

1 **A phosphorus index for use in intensive irrigated areas**

2 F. DECHMI, D. ISIDORO & T. STAMBOULI

3

4 *Agrifood Research and Technology Centre of Aragon, Soils and Irrigation Department*

5 *(EEAD-CSIC Associated Unit), Avda, Montañana 930, 50059 Zaragoza, Spain*

6

7 ***Corresponding author: fdechmi@aragon.es***

8

9 Short title: **P Index for intensive irrigated areas**

10

11

12 **Abstract**

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

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

28

29 **Introduction**

30 An increase in nutrient levels in fresh water bodies leads to undesirable changes in
31 ecological equilibrium and has been detected in recent decades. The P enrichment in
32 water bodies may contribute to their eutrophication (Carpenter *et al.*, 1998). This
33 phenomenon may occur in surface waters having P concentration as low as 0.02 mg l⁻¹
34 (Sharpley & Rekolainen, 1997). In agricultural systems, several studies suggest that most

35 of the P transported from soil to water originates in specific fields or from particular
36 actions by farmers (Weld *et al.*, 2001). Thus, the identification of areas that pose the
37 greatest risk for P loss to surface waters is a critical component in P management.
38 Since 1980 P concentrations have decreased in the main European rivers due to
39 development in waste water treatment and use of phosphate-free detergents (EEA,
40 2010). A reduction in phosphate concentration has been observed since 1989 in most of
41 the Ebro River tributaries, but P concentration still remained high in 2006 (Isidoro &
42 Aragüés, 2007). In a survey on water quality in several agricultural catchments in the
43 Ebro Valley (Spain), Skhiri & Dechmi (2011) conclude that diffuse P pollution is of
44 major significance and that this trend will continue without corrective action. High
45 nutrient concentrations were one of the reasons for the European Union adopting the
46 Water Framework Directive (EU, 2000) aimed at protecting and enhancing the status of
47 all European aquatic ecosystems by 2015. Now farmers are accepting the challenge by
48 making their practices more environmentally sustainable. Consequently, measures and
49 tools to assess diffuse P losses are required.

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

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

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

74

75 **Materials and methods**

76 The original P Index developed by Lemunyon & Gilbert (1993) was used as the starting
77 point for the new index (IPreg). Three new transport factors related to irrigation method
78 and management were included for the first time in the methodology for a P Index
79 (Skhiri & Dechmi, 2012). In total IPreg includes 10 factors: three accounting for P
80 availability in the soil (P source component, PSC) and seven for the P transport

81 processes (P transport component, PTC). For each factor, five risk classes are defined
82 based on the factor range and a score of 0, 2, 4, 6, or 8 is assigned to each class (from
83 minimum to maximum risk). Additionally, each individual factor is assigned a weight
84 (0, 1 or 2) based on expert judgement to account for the fact that some factors exert a
85 greater influence on P loss than others in irrigated arid areas. The products of the
86 weights and scores for each individual factor are summed to calculate PTC and PSC.
87 Unlike the original P index developed by Lemunyon & Gilbert (1993), IPreg relates P
88 source and transport components as a product rather than as a summation. This is
89 because the additive form will predict risk of P losses in the absence of transport
90 process whereas in irrigated areas, IRF is the dominant transport process and can be
91 controlled by appropriate irrigation management. Thus it was considered that it was
92 better to design an index which results in no P loss risk in the absence of transport
93 processes.

94 *P transport component (PTC)*

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

104 1. The soil erosion rate (E) was calculated by means of the Revised Universal Soil Loss
105 Equation (Renard *et al.*, 1991) and reported in $\text{tons}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$. For this data are needed
106 on rainfall erosivity (R), soil erodibility (K), topography (LS), land use practices and
107 crop type (C), and conservation practices (P), all of which were determined at the plot
108 level. Factor E was assigned the same weight (1.0) suggested by McFarland *et al.*
109 (1998) for the adapted P index. The ranges in E defining the 5 risk classes were the
110 same as proposed by van Bochove *et al.* (2007) (Table1).

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

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

121 4. Preferential flow (PF) is a key pathway for subsurface contaminant transport.
122 However, only a few P indices do incorporate PF (Dadfar *et al.*, 2010), possibly due to
123 the large number of factors affecting this process. The phosphorus index developed by
124 Beaulieu *et al.* (2006) and Goulet *et al.* (2006) included PF in a simple way, assuming
125 that PF was only related to soil texture. In this study the methodology of Beaulieu *et al.*
126 (2006) was selected for estimating the PF factor. The PF high risk class is associated

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

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

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

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

145 The highest weights (2.0) were assigned to the SIPI and IDE (the factors directly related
146 with water use management) in order to incorporate into the IPreg the high impact on P
147 transport attributed to irrigation water management. The other transport factors were
148 assigned a weight of 1.0 to reflect their lower impact compared to the irrigation water

149 management factors. The five risk classes adopted for the SIPI and IDE are presented in
150 Table 1.

