Evaluation of Best Management Practices under intensive irrigation using SWAT model

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Abstract

Land management practices such as conservation tillage and optimum irrigation are routinely used to reduce non-point source pollution and improve water quality. The calibrated and validated SWAT-IRRIG model is the first modified SWAT version that reproduces well the irrigation return flows (IRF) when the irrigation source is outside of the watershed. The application of this SWAT version in intensive irrigated systems permits to better evaluate the best management practices (BMPs) in such systems. This paper evaluates several BMPs on IRF, total suspended sediment (TSS), organic P (ORG_P), soluble P (SOL_P), and total P (TP) at the outlet Del Reguero stream watershed (Spain). Economic impacts of the BMPs on crop gross margin were also evaluated. In total, 20 BMPs scenarios were tested. The BMPs proposed considered tillage (conservation and no-tillage), fertilizer application (incorporated, recommended, and reduced), and irrigation (adjusted to crop needs). The measured data series corresponding to 2008 and 2009 years were considered to estimate IRF, TSS, ORG_P, SOL_P and TP losses as a reference to assess the effects of the considered BMPs. The results indicate that the best individual BMP (adjusted irrigation water use) reduced IRF by 31.4%, TSS loads

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by 33.5% and TP loads by 12.8%. When individual BMPs were combined, the load reductions were even increased. The BMP scenario combining optimum irrigation application, conservation tillage and reduced P fertilizer dose was the best, leading to a TP load reduction of about 22.6%. For corn and alfalfa, the best BMP scenario was the combination between conservation tillage and reduced P fertilizer dose, increasing the crop gross margin by 309 € ha^{-1} and 188 € ha^{-1}, respectively. For sunflower and barley, the best scenario combined the adjusted irrigation water use, conservation tillage and reduced P fertilizer dose (gross margin increase of 171 € ha^{-1} and 307 € ha^{-1}, respectively).

Keywords: Nutrients management practices; nutrients losses; phosphorus; sediment yield; Tillage.

.Abbreviations: AW (soil available water), BMPs **(**Best management practices), CST (conservation tillage), CVT (conventional tillage), DEPTIL (soil depth specified), DRW (Del Reguero watershed), EFFMIX (mixing efficiencies), ETc (crop evapotranspiration), ET$_0$ (reference evapotranspiration), HRU (hydrologic response unit), I_ADJ (adjusting irrigation water use), IRF (irrigation water return flows), Kc (crop coefficients), NIR (crop net irrigation requirement), NOT (no tillage), ORG_P (organic P), Pr (precipitation), Pr$_{ef}$ (effective precipitation), P_INC (Phosphorus fertilizer incorporation), P_REC (Recommended P fertilizer dose), P_RED (Reduced P fertilizer dose), SOL_P (soluble P), TAW (total available water), TP (total P), TSS (total suspended sediment).

1. Introduction

In intensive agricultural systems, nutrients loads are a key factor in surface water eutrophication problems (Monaghan et al., 2005). As phosphorus (P) is often the limiting nutrient for fresh water eutrophication, the development of management practices that reduce P loading is becoming increasingly relevant (Daroub et al., 2011). Despite the decrease in P concentrations in the main European rivers thanks to initiatives such as waste water treatment and use of phosphate-free detergents (EEA, 2010), surface water quality degradation continues due to diffuse P losses (Kronvang et al., 2003). This high nutrient transfer from agricultural land to water bodies was one of the reasons for the European Union to adopt the Water Framework Directive (WFD). The WFD aims to achieve good ecological and chemical conditions in all European aquatic ecosystems by 2015 (EU, 2000). In the Ebro basin (north-east Spain), irrigated agriculture is a major component of the hydrologic balance and, therefore, may have a significant impact on the rivers water quality in the basin. In a recent survey on water quality performed in several agricultural watersheds in the Ebro Valley (Spain), Skhiri and Dechmi (2011) concluded that diffuse P pollution is of major significance and that situation will continue in the absence of corrective action.

