A phosphorus index for use in intensive irrigated areas

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Abstract

In irrigated semi-arid areas, nutrient pollution from agriculture from irrigation return flows is one of the most important surface water quality problems and can lead to eutrophication. In this study a new phosphorus index called IPreg has been adapted as a management tool for application to irrigated farming systems and then applied within "Las Filadas" drainage basin (Spain) at a plot scale. Two new transport factors related to the irrigation management system were introduced: (1) the seasonal irrigation performance index and (2) the efficiency of the mean irrigation dose that represents average water losses below the root zone when an average irrigation dose is applied. IPreg includes 10 factors, three of which account for P availability in the soil and seven for P transport processes. The results indicate that 18 % of the study area had a high to very high risk of phosphorus loss and 60 % at medium risk. Corn and alfalfa had the highest IPreg values under intense irrigation and high fertilizer application rates. IPreg was also higher in phosphorus-rich soils and in plots treated with organic manure, especially pig slurry.

Keywords: phosphorus, pollution, soil management, water management.

Introduction

An increase in nutrient levels in fresh water bodies leads to undesirable changes in ecological equilibrium and has been detected in recent decades. The P enrichment in water bodies may contribute to their eutrophication (Carpenter *et al*., 1998). This phenomenon may occur in surface waters having P concentration as low as 0.02 mg l^{-1} (Sharpley & Rekolainen, 1997). In agricultural systems, several studies suggest that most of the P transported from soil to water originates in specific fields or from particular actions by farmers (Weld *et al.*, 2001). Thus, the identification of areas that pose the greatest risk for P loss to surface waters is a critical component in P management.

Since 1980 P concentrations have decreased in the main European rivers due to development in waste water treatment and use of phosphate-free detergents (EEA, 2010). A reduction in phosphate concentration has been observed since 1989 in most of the Ebro River tributaries, but P concentration still remained high in 2006 (Isidoro & Aragüés, 2007). In a survey on water quality in several agricultural catchments in the Ebro Valley (Spain), Skhiri & Dechmi (2011) conclude that diffuse P pollution is of major significance and that this trend will continue without corrective action. High nutrient concentrations were one of the reasons for the European Union adopting the Water Framework Directive (EU, 2000) aimed at protecting and enhancing the status of all European aquatic ecosystems by 2015. Now farmers are accepting the challenge by making their practices more environmentally sustainable. Consequently, measures and tools to assess diffuse P losses are required.

The transfer of P from soils to surface waters is a complex function of climate, topography, soil type and land management and varies both temporally and spatially (Heckrath *et al.*, 2008). Several models on phosphorus diffuse pollution have been developed in order to identify management practices that could reduce P losses. These models fall into two broad categories: numerical models that give a quantitative evaluation of P loss and models based on indices for predicting qualitatively the relative risk of P losses to surface waters (Lemunyon & Gilbert, 1993; Sharpley *et al.*, 2003; van Bochove *et al.*, 2006). The numerical models, such as the Soil and Water Assessment

Tool (Arnold & Fohrer, 2005), can predict in detail P losses at the catchment scale. However, such models usually require large quantities of detailed input data which are not always available; the result is that it is difficult for farmers or other stakeholders to be end-users of such models. The need is for more user-friendly and simpler tools to evaluate the risk of P loss. Input data are widely available for phosphorus indices which are also are much easier to use.

The P index approach (PI) ranks site vulnerability to P loss by accounting for P source and transport factors. In irrigated agricultural systems, the most relevant water outflow from agricultural land is irrigation return flow (IRF) which is the water leaving irrigated land as surface or sub-surface flow as a result of irrigation (Aragüés & Tanji, 2003). The volume of IRF is related directly to irrigation water management and use efficiency. Those factors are of paramount importance in irrigated systems, but are not considered in any P index available in current literature (Buczko & Kuchenbuch, 2007). This paper presents the development and methodology for the calculation of a new PI (called IPreg) that can act as a diagnostic tool for intensive irrigated areas. The IPreg approach was tested at plot scale in an irrigated basin and its limitations are discussed.

Materials and methods

The original P Index developed by Lemunyon & Gilbert (1993) was used as the starting point for the new index (IPreg). Three new transport factors related to irrigation method and management were included for the first time in the methodology for a P Index (Skhiri & Dechmi, 2012). In total IPreg includes 10 factors: three accounting for P availability in the soil (P source component, PSC) and seven for the P transport processes (P transport component, PTC). For each factor, five risk classes are defined based on the factor range and a score of 0, 2, 4, 6, or 8 is assigned to each class (from minimum to maximum risk). Additionally, each individual factor is assigned a weight (0, 1 or 2) based on expert judgement to account for the fact that some factors exert a greater influence on P loss than others in irrigated arid areas. The products of the weights and scores for each individual factor are summed to calculate PTC and PSC. Unlike the original P index developed by Lemunyon & Gilbert **(**1993), IPreg relates P source and transport components as a product rather than as a summation. This is because the additive form will predict risk of P losses in the absence of transport process whereas in irrigated areas, IRF is the dominant transport process and can be controlled by appropriate irrigation management. Thus it was considered that it was better to design an index which results in no P loss risk in the absence of transport processes.

P transport component (PTC)

The PTC accounts for the mechanisms that deliver particulate and dissolved P from agricultural land to surface water via erosion, surface runoff and infiltration as well as for the hydrological connectivity between sources and water bodies (preferential flow, distance to water body). For IPreg the factors considered in the PTC were (i) the soil erosion rate (E), (ii) the runoff risk (RR), (iii) the contributing distance (CD), and (iv) the preferential flow (PF) in addition to three factors dealing specifically with irrigation: (v) the irrigation system (IS), (vi) the seasonal irrigation performance index (SIPI), and (vii) the mean irrigation dose efficiency (IDE). All these individual factors are multiplied by their weights and added to yield the PTC.