151 *P source component (PSC)*

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

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

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

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

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

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

186

187 *IPreg algorithm*

188 A general IPreg flow diagram and algorithm are presented in Figure 1 and Table 1,
189 respectively. The range for the sum of the weighted PTC factors is 0-72 (sum of weights
190 = 9; maximum score = 8), and this was divided by 72 to limit the PTC range from 0 to 1
191 (Table 1). The PSC (sum of the weighted PSC factors) ranges from 0 to 44 (Table 1);
192 and thus the product of PTC (0 to 1) and PSC (0 to 44) was multiplied by 2.27 to
193 achieve a final IPreg in the range 0 to 100. This final IPreg was assigned to one of the
194 five classes of P loss risk: very low, low, moderate, high and very high (Table 1). The

195 higher the IPreg, the greater is the need to manage the soil, crop, irrigation water and
196 nutrient applications to minimize the risk of P loss from the soil.

197

198 *Calculation method and IPreg test*

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

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

216 The study area was characterised in detail to create a geo-referenced database as needed
217 to calculate each factor for 2007. Field surveys were performed to determine the spatial
218 distribution and total area of each crop. Farmers’ water management and farming

219 practices were determined through interviews in 2007. A total of 60 farmers were
 220 randomly selected for the interviews.

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

230 *Phosphorus transport component (PTC)*

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

$$235 \quad R = 1 / n \sum_{i=1}^n \sum_{j=1}^{12} (7.05 \text{ rain}_{10} - 88.92 \text{ days}_{10})_j \quad [1]$$

236 where n is the number of years, i is the year, j is the month, rain_{10} is the average of the
 237 daily precipitation $> 10 \text{ mm day}^{-1}$ in a given month, and days_{10} is the number of days in
 238 a month with $P > 10 \text{ mm}$. Precipitation records between 1987 and 2007 for the nearest
 239 six meteorological stations were used to estimate R. Factor K (soil erodibility) was
 240 calculated using soil manual # 430 of USDA (1983) from the average soil texture and

241 organic matter of each soil unit. The LS (slope-length) factor was calculated with the
242 Moore & Burch (1986a and 1986b) equation based on a 10 m Digital Elevation Model
243 and using a Geographic Information System (ArcGIS 9.0). The C factor (cover-
244 management) was parameterised incorporating information about land use data,
245 agricultural practices and type of irrigation system. The P factor (conservation practices)
246 was taken to be equal to 1 because conservation practices were not used in the study
247 area.

248 The runoff curve number (USDA-SCS, 1972) was determined for each plot from a
249 matrix using information on land use, cultural practice, hydrologic condition and soil
250 hydrologic group (determined as a function of surface soil texture). All these calculated
251 factors were then used to estimate the soil erosion rate (E) following Renard *et al.*
252 (1991).

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

263 *Phosphorus source component (PSC)*

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

272

273 **Results**

274 *Soil properties and management practices*

275 Most soils in the study area have a loam texture (67%) and the others are silt loam (16
276 %) and silty clay loam (Table 2). The results indicate great variability in soil depth, total
277 available water and P Olsen content. The loamy soils (except unit 7) have the lowest
278 depth (50 cm in average) and TAW (82 mm in average) to highlight the need for
279 frequent small irrigations. In these soils, inadequate water use can lead to important
280 water losses below the root zone. The soils with a silty clay loam texture were deeper
281 and had a greater TAW.

282 No relationship between soil texture and P Olsen content was found. The large
283 variability in average soil P content (from 6 to 45 ppm) was due to the combination of
284 different factor including soil characteristics, soil use and fertilizer practices. In the
285 deeper soils, average soil P content decreased with depth (data not shown) and had very
286 low values in the deeper layers (data not shown). In shallow soils (depth < 60 cm), no

287 sharp decrease in P soil content was observed between 0-30 cm and 30-60 cm.
288 According to López Ritas (1978), the P content in soil units 3 and 9 was considered
289 high (≥ 25 ppm for medium and coarse soil texture and ≥ 13 ppm for fine soil texture)
290 and therefore fertilizer application was not necessary (Table 2). In the upper layer of
291 soil units 3, 6, 8, 9 and 11, P content was high and so these units could be relevant
292 sources of P.

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

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

310 (Hernández Abreu, 1975), but all soil units had average P Olsen values for the layer 0-
311 30 cm ranging from 9 ppm to 75 ppm, indicating excessive P fertilizer application.
312 Also, the P in the harvested crops was lower than the P fertilizer applied to the main
313 crops, except for wheat (Table 3). SIPI is a useful index for analyzing irrigation water
314 use practices and only barley, sunflower and ray-grass had a SIPI > 100 % showing that
315 the water use did not meet crop needs. Sprinkler systems were more efficient in water
316 use than flood ones.

