Groundwater Leaching Effects of Agricultural Management Systems (GLEAMS) (Knisel, 1993) or similar (see the review of Lewis and McGechan, 2002). These have the advantage of focussing on the details of LU/LC management and its related environmental context (topography, soils, climate), based on physics, not based on simple scores. Hence, they are optimal tools for interpreting environment–anthropogenic interaction complexities and evaluate BMP effectiveness. The limitation of such models is the small area involved (a single landscape unit: one slope, one soil, one microclimate *etc.*), lacking the real loads for water bodies, which implies export into freshwater at basin scale.

(3) Running basin scale, dynamic models, such as Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1996) or Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) (Bouraoui and Dillaha, 1996). These kinds of models have the advantage of involving a wide area, often with highly detailed information, which is, at the same time, their main limitation, since they require a large quantity of input data for the whole basin, which are rarely available. Thus, validation is much more difficult or, more usually, impossible.

As a consequence of these considerations, all these approaches present advantages and drawbacks. In most cases, for management purposes, empirical and simple methods might be more appropriate for evaluating pollutant export into freshwater (Heathwaite, 2003). At the same time, it is also true that they are too simple for interpreting complexities such as NPS production and, above all, for sufficiently focussing on land management. The need to reach a compromise between simple methods and physical basin properties is one of the trends in current research. It is important to improve the interpretation of the practical requirements of legislation, such as the EU Water Framework Directive, by for example, the use of fuzzy systems which have great potential to be used as a decision support tool for policy makers (Schärer *et al.*, 2006).

This work proposes a compromise solution between physics based simulations and simple export indices, for evaluating phosphorus export into a lake. The effort consists in maximizing the advantages of physics models, while minimising their application difficulties. The aim of the work is not to propose a new model, but to find the best way of integrating existing models, *i.e.* it consists in a new approach, allowing land managers to optimise the advantages of both physical models and simple export methods to assess LU/LC impact on water resources.

2. Methods

The experimental site chosen was the Lake Vico basin, in Central Italy (about 60 km north of Rome, Fig. 1). It is ideal for investigating non-point pollution, because the land impact is almost all due to intensive agriculture (hazelnut trees), while civil and industrial settlements are negligible or absent (Leone and Marini, 1993). Land cover is prevalently agriculture (about 48%) and forest (about 41%) (Leone *et al.*, 2006).

The phosphorus content of water has sharply increased in recent years (Fig. 2) as a result of the changes in land use which took place in the 1960s and 1970s, when extensive agriculture switched to the present intensive hazel orchards (Leone and Marini, 1993). Fig. 1 shows a detail of the first preliminary assessment of P loads from different sources in the Lake Vico basin (Leone and Marini, 1993), based on mean export coefficients from literature (Beaulac and Reckhow, 1982).

The work is based on the following assumptions, regarding the Lake Vico basin: (i) intensive hazelnut tree cropping

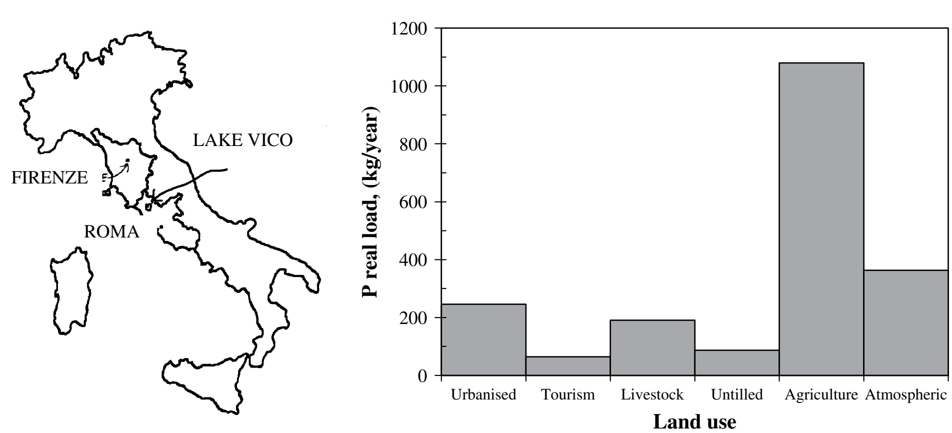

Fig. 1 – Localization of the study area and first rough assessment of P loads from different sources in the Lake Vico basin.

provides the greatest amount of nutrients exported into the lake, P in particular; (ii) the large amount of sediment produced by heavy rainfall runoff is a significant problem for the Lake Vico basin and, therefore, P loss from cultivated soil mainly occurs through particulate phosphorus (PP), *i.e.* P bound to eroded soil particles and organic matter; (iii) P pollution originates from spatially restricted areas within the basin; (iv) hazelnut tree cultivation requires bare soil to optimise mechanical harvesting, so increasing the risk of erosion. Consequently, the first BMP, which has been applied for around 10 years, resulted from the EU regulation 2078/92/EC and was: ‘Growing meadow under hazelnut trees’ (Caporali *et al.*, 1988).