Alternative land management practices such as on-farm nutrient management (rate and method of application), tillage operations (conservation and no-tillage), and irrigation management are routinely used to reduce non-point source pollution and improve water quality. In fact, a number of field studies have illustrated the positive effects of best management practices (BMPs) on water and nutrients fluxes (Smukler et al., 2012; Daroub et al., 2011; Inamdar et al., 2001). The reduction of tillage intensity increases infiltration rates and reduces surface runoff, nutrients loss and soil erosion (Schmidt et al., 2001). Conservation tillage could also reduce N leaching and algal available P transport (Sharpley and Smith, 1994). However, because of the time and cost involved in the field assessment of management impacts, models often represent a more efficient and feasible means of evaluating management alternatives and make management recommendations (Chaubey et al., 2010).

Among all the developed models for evaluating the best management practices, SWAT model (Arnold et al., 1998) includes the greatest number of agricultural management alternatives. This model has been used extensively in U.S. Department of Agriculture (USDA) sponsored research for assessment of BMPs impacts on water quality included in the Conservation Effects Assessment Project (CEAP) as described by Duriancik et al. (2008) and Richardson et al. (2008). Van Griensven et al. (2006) presented an illustration describing the developments around SWAT to support the implementation of the EU Water Framework Directive (WFD). The model was also used in the European Union to achieve the objectives of the WFD (Bärlund et al., 2007; Volk et al., 2008; 2009). However, those studies focused mainly on nitrogen reduction goals.

Other previous assessments of BMPs with SWAT reported that conservation tillage significantly reduced sediment yields and phosphorus loads (Zhao et al., 2001). However, the no-tillage practice could lead to an accumulation of nutrients at the surface which leads to enhanced nutrient loads in surface runoff (Djodjic et al., 2002). Tuppad et al. (2010) quantified the impacts of streambank stabilization, gully plugs, recharge structures, conservation tillage, terraces, contour farming, manure incorporation, and filter strips at the Bosque River Watershed (Texas) outlet. The implemented individual BMPs in this watershed reduced sediment loads from 3 to 37%, total nitrogen loads from 1 to 24% and total P loads from 3 to 30%. van der Salm et al. (2007) showed that reducing soil P to zero over a period of four years led to a strong (30-90%) reduction in both molybdate reactive P and molybdate unreactive P in the soil.

Up to now, SWAT studies describing irrigation application have been performed using irrigation input data estimated or adjusted to the crops water requirement after the soil water balance model calculation (Cau and Paniconi, 2007; Jie et al., 2010; Kannan et al., 2011). However, the application of SWAT in intensive irrigation systems considering real farmers irrigation management in each irrigated plot (depth and date of each irrigation event) indicated that the model is not able to correctly reproduce the total streamflow (Dechmi et al., 2012) when the irrigation source is outside the watershed. In order to improve its performance in such systems, a modification of the SWAT model was developed (named SWAT-IRRIG) and its ability to estimate water flow and sediment and phosphorus loads was evaluated in a representative intensive irrigation system of the middle Ebro River Valley of Spain (Dechmi et al., 2012).

In this paper, the SWAT-IRRIG was used in Del Reguero irrigated watershed (middle Ebro River Valley, Spain) to: (i) identify and test the effectiveness of several BMPs scenarios; (ii) evaluate their effect on water quality in terms of total irrigation return flows, sediment loads and phosphorus losses; and (iii) evaluate their economic impact on crops gross margin.

2. Material and methods

2.1. Model description

The SWAT-IRRIG model is a modification of SWAT2005 which is a continuous time, spatially semi-distributed, physically based model (Arnold et al., 1998). The SWAT model integrates all relevant eco-hydrological processes including water flow, nutrient transport and turn-over, vegetation growth, land use and water management. The watershed is divided into multiple subbasins, which are then further subdivided into areas with unique soil/land use characteristics called hydrologic response units (HRUs). The HRUs are the spatial units where the vertical flows of water and nutrients are calculated. The water balance for each HRU in SWAT is calculated upon four storage volumes: snow, soil profile (0-2 m), shallow aquifer (typically 2-20 m), and deep aquifer (> 20 m). Flow generation, sediment yield, and chemical loadings from all HRUs in a subbasin are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet. Plant water evaporation is simulated as a linear function of potential evapotranspiration, leaf area index, and root depth. Sediment yield is estimated for each HRU with the Modified Universal Soil Loss Equation (Williams et al., 1984). The phosphorus processes are handled in a similar approach as in the Erosion Productivity Impact Calculator (EPIC) model (Williams, 1990, 1995). The loss of dissolved phosphorus in surface runoff is estimated through the partitioning of phosphorus into the solution and sediment phases as described by Leonard and Wauchope (1980) for pesticides. The amount of soluble P removed in runoff is predicted using solution P concentration in the soil top 10 mm, the runoff volume and a partitioning factor. Sediment transport of phosphorus (particulate phosphorus) is calculated with the loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978).