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

318 The average soil potential loss (E) was ca. $0.787 \text{ t ha}^{-1} \text{ yr}^{-1}$ due to the gentle slopes of
319 the land for surface irrigation. Results also show that 83 % of the irrigated area had a
320 very low erosion potential risk (Figure 3a.). This demonstrates that erosion was not a
321 determining factor in IPreg in flood irrigation systems. These results may change
322 following conversion to a pressure irrigation system which does not require plot
323 levelling and removal of margins between irrigation basins. Over 79 % of the study area
324 had low runoff potential (Figure 3b), whereas only 5 % and 1 % of the total area were at
325 high and very high risk, respectively. All the plots in the study area were assigned to
326 only two risk classes of PF. The low risk class represented 70 % of the total area and
327 was associated with soils with loam and silt loam textures. The rest of the surface
328 corresponded to soils with a silty clay loam texture and therefore belonged to the
329 medium risk class. The absence of the high and very high risk classes was due to the
330 absence of sandy or clayey soil textures in the area. For the SIPI factor (Figure 3c), 13 %
331 and 29 % of the total area of 2056 ha belonged to the very high and high risk classes,
332 respectively (SIPI < 80 %), while only 27 % of total area was assigned to the low and

333 very low risk classes (SIPI > 100 %). Irrigation Dose Efficiency (IDE) was > 200 mm
334 ha⁻¹ (very high risk class) in 22 % of the total area (Figure 3d), with this highest IDE on
335 uncultivated plots where farmers applied irrigation water only for salt leaching. On the
336 other hand, the classes of medium (50 mm < IDE < 100 mm) and high (100 mm < IDE
337 < 200 mm) IDE risk each represented 19 % of the total area (1884 ha in total). The
338 majority of these high IDE risk plots were in the central part of the study area.
339 There were no plots within 10 m of the streams (contributing distance factor, CD). The
340 plots with CD > 300 m represented 30 % of the total area (1470 ha) and were assumed
341 not to contribute to the P transfer by this factor. In the study area, the irrigation system
342 factor (IS) did not have a great impact because most of the area had the same surface
343 irrigation system and a low potential for P transport risk (all the area was included in the
344 low risk class for IS). This will change after modernization of the study area.
345 The soil P risk (Figure 3a) was medium (available P Olsen in the soil layer 0-30 cm
346 between 10 and 25 ppm) in 80 % of the plots (57 % of total area). The area in the high
347 and the very high classes was very important (40 % of total area). These results were
348 due to different management practices (higher irrigation and fertilizer doses). However,
349 the high and very high risk classes for P excess (Figure 4b) were mainly in alfalfa
350 cultivated plots with manure (mainly pig slurry) application (20 % and 50% of the area
351 belonged to the high and very high risk classes, respectively).
352 31 % of the total area was in the high and very high PTC risk classes and > 50 % in the
353 medium risk class (Figure 5B). The source component did not show the same tendency.
354 In this case, > 70 % of the total area was at high and very high risk (Figure 5A). The
355 resulting IPreg scores ranged from 1 to 63. The spatial distribution of IPreg risk classes

356 (Figure 6) was somewhat similar to the risk classes for PTC. Finally, 18 % (810 ha) of
357 the study area was at high to very high risk ($IPreg > 30$) of phosphorus loss and 60 %
358 (2686 ha) at moderate risk ($15 < IPreg < 30$) (Table 4). As determination of the PF
359 factor was very simplified, an additional calculation of $IPreg$ was done without
360 considering PF in order to evaluate the impact of this factor and the results indicated no
361 change in the proportion of the total area in each of the five risk classes.

362

363 **Discussion**

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

378 application, the volume of irrigation water applied, and the timing and irrigation
379 amounts.

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

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

398

399 **Conclusion**

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

417

418 **Acknowledgements**

419 This work has been financed by “*Obra Social La Caixa*” and “*Comunidad General de*
420 *Riegos del Alto Aragón*” with the valuable collaboration of the laboratory staff of CITA-
421 DGA. We thank the Mediterranean Agronomic Institute of Zaragoza (IAMZ-CIHEAM)
422 for awarding a Fellowship to Talel Stambouli.

423

424 **References**

425 Allen, R.G., Pereira, L.S., Raes, D. & Smith, D. 1998. Crop evapotranspiration. Guides
426 for computing crop water requirements. *FAO Irrigation and Drainage Paper*. No **56**,
427 Italy, 333 PP.

428

429 Amezketa, E., Aragüés, R. & Gazol, R. 2005. Efficiency of sulfuric acid, mined
430 gypsum, and two gypsum by-products in soil crusting prevention and sodic soil
431 reclamation. *Agronomy Journal*, **97**, 983–989.

432

433 Aragüés, R. & Tanji, K.K. 2003. Water Quality of Irrigation Return Flows, in:
434 *Encyclopedia of Water Science* (Eds. B.A. Stewart and T.A. Howell) (New York,
435 Marcel Dekker Inc.), 502–506.

436

437 Arnold, J.G. & Fohrer, N. 2005. SWAT2000: current capabilities and research
438 opportunities in applied catchment modeling. *Journal of Hydrologic Processes*, **19**,
439 563–572.

440

441 Beaulieu, L., Gallichand, J., Duchemin, M. & Parent, L.E. 2006. Sensitivity analysis of
442 a phosphorus index for Quebec. *Canadian Biosystems Engineering*, **48**, 1.13–1.24.