1. The soil erosion rate (E) was calculated by means of the Revised Universal Soil Loss Equation (Renard *et al.*, 1991) and reported in tons·ha^{-1}·year^{-1}. For this data are needed on rainfall erosivity (R), soil erodibility (K), topography (LS), land use practices and crop type (C), and conservation practices (P), all of which were determined at the plot level. Factor E was assigned the same weight (1.0) suggested by McFarland *et al.* (1998) for the adapted P index. The ranges in E defining the 5 risk classes were the same as proposed by van Bochove *et al.* (2007) (Table1).

2. The Runoff Risk factor (RR) was incorporated into IPreg to account for runoff which can be important in arid conditions. This process depends on various factors such as drainage and meteorological conditions, cropping and tillage practices, soil characteristics and topography. As suggested by McFarland *et al.* (1998), the class categories for RR were estimated using a matrix relating the plots' slope to runoff curve numbers (USDA-SCS, 1972).

3. The contributing distance (CD) was calculated as the shortest distance from the edge of field to the nearest stream or drainage canal. Five CD risk classes were suggested given that the potential P contribution via surface and subsurface runoff was inversely proportional to the distance to the nearest drainage line (Table 1).

4. Preferential flow (PF) is a key pathway for subsurface contaminant transport. However, only a few P indices do incorporate PF (Dadfar *et al.*, 2010), possibly due to the large number of factors affecting this process. The phosphorus index developed by Beaulieu *et al.* (2006) and Goulet *et al.* (2006) included PF in a simple way, assuming that PF was only related to soil texture. In this study the methodology of Beaulieu *et al.* (2006) was selected for estimating the PF factor. The PF high risk class is associated

with heavy clay and coarse sand soil textures, and the very low risk class with sandy loam soils. Although preferential flow may play an important role in the nutrient transport, especially in the presence of a subsurface drainage network, the weight assigned to the PF factor was only 1.0. This lower weight was assigned to PF due to the simplifications and limitations in the methodology for estimating the PF factor. Both the CD and PF factors are very important in assessing P transport risk as they reflect the hydrological connectivity from land to surface water bodies.

5. For the types of irrigation systems (IS), five risk classes, each corresponding to a group of irrigation systems, were defined according to their ability to induce surface runoff and erosion (Table 1).

6. The SIPI represents a simplification of the standard irrigation efficiency concept defined by Burt *et al.* (1997). The SIPI is defined as the ratio expressed as a percentage of net irrigation requirement (NIR) to total applied water in the season and NIR is calculated as crop evapotranspiration minus effective precipitation (Faci *et al.*, 2000).

7. The IDE estimates the average water loss below the root zone in a single irrigation event when an average irrigation dose was applied. The IDE was calculated as the difference between the average irrigation amount applied to the crop and the total available water in the soil (TAW).

The highest weights (2.0) were assigned to the SIPI and IDE (the factors directly related with water use management) in order to incorporate into the IPreg the high impact on P transport attributed to irrigation water management. The other transport factors were assigned a weight of 1.0 to reflect their lower impact compared to the irrigation water management factors. The five risk classes adopted for the SIPI and IDE are presented in Table 1.

P source component (PSC)

The P source factors considered in IPreg were (i) the soil P test (P_{test}), (ii) the P excess (P_{exc}), and (iii) the P fertilizer application method. All these individual factors are multiplied by their weights and added to yield the PSC.

1. The P_{test} is intended to identify the soils with a P excess deemed high enough to contribute to nonpoint source pollution. The P soil tests most commonly used today are Bray and Kurtz P-1, Mehlich 1, Mehlich 3, and Olsen P. Phosphorus extracted by the Bray and Kurtz P-1 method has been shown to correlate well with crop yield response on most acid and neutral soils. Kuo (1996) reports that the Mehlich 1 soil test is unreliable for calcareous or alkaline soils because it extracts large amounts of nonlabile P in soils with pH > 6.5. In practice the Mehlich 3 test is used because it is well suited to a wide range of soils, both acidic and basic. However, the Olsen P method is best suited for calcareous soils, particularly those with > 2% calcium carbonate, but has been shown to be reasonably effective also for acidic soils (Fixen and Grove, 1990). As calcareous soils dominate arid and semi-arid areas where most irrigation takes place, the Olsen P test was selected as the most adequate for the P_{test} factor to include in IPreg. The depth of the soil layer to measure P_{test} depends on soil type, surface slope, rainfall intensity and crop residue. Sharpley (1985) states that for most agricultural soils, a depth of 20 mm would define accurately the effective depth of runoff interaction generated by moderate to high rainfall intensity (< 50 mm/h). Thus, the P_{test} (Olsen P) in the upper 30 cm layer was selected for IPreg as it shows the P available for leaching by

runoff and also by drainage. The ranges for the Olsen P soil test were adapted from the soil analysis interpretation given by López Ritas (1978) (the soil P content is considered high when soil Olsen P is $\geq$ 25 ppm for a medium soil texture).

2. The P excess factor (P_{exc}) was calculated as the difference between P inputs (both fertilizer and manure) and crop P uptake. The P manure indicates the quantity of P from manure applied in each plot, the P mineral estimates the quantity of P from phosphated mineral fertilizers used for crops at plot scale and P uptake estimates the seasonal quantity of P in crop harvests. The amount of P exported by crops was estimated as the product of the average crop yields and their phosphorus contents.

The two factors P_{test} and P_{exc} are important in intensive agricultural systems and have a great impact on P loss and therefore they were assigned the highest weight (2.0). The five risk classes adopted for the P_{test} and P_{exc} are presented in Table 1.

3. For applying organic or inorganic fertilizers, the same risk classes and weights defined in the original P index by Lemunyon & Gilbert (1993) were chosen (Table 1).

IPreg algorithm

A general IPreg flow diagram and algorithm are presented in Figure 1 and Table 1, respectively. The range for the sum of the weighted PTC factors is 0-72 (sum of weights = 9; maximum score = 8), and this was divided by 72 to limit the PTC range from 0 to 1 (Table 1). The PSC (sum of the weighted PSC factors) ranges from 0 to 44 (Table 1); and thus the product of PTC (0 to 1) and PSC (0 to 44) was multiplied by 2.27 to achieve a final IPreg in the range 0 to 100. This final IPreg was assigned to one of the five classes of P loss risk: very low, low, moderate, high and very high (Table 1). The higher the IPreg, the greater is the need to manage the soil, crop, irrigation water and nutrient applications to minimize the risk of P loss from the soil.