2.1. Phosphorus field scale and basin scale losses

First of all, a phosphorus critical area evaluation method was developed, based on field scale runs of 50 hydrological years by the GLEAMS model (Leone *et al.*, 2001), a field scale, management oriented model, developed by the US Department of Agriculture, in co-operation with the University of Georgia, USA (Knisel, 1993).

The model takes into consideration four major components: hydrology, erosion, pesticides and nutrients. Regarding P, GLEAMS simulates: mineralisation, immobilisation, fertiliser and animal waste application; and, furthermore, crop uptake, together with runoff, sediment and leaching losses are considered. It allows the effects of agricultural management systems to be evaluated within and throughout the plant root zone, considering the consequences of management and natural inputs and their influence on hydrology, erosion, and chemical processes, both on the soil surface and within the soil profile. The model provides output data concerning the quantities of nitrogen, phosphorus, sediments and pesticides that reach the edge of the field and the bottom of the root zone and are, therefore, potentially able to pollute water bodies.

Given that slope is the main limiting factor for soil erosion and P loss, a meta-model was developed, by a simple regression (Leone *et al.*, 2001; Leone *et al.*, 2006), to evaluate both processes. A meta-model is a simple approximation of a complex simulation model (Schoumans *et al.*, 2002).

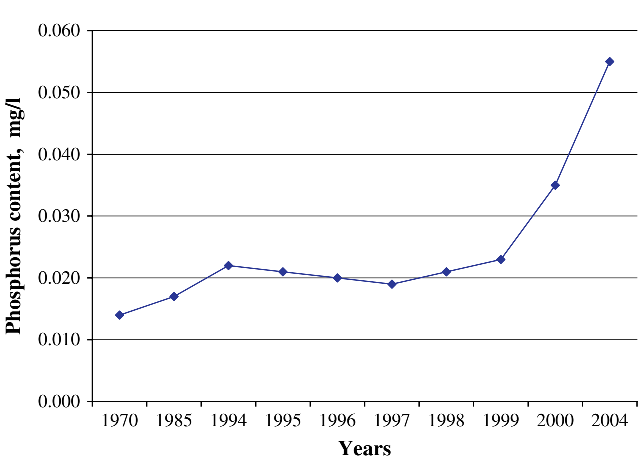

Fig. 2 – Phosphorus water content in Lake Vico during the period 1970–2004.

In this way, the simulated output of the GLEAMS model is related to the main input data of the same simulation model. The meta-model structure is:

$$Y = ax^b \tag{1}$$

where Y is the land use impact (soil erosion and phosphorus export with and without BMP, in this case); x is the slope (dimensionless); and a and b are the coefficient and the exponent, respectively.

This meta-model is a simple formula, explicitly related to the main limiting factor, but all the other factors of the complex environmental–anthropogenic system (tillage, soil kind, climate, *etc.*) are not rejected, as in other simple methods and NRCS P index. The latter, in fact, considers tillage, soil kind, climate, but only as parameters from which to calculate scores. In the proposed meta-models they are present in implicit form in coefficient a and in exponent b of Eq.. (1).

Values for coefficient a and exponent b for soil erosion and P loss are reported in Table 1.

These simple formulae also allow the GLEAMS results to be extended to the basin, using a geographic information system (GIS) and a digital terrain model (DTM). In Fig. 3 the related maps for soil yield and P loss are shown. Furthermore, these maps can be produced for each land management scenario, developing a comparison of planned BMPs. For example, using the same GLEAMS–GIS approach to the actual BMP, the effectiveness was evaluated using the following formula:

$$E = \frac{Y_0 - Y_{BMP}}{Y_0} \tag{2}$$

where E is the effectiveness of the BMP for parameter Y (soil erosion or phosphorus loss), ($Y_0 - Y_{BMP}$) is the loss due to conventional tillage export reduction, having adopted the BMP and Y_0 is the soil erosion or phosphorus loss due to conventional tillage.

An immediate management result is the map of BMP efficiency zoning (Fig. 4).