443

444 Bruckler, L., Lafolie, F., Ruy, S., Granier, J. & Baudequin, D. 2000. Modeling the
445 agricultural and environmental consequences of non-uniform irrigation on a corn crop.
446 1. Water balance and yield. *Agronomie*, **20**, 609–624.

447

448 Buczko, U. & Kuchenbuch, R.O. 2007. Phosphorus indices as risk assessment tools in
449 the U.S.A. and Europe. A review. *Journal of Plant Nutrition and Soil Science*, **170**,
450 445–460.

451

452 Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D, Hardy,
453 L.A., Howell, T.A. & Eisenhauer, D.E. 1997. Irrigation performance measures:
454 Efficiency and Uniformity. *Journal of Irrigation and Drainage Engineering*, *23*(6),
455 423–442.

456

457 Carpenter, S.R., Caraco, N.F., Correll, D.L., Howath, R.W., Sharpley, A.N. & Smith,
458 V.H. 1998. Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen.
459 *Ecological Applications*, **8** (3), 559–568.

460

461 Cuenca, R.H. 1989. Irrigation system design. An engineering approach. Prentice Hall
462 Inc. Englewood Cliffs. New Jersey, USA.

463

464 Dadfar H., Allaire, S.E., De Jong, R., van Bochove, E., Denault, J.T., Thériault, G., &
465 Dechmi. F. 2010. Development of a method for estimating the likelihood of crack flow
466 in Canadian agricultural soils at the landscape scale. [*Canadian Journal of Soil Science*](#),
467 **90**(1), 129–149.

468

469 European Environmental Agency (EEA). 2010. The European Environment. State and
470 Outlook 2010. Freshwater Quality. European Environmental Agency, Copenhagen. 30p.
471

472 European Union (EU). 2000. Directive 2000/60/EC of the European Parliament and of
473 the Council of 23 October 2000 establishing a framework for Community action in the
474 field of water policy, Official Journal of the European Communities L 327, 22/12/2000
475 pp. 1–73.
476

477 Faci, J.M., Bensaci, A., Salti, A. & Playán, E. 2000. A case study for irrigation
478 modernisation. I. Characterisation of the district and analysis of water delivery records.
479 *Agricultural Water Management*, **42**, 315–334.
480

481 Fixen, P.E. & Grove, J.H. 1990. Testing soils for phosphorus. In: *Soil Testing and Plant*
482 *Analysis*. (ed. R.L. Westerman). SSSA, Madison, WI. p. 141–180.
483

484 Goulet, M., Gallichand, J., Duchemin, M. & Giroux, M. 2006. Measured and computed
485 phosphorus losses by runoff and subsurface drainage in Eastern Canada. *Applied*
486 *Engineering in Agriculture*, **22**, 203–213.
487

488 Heckrath, G., Bechmann, M., Ekholm, P., Ulén, B., Djodjic, F. & Andersen, H.E. 2008.
489 Review of indexing tools for identifying high risk area of phosphorus loss in Nordic
490 catchments. *Journal of Hydrology*, **349**, 68–87.
491

492 Hernández Abreu, J.M. 1975. Seminario sobre interpretación de análisis químicos de
493 suelos. C.R.E.A. Tarancote.
494

495 Isidoro, D. & Aragüés, R. 2007. River water quality and irrigated agriculture in the Ebro
496 River Basin: An Overview. *International Journal of Water Resources Development*, **23**
497 (1), 91–106.
498

499 IUSS Working Group WRB. 2007. World Reference Base for Soil Resources 2006, first update
500 2007. World Soil Resources Reports No. 103.
501

502 Kuo, S. 1996. Phosphorus. In: *Methods of Soil Analysis: Part 3- Chemical Methods*.
503 (ed. D. L. Sparks). SSSA, Madison, WI. p. 869–919.
504

505 Lafolie, F., Mary, B., Bruckler, L., & Ruy, S. 2000. Modeling the agricultural and
506 environmental consequences of non-uniform irrigation on a maize crop. 2. Nitrogen
507 balance. *Agronomie*, **20**, 625–642.
508

509 Lemunyon, J.L. & Gilbert, R.G. 1993. The Concept and Need for a Phosphorus
510 Assessment Tool. *Journal of Productive Agriculture*, **6**, 483–486.
511

512 Li, J., Li, B. & Rao M. 2005. Spatial and temporal distributions of nitrogen and crop
513 yield as affected by nonuniformity of sprinkler fertigation. *Agricultural Water*
514 *Management*, **76**, 160–180.

515

516 López Ritas, J. 1978. El diagnóstico de suelos y plantas. Ed. Mundi Prensa.

517

518 Loureiro, N.D. & Coutinho, M.A. 2001. A new procedure to estimate the RUSLE EI30
519 index, based on monthly rainfall data and applied to the Algarve region, Portugal.

520 *Journal of Hydrology* **250**, 12–18.

521

522 Martínez-Cob, A., Faci, J.M. & Bercero, A. 1998. Evapotranspiración y necesidades de
523 riego de los principales cultivos en las comarcas de Aragón. Publicación 1882.