Calculation method and IPreg test

The methodology was tested in "Las Filadas" catchment, 35 km south-east of Huesca, Spain (Figure 2), part of the Alto Aragón Irrigation System (the most important irrigated system in the middle Ebro River Basin with an irrigated area > 120000 ha). The catchment irrigated area is 4920 ha (ca. 53 % of the total area), and comprises 1938 plots of heterogeneous size (2.5 ha on average), managed by three irrigation districts (Lanaja, Orillena and Lalueza). In 2007 90 % of the area was flood irrigated for field crops, mainly alfalfa, corn and wheat. Then IPreg was calculated for 2007 for each of these surface irrigated plots by identifying all the plot factors. Most of these surface irrigated plots are being converted to sprinkler irrigation. Evaluating IPreg under sprinkler irrigation and comparing P losses under both irrigation systems will be of interest in the future.

The climate is semiarid, with an average annual rainfall of 392 mm and an average reference evapotranspiration (ETo) of 1154 mm. According the world reference base for soil resources (IUSS Working Group WRB, 2007), Cambisols are the main soil group in the catchment (85 % of the area), followed by Xerosols (10%) and Fluvisols (5 %). At the catchment outlet, average water flow was 334 l s^{-1} and the average phosphate concentration was high (0.16 mg l^{-1}) with dissolved P as the dominant form.

The study area was characterised in detail to create a geo-referenced database as needed to calculate each factor for 2007. Field surveys were performed to determine the spatial distribution and total area of each crop. Farmers' water management and farming practices were determined through interviews in 2007. A total of 60 farmers were randomly selected for the interviews.

A soil survey was done in 2007 to determine the main soil physical and hydraulic properties in the study area as needed for the determination of the factors IDE (total available water), PF and P_{test}. Eleven homogenous soil units were considered on the basis of their topography, FAO soil classification and lithology. A total of 31 auger holes (one point per 150 ha) were bored in all the soil units. In each point soil samples were collected for each 0.3 m layer down to 1.2 m when possible to give a total of 81 soil samples. For each sample, soil texture, organic mater, P Olsen, bulk density, field capacity (FC) and wilting point (WP) were determined. Total available water (TAW, mm) was calculated after Walker & Skogerboe (1987).

Phosphorus transport component (PTC)

The RUSLE estimation of the erosivity factor (R) uses the maximum 30-min rainfall intensity data. However, the precipitation data in the study area were only available on a daily basis. Thus, the RUSLE factor R was estimated from the daily precipitation following Loureiro & Coutinho (2001):

$$R = 1/n \sum_{i=1}^{n} \sum_{j=1}^{12} (7.05\ \mathrm{rain}_{10} - 88.92\ \mathrm{days}_{10})_j \qquad [1]$$

where n is the number of years, i is the year, j is the month, rain_{10} is the average of the daily precipitation > 10 mm day^{-1} in a given month, and days_{10} is the number of days in a month with P >10 mm. Precipitation records between 1987 and 2007 for the nearest six meteorological stations were used to estimate R. Factor K (soil erodibility) was calculated using soil manual # 430 of USDA (1983) from the average soil texture and organic matter of each soil unit. The LS (slope-length) factor was calculated with the Moore & Burch (1986a and 1986b) equation based on a 10 m Digital Elevation Model and using a Geographic Information System (ArcGIS 9.0). The C factor (cover-management) was parameterised incorporating information about land use data, agricultural practices and type of irrigation system. The P factor (conservation practices) was taken to be equal to 1 because conservation practices were not used in the study area.

The runoff curve number (USDA-SCS, 1972) was determined for each plot from a matrix using information on land use, cultural practice, hydrologic condition and soil hydrologic group (determined as a function of surface soil texture). All these calculated factors were then used to estimate the soil erosion rate (E) following Renard *et al.* (1991).

The contributing distance (CD) was taken as the shortest distance from the edge of field to the nearest ditch and was calculated using GIS. The preferential flow (PF) risk factor was determined from the dominant soil texture in each plot (Beaulieu *et al.*, 2006). The seasonal irrigation dose for each field was provided by district managers. Net irrigation requirements were determined for each crop (ETc – PE). The standard FAO procedure (Allen *et al.*, 1998) was used to determine the Penman-Monteith reference evapotranspiration (ET_0) and crop evapotranspiration (ETc) with the crop coefficients (Kc) taken from Martinez-Cob *et al.* (1998) and the records from the Lanaja meteorological station for 2007. The PE was determined using the USDA method (Cuenca, 1989) and the same meteorological methods.

Phosphorus source component (PSC)

The P soil test factor (P_{test}) was determined from the measured P Olsen in the upper soil layer (0-30 cm). Mean fertilizer and manure P applications were determined for each crop from the farmers' interviews. Every plot with a given crop was assumed to receive the mean P application for that crop. The amount of P exported by the crops was determined as the product of average the crop yields (gathered from field surveys) and their phosphorus content (MAPA, 2007). The P fertilizer application factor was determined for each plot and crop following the farmers' interviews and guidance from irrigation district managers.

Results

Soil properties and management practices

Most soils in the study area have a loam texture (67%) and the others are silt loam (16 %) and silty clay loam (Table 2). The results indicate great variability in soil depth, total available water and P Olsen content. The loamy soils (except unit 7) have the lowest depth (50 cm in average) and TAW (82 mm in average) to highlight the need for frequent small irrigations. In these soils, inadequate water use can lead to important water losses below the root zone. The soils with a silty clay loam texture were deeper and had a greater TAW.

No relationship between soil texture and P Olsen content was found. The large variability in average soil P content (from 6 to 45 ppm) was due to the combination of different factor including soil characteristics, soil use and fertilizer practices. In the deeper soils, average soil P content decreased with depth (data not shown) and had very low values in the deeper layers (data not shown). In shallow soils (depth < 60 cm), no sharp decrease in P soil content was observed between 0-30 cm and 30-60 cm. According to López Ritas (1978), the P content in soil units 3 and 9 was considered high (≥ 25 ppm for medium and coarse soil texture and ≥ 13 ppm for fine soil texture) and therefore fertilizer application was not necessary (Table 2). In the upper layer of soil units 3, 6, 8, 9 and 11, P content was high and so these units could be relevant sources of P.