2.2. Phosphorus transportation (from P field scale loss to P export into freshwater)

These results give P loss for each cell and not export into the lake which is the real impact of land use and can be influenced by factors such as distance from waterways and slope change. The next step was then the evaluation of the real P load, through the concept of sediment delivery ratio (SDR), which is the ratio of the sediment yield to the gross erosion rate, expressed as a dimensionless number or a percentage (Novotny and Chesters, 1989).

Table 1 – Values of coefficient a and exponent b in Eq. (1)

Parameter (Y)	Tillage option	a	b
Soil erosion, Mg ha^{-1} $year^{-1}$	Conventional	287.73	1.216
	BMP (weeds under orchards)	84.85	1.340
P export, kg ha^{-1} $year^{-1}$	Conventional	26.21	0.100
	BMP (weeds under orchards)	13.89	0.041

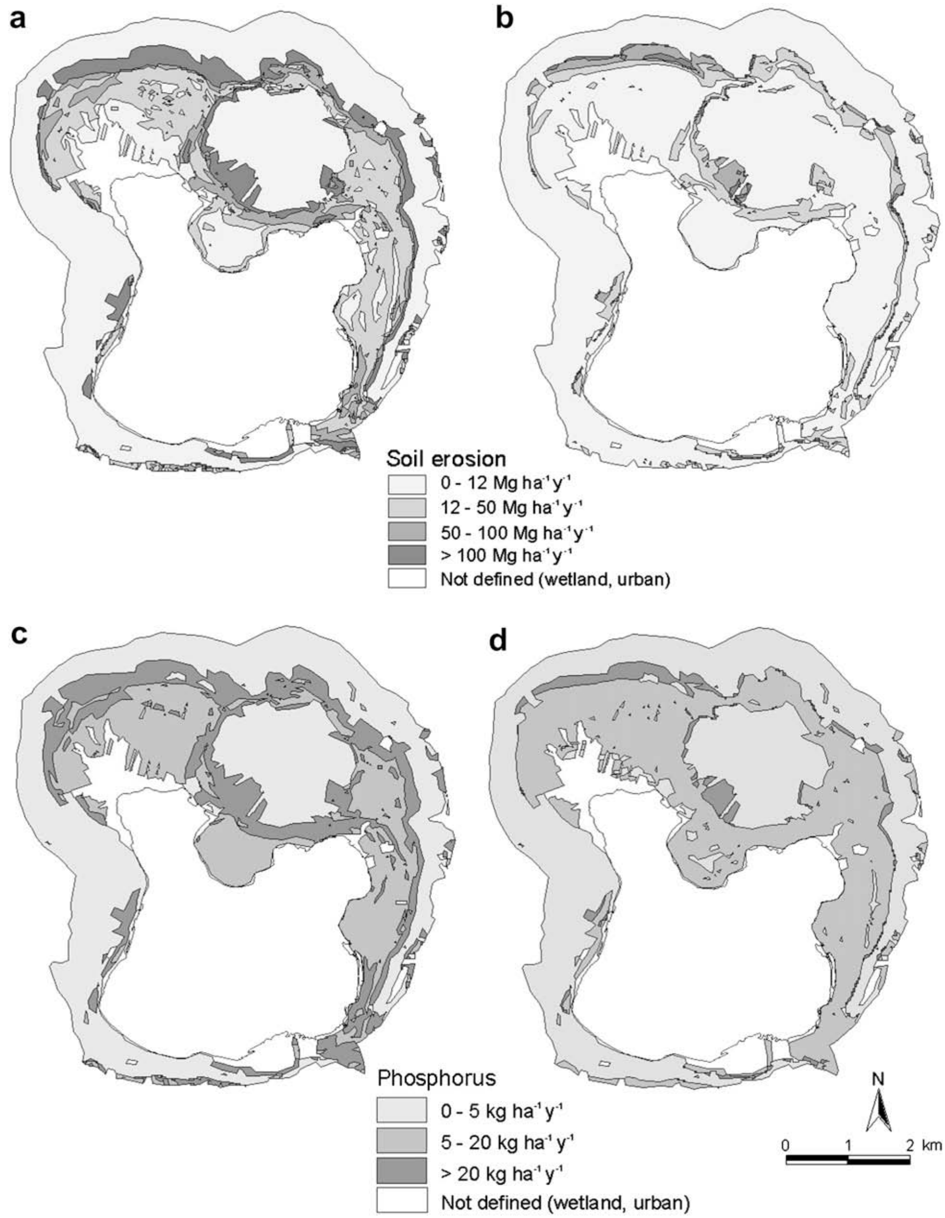

Fig. 3 – GLEAMS simulated soil and phosphorus yield: conventional (a, c) and with BMPs (b, d).