524 Institución Fernando el Católico (CSIC), Zaragoza.

525

526 McFarland, A., Hauck, L., White, J., Donham, W., Lemunyon J. & Jones, S. 1998.

527 Manure management in harmony with the environment and society. SWCS, Ames, IA.

528

529 Ministerio de Agricultura Pesca y Alimentación (MAPA), 2007. Balance de fósforo en
530 la agricultura española (Año 2005). Secretaría General de Agricultura y Alimentación,
531 Dirección General de Agricultura, pp. 10.

532

533 Moore, I. & Burch, G. 1986a. Physical basis of the length-slope factor in the universal
534 soil loss equation. *Soil Science Society of America Journal*, **50**, 1294–1298.

535

536 Moore, I. & Burch, G. 1986b. Modelling erosion and deposition: topographic effects.

537 *Transactions of the ASAE*, **29**(6):1624–1640.

538

539 Renard, K.G., Foster, G.R., Weesies, G.A. & Porter, J.P. 1991. RUSLE, Revised
540 universal soil loss equation. *Journal of Soil Water Conservation*, **46**(1), 30–33.

541

542 Sharpley, A.N. 1985. Depth of surface soil-runoff interaction as affected by rainfall, soil
543 slope, and management. *Soil Science Society of America Journal*, **49**, 1010–1015.

544

545 Sharpley, A.N., & Rekolainen, S. 1997. Phosphorus in agriculture and its environmental
546 implications. In: *Phosphorus loss from soil to water* (Eds. H. Tunney, O.T. Carton, P.C.
547 Brooks & A.D. Johnston), CABI Publ. Cambridge, pp.1–54.

548

549 Sharpley, A.N., Weld, J.L., Beegle, D.B., Kleinman, P.J.A., Gburek, W.J., Moore, P.A.
550 & Mullins, G. 2003. Development of phosphorus indices for nutrient management
551 planning strategies in the United States. *Journal of Soil and Water Conservation*, **58**(3),
552 137–151.

553

554 Skhiri, A. & Dechmi, F. 2011. Irrigation return flows and phosphorus transport in the
555 Middle Ebro River Valley (Spain). *Spanish Journal of Agricultural Research*, **9** (3),
556 938–949.

557 Skhiri, A. & Dechmi, F. 2012. Impact of sprinkler irrigation management on the Del
558 Reguero river (Spain). I: Water balance and irrigation performance. *Agricultural Water
559 Management*, 103, 120–129.

560

561 Ulén, B., Djodjic, F., Etana, A., Johansson, G. & Lindström J. 2011. The need for an
562 improved risk index for phosphorus losses to water from tile-drained agricultural land.
563 *Journal of Hydrology*, **400**, 234–243.
564

565 United States Department of Agriculture, Soil Conservation Service. 1972. Hydrology.
566 In: *National engineering handbook*. Washington, D.C. pp. 105–106.
567

568 USDA (1983) National Soil Survey Handbook. # 430. US Department of Agriculture,
569 Wahsington, DC, USA.
570

571 van Bochove, E., Thériault, G., Dechmi, F., Rousseau, A.N., Quilbé, R. Leclerc, M.L. &
572 Goussard, N. 2006. Indicator of Risk of Water Contamination by Phosphorus from
573 Canadian Agricultural Land. *Water Science and Technology*, **53**, 303–310.
574

575 van Bochove, E., Thériault, G., Dechmi, F., Leclerc, M.-L. & Goussard, N. 2007.
576 Indicator of Risk of Water Contamination by phosphorus: temporal trends for Quebec
577 Province from 1981 to 2000. *Canadian Journal of Soil Science*, **87**(2), 121–128.
578

579 Walker, W.R. & Skogerboe, G.V. 1987. Surface irrigation. Theory and practice.
580 Prentice-Hall, Inc., Englewood Cliffs, New Jersey, USA.
581

582 Weld, J.L., Sharpley, A.N., Beegle, D.B. & Gburek, W.J. 2001. Identifying critical
583 source of phosphorus export from agricultural catchments. *Nutrient Cycling in*
584 *Agroecosystems*, **59**, 29–38.

585 **List of Tables**

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

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

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

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

601

List of Figures

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.

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.

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

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

1 **Table 2.** Description of the soil units in the study area: Percent area occupied (Surface);
 2 average slope, soil depth, total available water (TAW), and phosphorus Olsen content
 3 (P); and textural class (Texture). The standard deviation is given in brackets for P.
 4