The average applied seasonal irrigation water was 8155 m^3 ha^{-1} which is in the normal range for surface irrigated systems in the Middle Ebro Valley. Table 3 shows that sunflower and ray-grass net irrigation requirements (NIR) were not met by irrigation (NIR > average water applied, WU). Thus, no water losses were assumed from the sunflower and ray-grass cultivated fields as long as the applied irrigation dose was equal or lower than the soil TAW. For the rest of crops, the applied water exceeded the NIR (WU > NIR; Table 3). Therefore the drainage originating from these over-irrigated areas (94 % of total area) led to high irrigation return flows and could potentially have lead to high P losses. The average irrigation was > 100 mm for alfalfa, corn and winter cereal. Wheat and barley required a greater amount because they received, in general, only 1 or 2 Spring irrigations; the higher rates were justified for alfalfa and corn by their higher economic return (Table 3). Only 26 % of total area received average irrigation less than the TAW. In those plots no P loss risk can have occurred if the irrigation events were sufficiently separated in time and the uniformity of applied water was good.

The P fertilizer applications (expressed in P_2O_5) were >100 kg ha^{-1} $year^{-1}$ for alfalfa, corn, ray-grass and rice, but <60 kg ha^{-1} yr^{-1} for wheat and barley (Table 3). These fertilizer rates were more than sufficient for soils with a P Olsen content > 5 ppm

(Hernández Abreu, 1975), but all soil units had average P Olsen values for the layer 0-30 cm ranging from 9 ppm to 75 ppm, indicating excessive P fertilizer application. Also, the P in the harvested crops was lower than the P fertilizer applied to the main crops, except for wheat (Table 3). SIPI is a useful index for analyzing irrigation water use practices and only barley, sunflower and ray-grass had a SIPI > 100 % showing that the water use did not meet crop needs. Sprinkler systems were more efficient in water use than flood ones.

Application of the Phosphorus index (IPreg) to the study area

The average soil potential loss (E) was ca. 0.787 t ha^{-1} yr^{-1} due to the gentle slopes of the land for surface irrigation. Results also show that 83 % of the irrigated area had a very low erosion potential risk (Figure 3a.). This demonstrates that erosion was not a determining factor in IPreg in flood irrigation systems.These results may change following conversion to a pressure irrigation system which does not require plot levelling and removal of margins between irrigation basins. Over 79 % of the study area had low runoff potential (Figure 3b), whereas only 5 % and 1 % of the total area were at high and very high risk, respectively. All the plots in the study area were assigned to only two risk classes of PF. The low risk class represented 70 % of the total area and was associated with soils with loam and silt loam textures. The rest of the surface corresponded to soils with a silty clay loam texture and therefore belonged to the medium risk class. The absence of the high and very high risk classes was due to the absence of sandy or clayey soil textures in the area.For the SIPI factor (Figure 3c), 13 % and 29 % of the total area of 2056 ha belonged to the very high and high risk classes, respectively (SIPI < 80 %), while only 27 % of total area was assigned to the low and very low risk classes (SIPI > 100 %). Irrigation Dose Efficiency (IDE) was > 200 mm ha^{-1} (very high risk class) in 22 % of the total area (Figure 3d), with this highest IDE on uncultivated plots where farmers applied irrigation water only for salt leaching. On the other hand, the classes of medium (50 mm < IDE < 100 mm) and high (100 mm < IDE < 200 mm) IDE risk each represented 19 % of the total area (1884 ha in total). The majority of these high IDE risk plots were in the central part of the study area.

There were no plots within 10 m of the streams (contributing distance factor, CD). The plots with CD > 300 m represented 30 % of the total area (1470 ha) and were assumed not to contribute to the P transfer by this factor. In the study area, the irrigation system factor (IS) did not have a great impact because most of the area had the same surface irrigation system and a low potential for P transport risk (all the area was included in the low risk class for IS). This will change after modernization of the study area.

The soil P risk (Figure 3a) was medium (available P Olsen in the soil layer 0-30 cm between 10 and 25 ppm) in 80 % of the plots (57 % of total area). The area in the high and the very high classes was very important (40 % of total area). These results were due to different management practices (higher irrigation and fertilizer doses). However, the high and very high risk classes for P excess (Figure 4b) were mainly in alfalfa cultivated plots with manure (mainly pig slurry) application (20 % and 50% of the area belonged to the high and very high risk classes, respectively).

31 % of the total area was in the high and very high PTC risk classes and > 50 % in the medium risk class (Figure 5B). The source component did not show the same tendency. In this case, > 70 % of the total area was at high and very high risk (Figure 5A). The resulting IPreg scores ranged from 1 to 63. The spatial distribution of IPreg risk classes

(Figure 6) was somewhat similar to the risk classes for PTC. Finally, 18 % (810 ha) of the study area was at high to very high risk (IPreg > 30) of phosphorus loss and 60 % (2686 ha) at moderate risk (15 < IPreg < 30) (Table 4). As determination of the PF factor was very simplified, an additional calculation of IPreg was done without considering PF in order to evaluate the impact of this factor and the results indicated no change in the proportion of the total area in each of the five risk classes.

Discussion

The global analysis of management practices and results from soil sampling in the study area showed that irrigation and P fertilizer rates were excessive in 2007, and that P Olsen soil content was generally high. The high drainage water P concentration measured at the outlet of the catchment (0.16 mg l^{-1} on average) indicated P export from the cultivated soils. Measuring the P export from each cultivated plot reaching the surface waters is extremely difficult. However, use of IPreg helped to identify potential P loss from all the plots in the study area and thus it was possible to assign each to one of the five risk classes. Corn and alfalfa cultivated plots had the highest IPreg values in the study area as a result of the large volumes of applied irrigation water and excessive phosphorus fertilizers. Also, plots on which organic fertilizers (especially pig slurry) were used had a higher IPreg than the others and the same was found with phosphorus-rich soils. The IPreg results indicate the need to modify fertilizers and irrigation management in some plots in order to improve the quality of the IRF. Many practices can be tested in those plots, including changes in the rate and method of nutrient application, the volume of irrigation water applied, and the timing and irrigation amounts.