Since the main P export from agricultural land is PP (bound to soil particles), the ratio of the P exported into the lake to the gross removal rate in each field (P loss in Fig. 3) could be defined as the phosphorus delivery ratio (PDR). Numerically, SDR and PDR coincide and, therefore, the P load on the lake was considered as the gross production load of Fig. 3, multiplied for each basin SDR.

Therefore, the Lake Vico basin was divided into five areas, defined by groups of smaller homogeneous sub-basins (Fig. 5).

Many factors affect SDR, but, in general, it is negatively correlated with drainage basin area and positively correlated with drainage density, channel slope, valley-side slope and relief.

SDR evaluation is empirical and consequently there are a large number of formulae available in the literature (see, for example, the review of Ouyang and Bartholic, 1997). Naturally, there is a very high degree of uncertainty in the estimation of this parameter and only a thorough knowledge of the basin and carefully selected choices by the expert (possibly based on critical evaluation of experimental data) can give sufficient assurance.

In this case, the following formulae for the SDR were considered (for referencing, see the paper of Ouyang and Bartholic, up-dated on the cited web site):

$$\mathrm{SDR} = 1.36 \times 10^{-11}(A)^{-0.0998}(Z/L)^{0.3629}\mathrm{CN}^{5.444} \tag{3}$$

$$\mathrm{SDR} = 0.51 \times A^{-0.11}(\text{or } 0.42 \times A^{-0.125}) \tag{4}$$

$$\log(\mathrm{SDR}) = 2.943 - 0.824 \times \log(L/R) \tag{5}$$

$$\mathrm{SDR} = 0.627 \times S_{\mathrm{LP}}^{0.403} \tag{6}$$

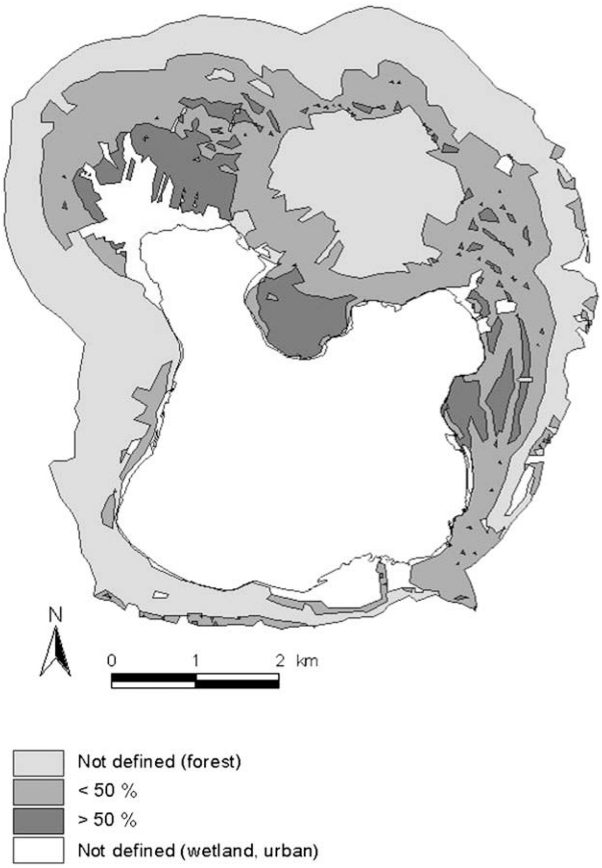

Fig. 4 – Effectiveness of BMPs in reducing phosphorus export.