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

5
 6
 7

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

11

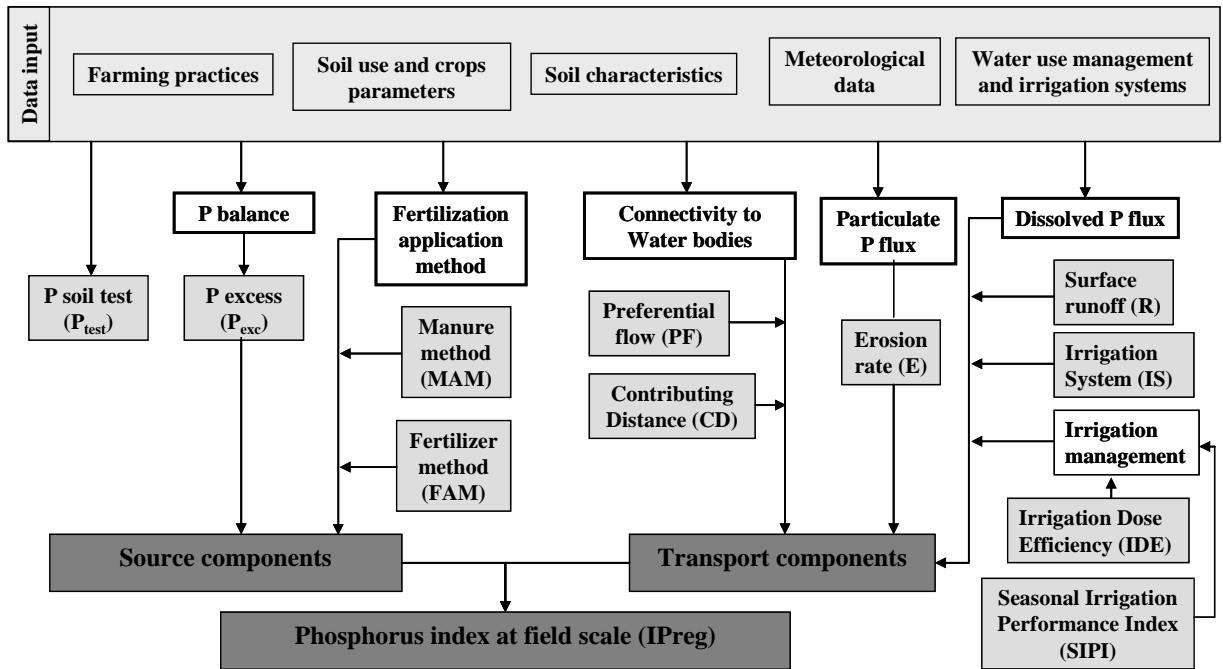
12

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

13 **Table 4.** Risk classes established: Range of IPreg for each class, surface occupied in the
14 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.

15
16
17
18
19
20
21
22
23
24
25
26
27
28

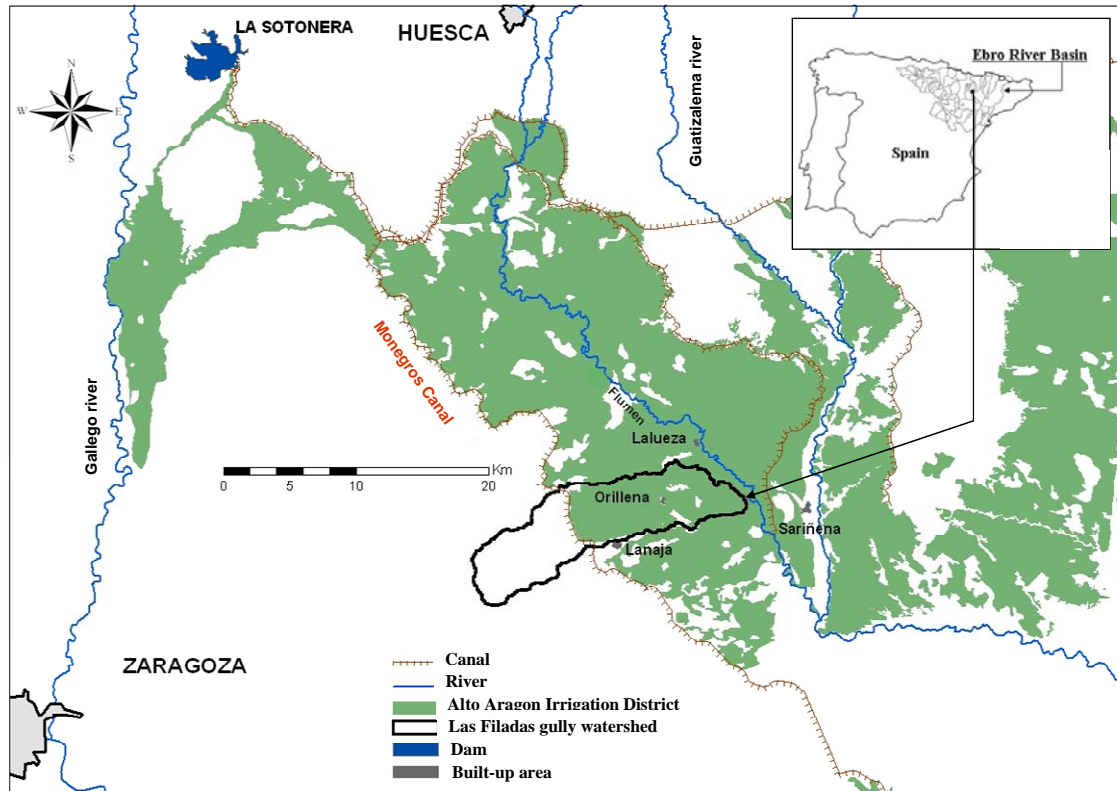


30

31

32 **Figure 1.** IPreg general flow diagram.