The IPreg results are subject to a number of limitations and uncertainties associated with the calculation of the factors' potential risk. The main limitation of the PTC was that subsurface drainage could not be incorporated in the IPreg as has been done in other P indexes (van Bochove *et al.*, 2006; Ulén *et al.*, 2011). In addition, the PF did not have an impact on P risk assessment using IPreg. The importance of this in irrigated semi-arid areas (Amezketa *et al.*, 2005) suggests the need to incorporate PF into IPreg. To improve IPreg, the impact of irrigation water distribution on deep percolation losses and therefore on nutrient transfer should be addressed (Bruckler *et al.*, 2000; Lafolie *et al.*, 2000; Li *et al.*, 2005).

The inclusion of irrigation efficiency through SIPI introduced a degree of uncertainty due to the use of the maximum crop evapotranspiration (ETc) rather than actual crop evapotranspiration (ETa). However, this simplification of actual crop water uptake is only important in surface irrigation systems. In sprinkler irrigation systems, ETr is in general similar to ETc (Skhiri & Dechmi, 2012). However, the rate of the water erosion (factor E) could be a major source of uncertainty in the PTC calculation because the eroded soil can be deposited at various locations in the drainage network. Improving the estimation of the potential risk induced by the erosion process through a soil delivery ratio is important primarily for sprinkler irrigation systems.

Conclusion

IPreg included new transport factors to account for irrigation management practices. The application of IPreg in the semi-arid case study allowed identification of critical areas for P transfer as induced by high irrigation treatments and excessive applications of phosphorus fertilizers. However, IPreg as presented in this paper must be regarded as a first approximation. The study shows that IPreg can be applied to medium-sized irrigated areas using basic soil and management information and yielded results which indicated the main management issues causing P losses. Results must be compared with data from actual plots or single-use irrigation basins where P exports can be determined in order to assign weights and to establish ranges for risk classes for each factor that best suit observed P export rates. This calibration process may also reveal the need for new factors for inclusion. IPreg results with calibrated weights and class definitions must be further validated with additional observations. This laborious and intensive data-demanding process is the next step to be carried out in the development of IPreg as more detailed information about management practices and P losses become available. Further field verification is necessary before general acceptance of the results, but IPreg as described can be used as a screening tool to identify irrigated areas subject to a critical risk of P loss.

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Table 1. Weights and rating values for each factor in IPreg: Erosion (E), runoff risk (RR), preferential flow (PF), contributing distance (CD), seasonal irrigation performance index (SIPI), irrigation dose efficiency (IDE), type of irrigation system (IS), P soil test (P_{test}), P manure and fertilizer excess (P_{exc}), manure application method (MAM) and fertilizer application method (FAM). The algorithms for the calculation of the P transport component (PTC), P source component (PSC) and IRreg are also presented.

<table>
<tr><th rowspan="2">Field factor</th><th rowspan="2">Weight</th><th colspan="5">Risk classes</th></tr>
<tr><th>Very Low (0)</th><th>Low (2)</th><th>Medium (4)</th><th>High (6)</th><th>Very High (8)</th></tr>
<tr><td>E (tons ha^{-1} yr^{-1})</td><td>1.0</td><td>< 0.5</td><td>0.5 – 2</td><td>2 – 6</td><td>6 – 15</td><td>> 15</td></tr>
<tr><td>RR (-)</td><td>1.0</td><td>Very Low</td><td>Low</td><td>Medium</td><td>High</td><td>Very High</td></tr>
<tr><td>PF (-)</td><td>1.0</td><td>Very Low</td><td>Low</td><td>Medium</td><td>High</td><td>Very High</td></tr>
<tr><td>CD (m)</td><td>1.0</td><td>> 300</td><td>150 – 300</td><td>50 – 150</td><td>10 – 50</td><td>< 10</td></tr>
<tr><td>SIPI (%)</td><td>2.0</td><td>Not applicable</td><td>> 100</td><td>80 – 100</td><td>50 – 80</td><td>< 50</td></tr>
<tr><td>IDE (mm)</td><td>2.0</td><td>< 0</td><td>0 – 50</td><td>50 – 100</td><td>100 – 200</td><td>> 200</td></tr>
<tr><td>IS (-)</td><td>1.0</td><td>Not applicable</td><td>Basin and Border</td><td>Furrow Sprinkler + slope < 2 %</td><td>Sprinkler + slope < 4 %</td><td>Sprinkler + slope > 4 %</td></tr>
<tr><td>P transport component</td><td colspan="6">PTC= [E+RR+PF+CD+IS+2(SIPI+IDE)]/72</td></tr>
<tr><td>P soil test, ppm (P_{test})</td><td>2.0</td><td>Not applicable</td><td>< 10</td><td>10 – 25</td><td>25 – 50</td><td>> 50</td></tr>
<tr><td>P_{exc} (ppm)</td><td>2.0</td><td>< 0</td><td>0 –10</td><td>10 – 25</td><td>25 – 50</td><td>>50</td></tr>
<tr><td>MAM (-)</td><td>1.0</td><td rowspan="2">None Applied</td><td rowspan="2">Injected deeper than 5 cm</td><td rowspan="2">Injected no deeper than 5 cm</td><td rowspan="2">Surface applied and incorporated immediately (< 24 h)</td><td rowspan="2">Surface applied, not incorporated</td></tr>
<tr><td>FAM (-)</td><td>0.5</td></tr>
<tr><td>P source component</td><td colspan="6">PSC = 2 (P_{exc} + P_{test}) + 0.5 MAM + FAM</td></tr>
</table>

P Index	IPreg = PTC · PSC · 2.27				
	IPreg risk classes				
	Very low 0 - 5	Low 5 -15	Moderate 15 - 30	High 30 – 50	Very high 50 - 100

Table 2. Description of the soil units in the study area: Percent area occupied (Surface); average slope, soil depth, total available water (TAW), and phosphorus Olsen content (P); and textural class (Texture). The standard deviation is given in brackets for P.