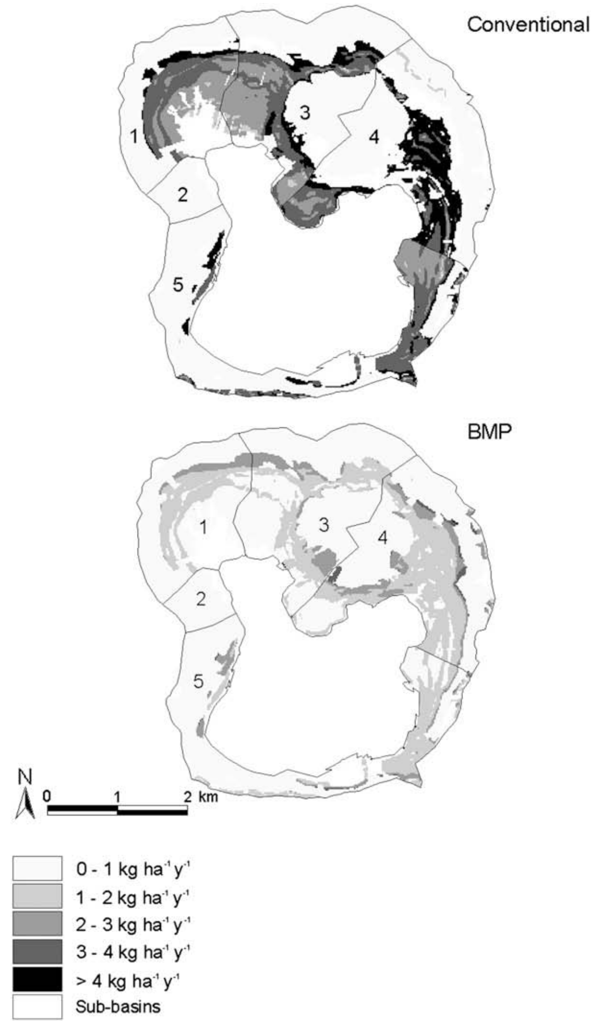

Fig. 5 – Export of phosphorus for conventional and BMPs scenario.

$$SDR = 0.488 - 0.00064 \times A + 0.0099 \times R_O \quad (7)$$

where SDR is the sediment delivery ratio; A is the drainage area in km^2; Z/L is the relief-length factor, in m km^{-1}, ratio between difference in elevation in m, of the watershed and the mouth of the stream, *versus* length of watershed (along the main stream, in km); CN is the long term, average US Soil Conservation Service (SCS) Curve Number; L/R is the dimensionless ratio of length of watershed (along the main stream) *versus* difference in elevation of the divide and the mouth of the stream; S_{LP} is the gradient of the stream, in %; R_O is the runoff, in cm.

They represent all the requirements for SDR evaluation: from the more immediate, related only to simple topographic factors such as the area (Eq. (4)) or the slope (Eq. (6)) or a relief factor (Eq. (5)), to the more complex, related to topography and land use (Eq. (3)) or topography and hydrology land use (Eq. (7)).

The results for Lake Vico are reported in Table 2.

The choice of the best equation was derived from the following considerations and evidence:

- the basin morphology is rather irregular, with very steep slopes in the higher part of the basin and much more gentle slopes down in the valley, around the lake. So, this part of the landscape works as a sort of sedimentation zone, since sediment from diffuse erosion has more probability of being trapped before reaching streams and the lake, thus reducing the SDR. Simple formulae considering only the area or the morphology (slope, relief *etc.*) are not able to interpret these characteristics;
- the Lake Vico basin soils are very coarse sands and, consequently, runoff events are rare, occurring only in particular hydrological conditions (Leone *et al.*, 2000); furthermore, the drainage net is not well developed, with few confluences and scarce stream density, due to the geologically young landscape.

Eqs. (4)–(6) are not able to interpret these two fundamental characteristics, because they are based only on basin morphology. In fact, they give SDR values which are too high (in one case there is also an overflow figure: area 2, Eq. (6)), which is not credible considering the basin's situation, which forces the SDR towards lower values. As a consequence, Eq. (3) was preferred, because it contains the US SCS Curve Number method (CN), which allows soil structure to be considered, to highlight better the role of land use, the real focus of the

Table 2 – SDR in each Lake Vico sub-basin, calculated by the five equations considered

Sub-basins	SDR						
	Eq. (3)		Eq. (4)		Eq. (5)	Eq. (6)	Eq. (7)
	Conventional tillage	BMP	Conventional tillage	BMP			
1	0.047	0.028	0.385	0.472	0.182	0.602	0.226
2	0.006	0.005	0.468	0.461	0.707	1.170	0.489
3	0.052	0.029	0.368	0.554	0.345	0.825	0.079
4	0.072	0.042	0.363	0.448	0.385	0.870	0.024
5	0.051	0.036	0.373	0.459	0.490	0.978	0.130

problem. Furthermore, the CN factor was experimentally verified on the basis of the results of a rainfall-runoff monitoring station in the Scardenato creek (Leone *et al*., 2000 and other unpublished data). The Scardenato creek sub-basin is in area 4.

2.3. *Total P lake concentration*

Having stated this result and considering the P loss maps in Fig. 3, the P export into the lake can be evaluated comparing both scenarios, without and with BMP (Fig. 5).