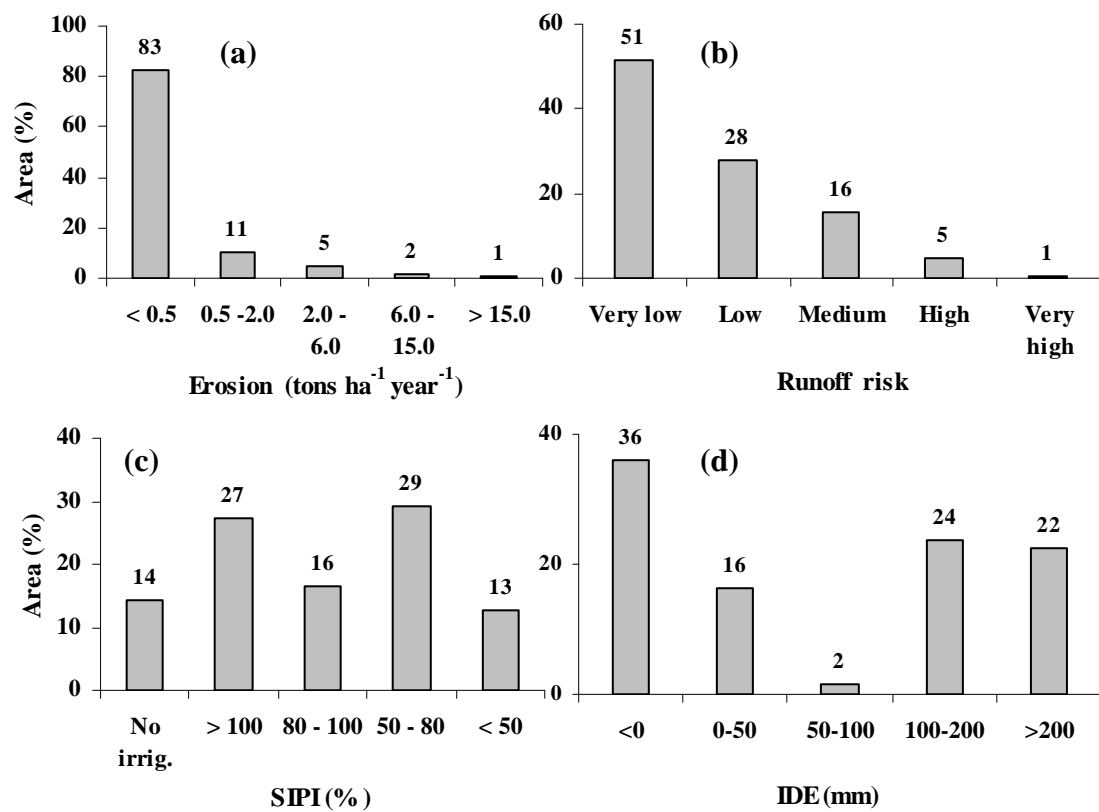
33



35

36 **Figure 2.** Location of the study area.

37



38

39

40 **Figure 3.** Percent surface distribution of the study area in factors risk classes of (a)

41 erosion, (b) runoff risk, (c) seasonal irrigation performance index (SIPI) and (d)

42 irrigation dose efficiency (IDE).