Soil Unit	**Surface (%)**	**Slope (%)**	**Depth (cm)**	**TAW (mm)**	**P (ppm)**	**Texture (-)**
1	1.2	3 - 5	45	107	19 (22)	Silt loam
2	5.8	10 - 15	38	49	13 (13)	Loam
3	15.9	10 - 15	51	76	30 (31)	Loam
4	14.9	10 - 15	88	184	6 (14)	Silt loam
5	20.2	2 - 4	44	64	17 (17)	Loam
6	15.9	2 - 4	120	212	10 (22)	Silty clay loam
7	7.1	10 - 15	80	208	7 (14)	Loam
8	12.6	0 - 3	55	112	19 (31)	Loam
9	1.3	0 - 6	60	108	45 (75)	Loam
10	3.7	10 - 15	50	81	8 (9)	Loam
11	1.3	0 - 5	120	215	7 (14)	Silty clay loam

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Table 3. Management practices for the main irrigated crops in Las Filadas Gully: Water Use (WU); Net Irrigation Requirement (NIR); mean Irrigation Dose (ID), phosphorus fertilizer applied (P_2O_5) and phosphorus uptake (P_2O_5 Uptake), both expressed as P_2O_5.

Crop	Surface (ha)	WU (mm)	NIR (mm)	ID (mm)	P_2O_5 (kg ha^{-1})	P_2O_5 Uptake (kg ha^{-1})
Alfalfa	1600.0	1326.0	774	126.3	174	75.2
Rice	34.1	1250.0	968	-	105	45.0
Barley	1486.4	448.9	392	200.0	60	38.8
Sunflower	15.5	472.0	596	100.0	60	21.3
Corn	573.0	1288.6	645	183.3	126	72.7
Ray Grass	237.1	549.2	642	100.0	120	82.2
Wheat	314.5	606.0	447	185.0	59	60.1

Table 4. Risk classes established: Range of IPreg for each class, surface occupied in the study area, meaning and implication**.**

Classes of risk	**Surface (ha)**	**Meaning; Implication**
Very low (0–5)	86.5	Sustainable; In general this level of risk is negligible.
Low (5–15)	907.6	Low P transport potential. Probably sustainable; In most cases this level of risk is acceptable.
Moderate (15–30)	2685.8	Near sustainable. Awareness of the situation is important. The trend towards or away from sustainability needs to be assessed.
High (30–50)	709.3	Probably not sustainable; High concern is warranted.
Very high (50–100)	100.5	Not sustainable; Immediate action is required.

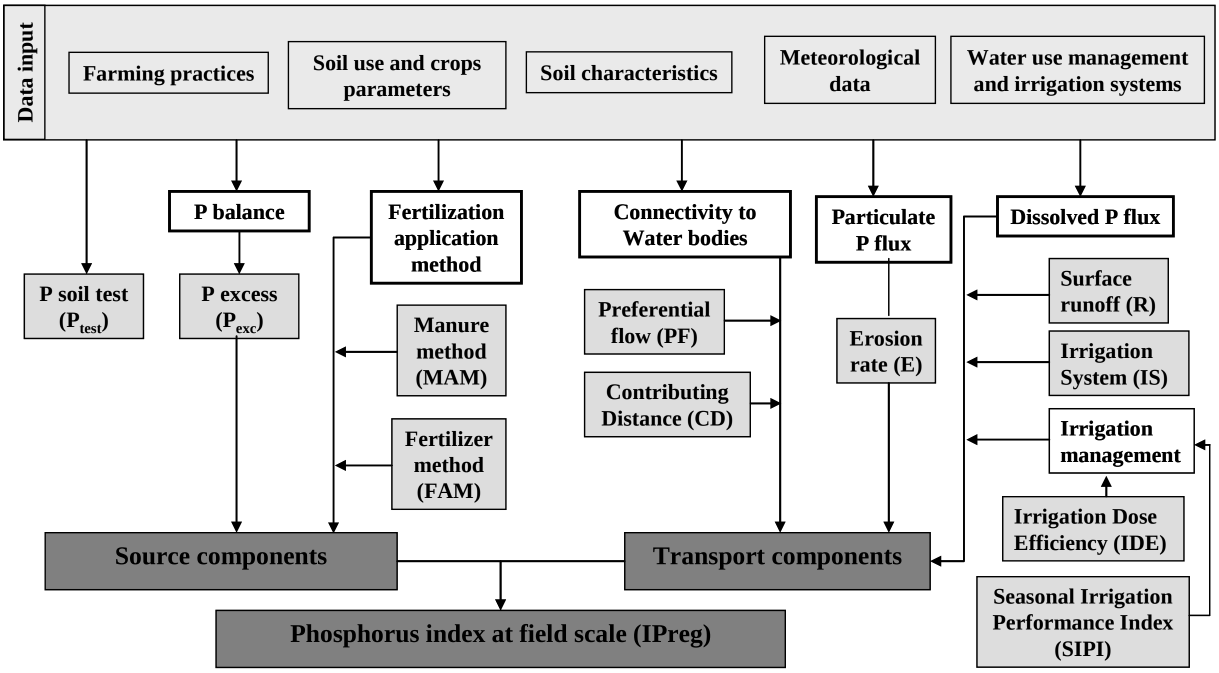

Figure 1. IPreg general flow diagram.