Quantitative evaluation of P export into the lake allows the Vollenweider (1976) model to be applied:

$$[P] = \frac{L(P)t_w}{z(1+\sqrt{t_w})}\left(\mu g\, l^{-1}\right) \tag{8}$$

where [P] is the equilibrium total P water concentration, expressed in $\mu g\, l^{-1}$ (the consequence of long term land use); $L(P)$ is the real P lake load, *i.e.* the ratio between phosphorus export and lake surface area, in $kg\,[P]\,km^{-2}\,year^{-1}$; t_w is hydraulic residence time, in years; z is the mean lake depth, in m. The calculus is illustrated in Table 3.

Furthermore, by means of this model, it is possible to compare LU/LC scenarios in terms of their consequence on lake trophic status, adopting the Organization for Economic Cooperation and Development (OECD) probabilistic trophic classification, as shown in Fig. 6.

3. Results and discussion

Fig. 5 reports the P export values produced by applying the model. The simulated mean water content for conventional management resulted 48.1 $\mu g\, l^{-1}$ [P], while that for the adopted BMP resulted 22.5 $\mu g\, l^{-1}$, compared to the last available monitoring figure of 55.0 $\mu g\, l^{-1}$ (ARPA, 2004) and a natural status of 14 $\mu g\, l^{-1}$ (Leone and Marini, 1993). Applying Eq. (2) to LU/LC with conventional agriculture, the simple bibliographic export coefficients method gave a value for the equilibrium total P concentration of 26.0 $\mu g\, l^{-1}$ (Leone and Marini, 1993).

Fig. 3a and b shows the soil erosion risk maps obtained by running the GLEAMS model. An alternative simulation method, the 'classical' Universal Soil Loss Equation (USLE) of Wischmeier and Smith (1978), was also used, giving quite similar results (Leone *et al*., 2001). However, the USLE is more difficult to apply at basin scale and gives a more relevant impact to very subjective factors (all multiplicative), especially to the soil cover factor C (USLE, Wischmeier and Smith, 1978). Both approaches, in any case, were congruent with magnitude order and, when compared with experimental data, demonstrate their ability to interpret well the higher risk zones in the northern and eastern part of the basin (Leone *et al*., 2001, 2006). For management purposes (BMP zoning and comparison) these results can be considered encouraging, although absolute quantities cannot be validated, at the moment, as detailed knowledge of the basin's hydrology in conditions of extreme rainfall is not available, nor is it an immediate research priority.

The same considerations are valid for phosphorus loss evaluation. The absolute values (see Fig. 3c and d) might appear too high at a glance, but are in fact reasonable if the very high natural soil phosphorus content is taken into consideration. In fact, total phosphorus soil text (P_{tot}), gave average values between 1217 and 2942 ppm (Leone *et al*., 2000). Compared to these values, the GLEAMS simulations of P losses range between 0.005% and 0.1%, not far from the experimental values cited in literature, for example: Frink (1991), Mattikalli

Table 3 – Phosphorus load evaluation from Lake Vico[a] basin land use and phosphorus water concentration by Vollenweider model; BMP

Sub-basins	Phosphorus load, $kg\,year^{-1}$	
	Conventional tillage	BMP
1	448.0	150.7
2	9.6	5.5
3	915.2	291.1
4	1250.4	496.7
5	560.3	215.5
Total from basins	3183.3	1154.8
Other P production		
Urbanised	246	246
Tourist	64	64
Livestock	191	191
Atmospheric	363	363
Total	3792.3	1763.8
P lake concentration, $\mu g\, l^{-1}$[b]	48.1	22.5

a Lake Vico characteristics: lake surface, 12.1 km^2; renewal time t_w, 17.0 years; mean lake depth z, 21.6 m.
b By Vollenweider (1976) model.

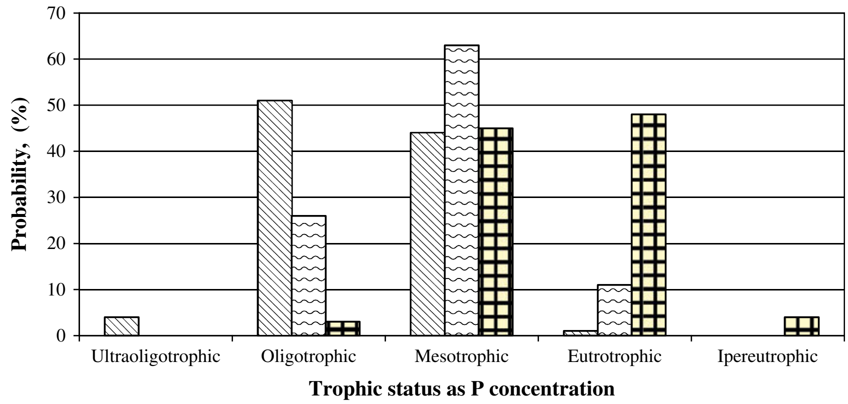

Fig. 6 – Lake trophic status, adopting the OECD probabilistic trophic classification (OECD, 1982): natural 0.014 mg/l, BMP adoption 0.022 mg/l, conventional tillage 0.048 mg/l.