43

44

45

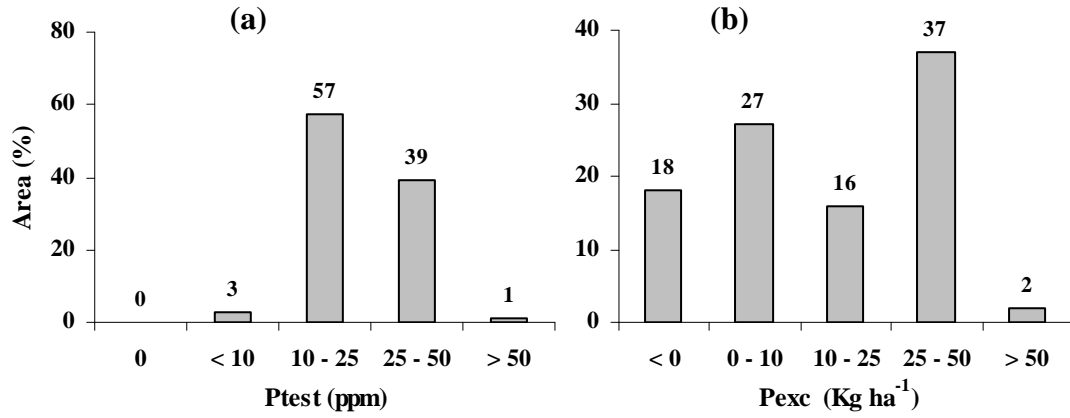
46

47

48

49

50



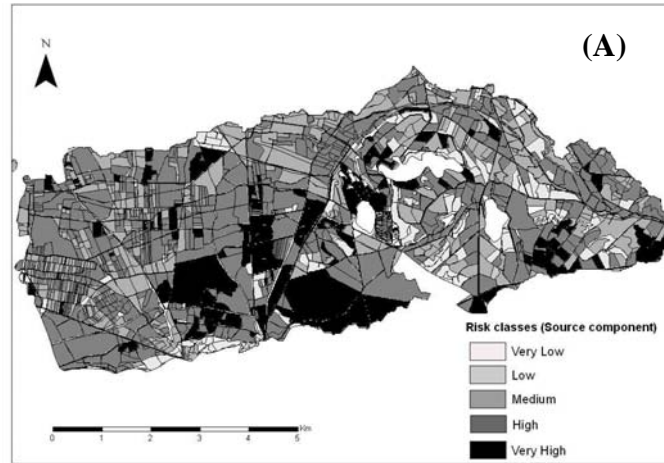
51

52 **Figure 4.** Percent surface distribution in the study area of risk classes for factors (a)

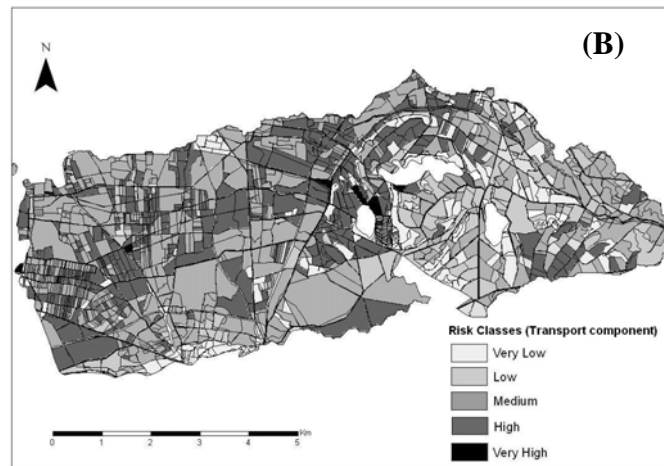
53 phosphorus soil test (P test) and (b) phosphorus excess (P exc).

54

55



56



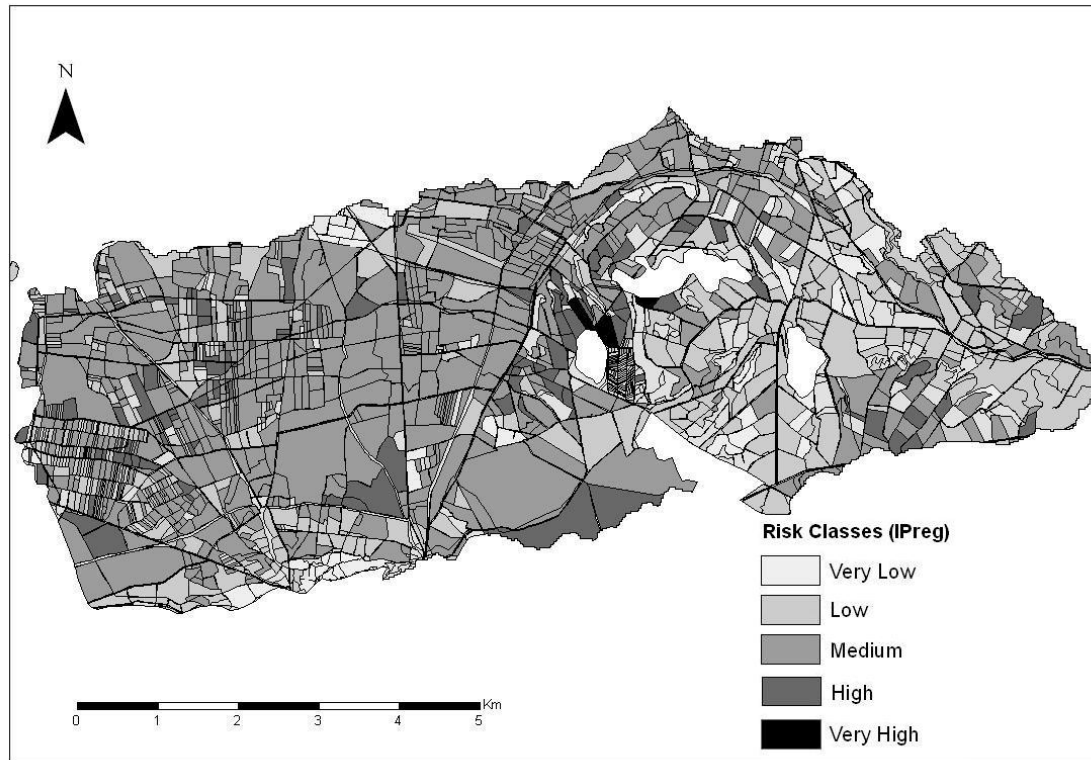
57

58

59 **Figure 5.** Spatial distribution of the risk classes for the phosphorus source component

60 (A) and the phosphorus transport component (B).

61



63

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

65

66

67