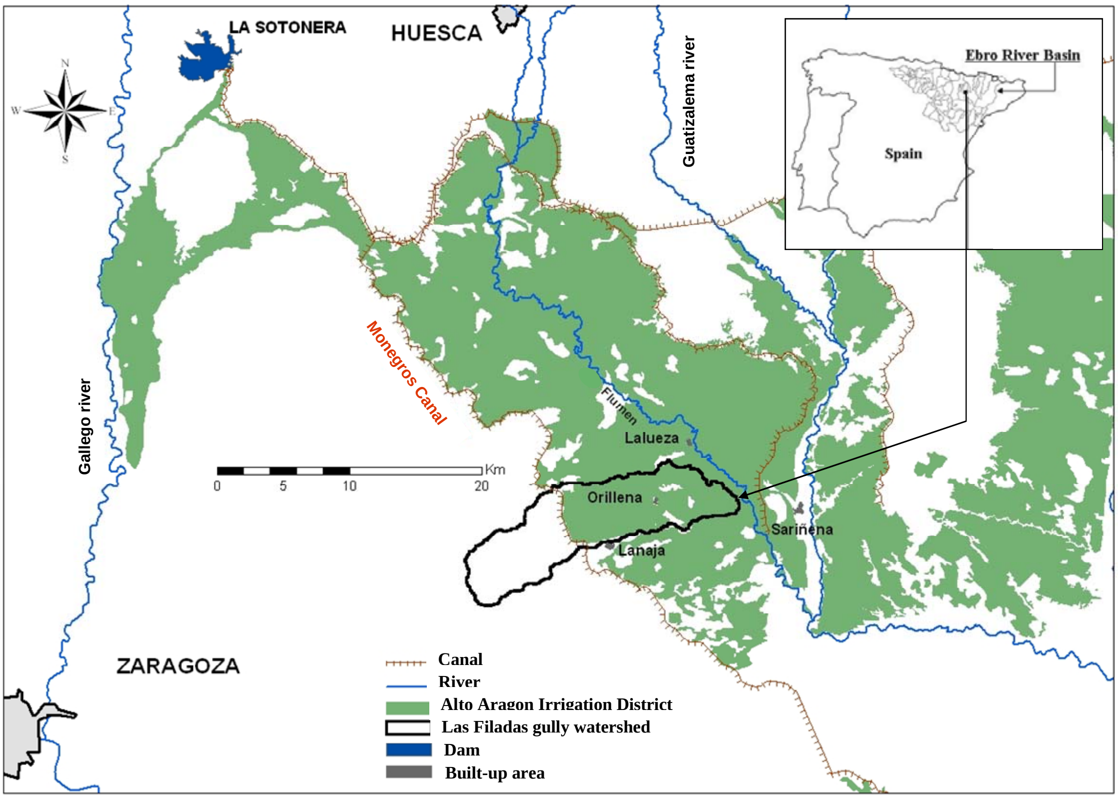

Figure 2. Location of the study area.

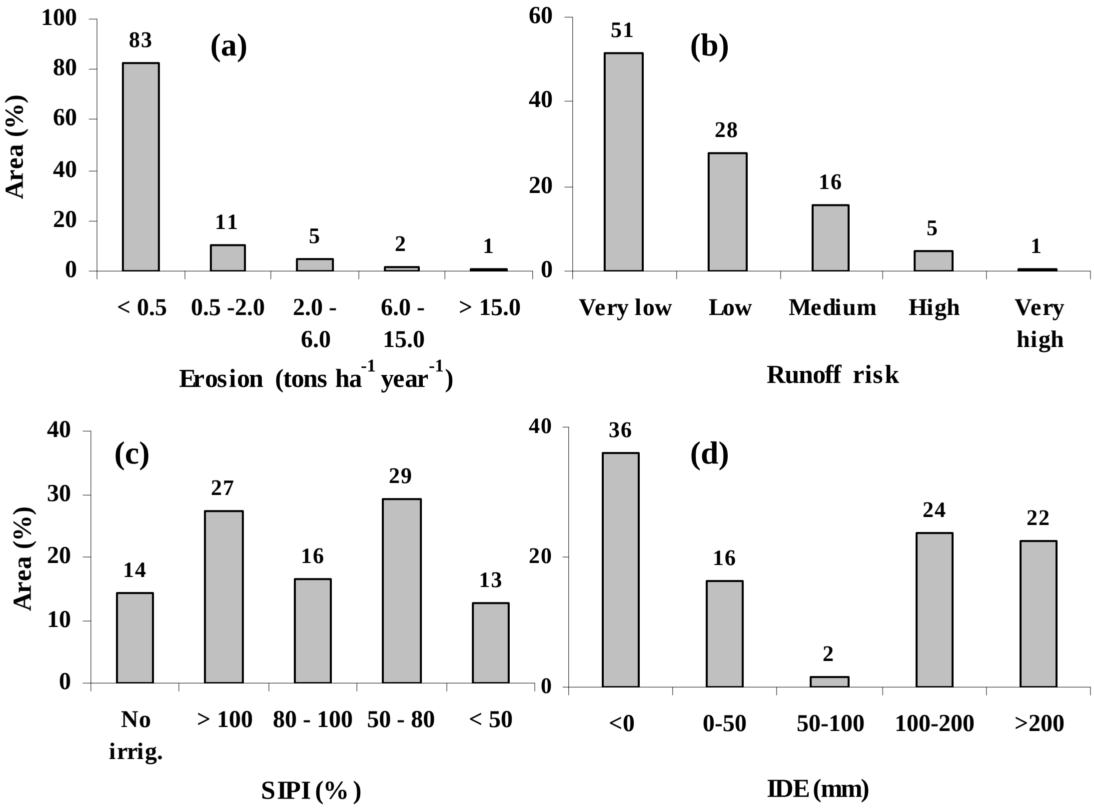

Figure 3. Percent surface distribution of the study area in factors risk classes of (a) erosion, (b) runoff risk, (c) seasonal irrigation performance index (SIPI) and (d) irrigation dose efficiency (IDE).