and Richards (1996): Pote *et al.* (1996), Whiters *et al.* (2001), Pandey *et al.* (2005) and Mushtak *et al.* (2005).

Further confirmation comes from the experimental apparatus in the Lake Vico basin, where the runoff events registered in the last 5 years gave a P_{tot} loss from 5.2 to 18.0 kg ha^{-1}, due to rains of 2–30 years return time (Strauss *et al.*, 2007).

The proposed approach is an attempt to satisfy both the complexity required for the interpretation of the anthropogenic and environmental system and the simplicity required for management. The first, because its core is the GLEAMS model simulations, focuses on LU/LC; the latter, thanks to the very simple structure of the meta-model, can also be applied at basin scale. Both meet the requirements of land managers.

This compromise appears particularly useful in the frequently occurring situation where data is lacking, and thus it is impossible to calibrate and validate basin scale, physical models.

The advantages of more rational land management are evident and various, they include:

(1) landscape zoning in terms of sediment and phosphorus losses. This may seem banal, but it is fundamental, because it clearly highlights that the same LU/LC can have dramatically different impacts. In consequence, the same BMP can give very different contributions (from very low to very high) to agriculture sustainability, depending heavily on the environmental context;
(2) the possibility of evaluating planned BMPs, in terms of their environmental protection efficiency, which is evident from a simple visual comparison of Fig. 3 and from the spatialisation of the results of Eq. (2);
(3) the highlighting of zones where even BMPs produce too high P losses (the dark patches in Figs. 3d and 5b). In these zones, the slope is so steep that land managers would recommend natural rather than agricultural land use. A slope limit also derives from this, that discriminates sustainable and unsustainable agriculture, and it is a very powerful land management datum.

These results show what clear powerful answers, concerning the fundamentals of agricultural environmental sustainability can be obtained by land managers.

In future, these needs will become more and more pressing, considering, for example, the new European Common Agricultural Policy which will be funded on the principle of the eco-conditionality of financial support.

The proposed procedure has general validity, because it remains the same, even though single situations and site specificities (data availability, long series monitoring *etc.*) could modify the instruments required to implement it: model choice, the SDR approach, *etc.* For example, if a watershed is well monitored and a basin scale physical model is sufficiently calibrated and validated, the meta-model can be derived directly from it. In other words, specific situations could lead to a change in tools, but the following steps remain general:

(1) a preliminary assessment and consequent simulation of the problems and characteristics of the basin to be studied, using GLEAMS, or a similar model, to evaluate LU/LC systems and the related environment, aimed at interpreting complexity;
(2) a transformation of the previous results into 'simple and easy to apply' meta-models, for management necessities; this phase requires the use of *ad hoc* P export coefficients or P loss indices.

In this way, the 'simple and easy to apply' index does not come from generic literature tables or procedures, but it is specifically tailored to a well defined and checked situation, based on previous runs of a complex, physics based model. Hence, the advantages of both parametric or simple export coefficients and physical models are optimised.

Since a direct validation of the proposed approach is practically impossible, more indirect verification was carried out, by means of experimental evidence. The latter shows that, from different and independent points of view, the results can be considered satisfactory. Phosphorus export from agricultural areas (Fig. 3) is reasonable, in the magnitude of literature ranges and experimental evidence.

The lake water P content was calculated from P export values using the Vollenweider model (Table 3), and then compared to that obtained from monitoring. The similarity between the values provided further verification of the adopted procedure. Table 3, in fact, correlates lake P concentration to LU/LC, by means of the Vollenweider model. In particular, the first column, considers conventional tillage, *i.e.* the lake basin management until a few years ago, which can be considered as a synthesis of agricultural factors on the trophic status of the lake. The second column represents trophic evolution of the lake in recent years following implementation of the BMP.

The Vollenweider model application derives from Table 3; it gives a lake P concentration of 48.1 $\mu g\,l^{-1}$, very close to the experimental figure of 55,0 $\mu g\,l^{-1}$ (ARPA, 2004).

At the very least, these results are probably sufficient to compare scenarios, where uncertainty is mitigated by the fact that the environmental context is the same and changes are in land use (with and without BMP). Alternative methods cannot give the same effectiveness for land management objectives. Indeed, it is by no means certain that traditional methods and direct model validation would be able to give the same easily applied results.

The Lake Vico monitoring example (and other examples e.g. Heathwaite, 2003) supports this assumption: since 1999 a monitoring station has been installed in the lake basin, to record rainfall, runoff, sediment yield and the water quality of runoff in a representative sub-basin (2.66 km^2 of the total Lake Vico basin of 40.1 km^2). However, due to the intense drought of recent years, few relevant events have been recorded by this station and, at present, it is not possible to foresee when an adequate time series record will be available for satisfactory model validation. Furthermore, experimental data are site specific and, therefore, not immediately applicable to other landscapes where specific monitoring time series should be available.

This means that, rather than exact forecasts, at least in the first phase, it is more useful to address efforts to comparing land use scenarios and to the implementing territory informative systems. This requires the application of models, but with a less refined approach, oriented to comparison. The results can be verified by simpler indirect methods, because the comparative approach is less demanding and reduces uncertainty.

An advantage of the method is surely the possibility of zoning the territory according to level of risk in a completely distributed approach (cell by cell, Fig. 3), that, in many cases is more effective than a semi-distributed or lumped approach. In this case, it is due to the topography of the Lake Vico basin that quickly changes from the very steep slopes of the higher part of the basin to the flat zones around the lake. This means that the sub-basin approach of semi-distributed models such as SWAT proved inadequate, requiring not only a very refined DTM (the 25 m raster of the available DTM, normally considered very refined, was still not sufficient in this case), but also a division of the basin into an enormous, impractical number of sub-basins (Leone *et al.*, 2003).

Other advantages in decision-making are clear: it is possible to compare scenarios and evaluate the efficiency of mitigation scenarios (Figs. 4 and 5), also in terms of shifting lake trophic status, that is a consequence of landscape order and, in particular, of agricultural land management (Fig. 6). Fig. 6 summarises how lake hydro-biology changes in consequence of LU/LC scenarios that are a very powerful tool for decision-making and agricultural environmental sustainability assessment.

This is the real usefulness of the proposed method, which maintains the frame of simple export index approaches, but also interprets the complex environmental context (climate, soil, topography *etc.*). Hence, it can be considered a contribution to more process-oriented land management and a stimulus towards a more rational use of agriculture sustainability subsidies.

Furthermore, the evaluation of P export into freshwater allows an integrated approach, that considers the joint contribution of the whole LU/LC and related consequences on final water bodies. In fact, this study also shows how it is possible to evaluate the consequences of LU/LC changes in the watershed on receiving water bodies associating to each scenario an environmental quality index (lake trophic status, in this case).

4. Conclusions

The aim of this work was to evaluate how landscape order could affect water body quality, focussing scenarios for sustainable agricultural systems. By the use of models BMP environmental efficiency and risk areas were evaluated, in terms of soil conservation and phosphorus loss reduction.

The literature is rich in models and approaches, each with advantages and drawbacks. The present study proposes a method that attempts to maximise the advantages of complex, physics based, distributed models while offering land managers simple export indices of freshwater P loads.

The suggested approach solves various aspects of land management sustainability, by including: (i) a more rigorous and objective (process oriented) evaluation of different land management scenarios; (ii) the possibility of landscape zoning according to level of risk, with and without BMPs and, at the same time, quantifying related environmental efficiency; (iii) an integrated evaluation of LU/LC, in terms of its impact on freshwater ecological status; and (iv) a forecasting of long-term water body condition, as a consequence of LU/LC.

These results when compared to experimental evidence appear reasonable, at least for BMP evaluation and land planning, but they are also encouraging from the point of view of absolute forecasts.

Regarding the general validity of this study, it is the proposed procedure, that remains generally valid, even though data availability, long series monitoring *etc.* could modify the instruments required to implement it (model type, SDR approach, *etc.*), depending on specific situations. The steps to be performed, which are widely applicable, encourage land planners to base choices on a 'simple and easy to apply' index, that does not come from generic literature tables or procedures, but is specifically tailored on previous runs of a complex, physics based, validated model.

In this way, the advantages of both parametric or simple export coefficients and physical models can be optimised, providing land managers with more quantitatively supported tools for their decision-making.

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