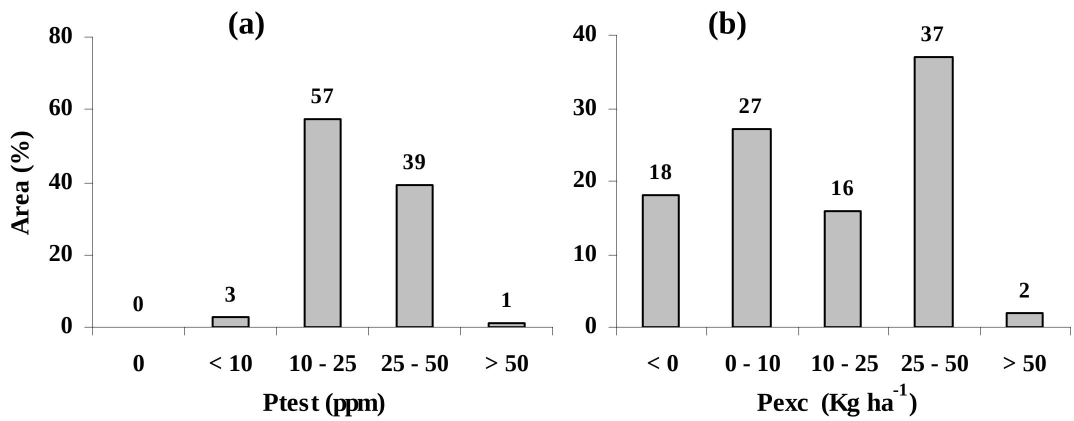

Figure 4. Percent surface distribution in the study area of risk classes for factors (a) phosphorus soil test (P test) and (b) phosphorus excess (P exc).

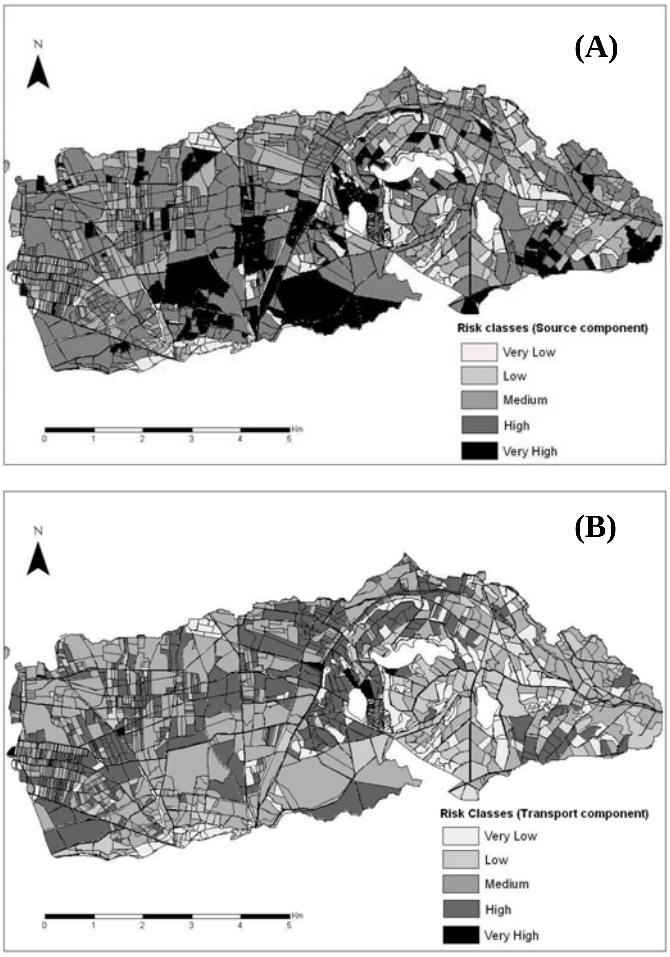

Figure 5. Spatial distribution of the risk classes for the phosphorus source component (A) and the phosphorus transport component (B).

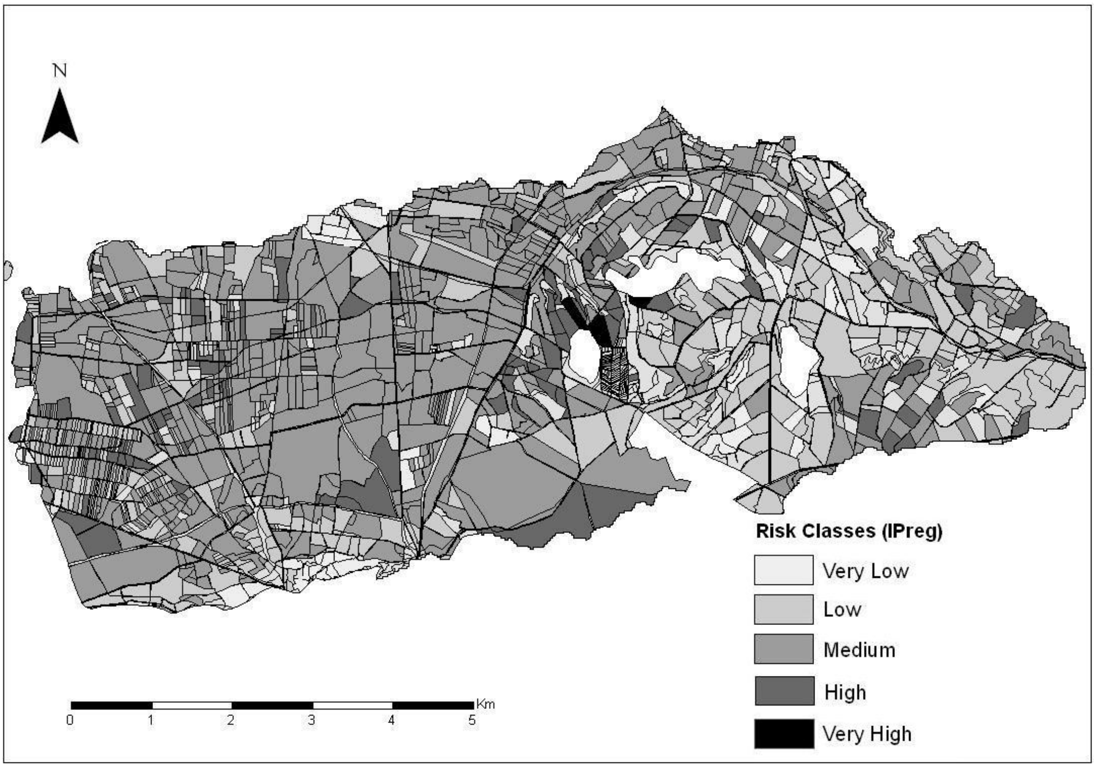

Figure 6. Spatial distribution of IPreg risk classes over the study area.