The modifications of the SWAT2005 original version were performed because it was found that SWAT2005 was not able to appropriately reproduce the total streamflow in Del Reguero watershed when using actual farmers irrigation practices (Dechmi et al., 2012). In fact, the SWAT2005 prediction for total irrigation return flow (IRF) was underestimated by 117.6% in comparison with the SWAT-IRRIG prediction. This indicated a very large difference between simulated and observed stream discharge. The difference was due to the fact that the excesses of applied irrigation water were lost (returned to the source) and not used in the soil daily balance calculation. As a result of SWAT performance improvement, the Nash and Sutcliffe efficiency (NSE) increased from -0.50 using SWAT2005 to 0.90 using SWAT-IRRIG.

SWAT-IRRIG was previously calibrated and validated for crop yield (corn, alfalfa, sunflower and barley), total streamflow, total suspended sediment loads and phosphorus loads using field survey information and water quantity and quality data from years 2008 (calibration) and 2009 (validation). The main calibrated crop parameter values are presented in Table 1. Dechmi et al. (2012) indicate a good adjustment between simulated and observed mean crop yields obtained during the calibration and validation periods of the SWAT-IRRIG crop model.

Monthly model calibration (NSE = 0.90, percent bias (PBIAS) = 1.1%, and RMSE-observation standard deviation ratio (RSR) = 0.33) and validation results (NSE = 0.80, PBIAS = 3.2%, and RSR = 0.45) indicated a “very good” performance in describing irrigation IRF at the outlet of the study area. The performance of SWAT-IRRIG in describing total phosphorus and sediment loads was “good” and “satisfactory”, respectively.

2.2. Study area description and model input

The Del Reguero stream is an affluent of the Alcanadre River located on the left bank of the middle Ebro River Basin in Spain (41º54´ N and 3º34´W) (Fig. 1). A total of 1,865 ha are drained by the Del Reguero stream. The Pertusa canal crosses the entire Del Reguero watershed and separates the irrigated land (1,355 ha, all pertaining to the Alconadre Irrigation District) from the non-irrigated land. The Alconadre Irrigation District is included in the Alto Aragon Irrigation System, the largest irrigated area in the middle Ebro River Valley (around 120,000 ha). A dense network of open ditches and buried tile drains collects the drainage water from the irrigated lands. The most widely adopted irrigation system in the study area was solid-set sprinkler irrigation (96% of the irrigated area) followed by pivot (3%) and drip irrigation (1%).

The daily meteorological records for this study were retrieved from the Huerto meteorological station (41º56'59"N and 00º08'09"W). The climate is semi-arid with a mean annual precipitation of 391 mm and a mean annual reference evapotranspiration (ET_0) of 1,294 mm. The highest precipitation takes place in spring (139 mm), with the highest average monthly ET_0 taking place in July (205 mm) and the lowest in December (28.3 mm). The mean annual temperature is 13.1ºC with a large difference between winter and summer: the average minimum temperature of the coldest month (December) is -0.1ºC, and the average maximum temperature of the warmest month (July) is 31.4 ºC.

According to the geomorphologic map of the area and the soil survey conducted during the study period, two geomorphologic units were distinguished in the study zone. The first unit (38% of the total area) corresponded to plateau soils or cambisols. These soils were characterized by shallow depth (0.6 m on average), presence of calcareous horizon, and high content of stones. The second unit covered the remaining watershed area and corresponded to alluvial soils, mostly stone-free and with soil depth varying from 0.6 m to more than 1.2 m. This unit was divided in two sub-units (shallow alluvial and deep alluvial soils).

For this study, all model inputs were recorded during two hydrological years (2008 and 2009). The main irrigated crops during the study years were corn (39.1 and 42.0% of the total cropped area), alfalfa (15.6 and 14.6%), sunflower (11.1 and 6.7%), and barley (18.3 and 19.4%). A small fraction of the irrigated area was also dedicated to horticultural crops and fruit trees (1.5 and 2.5% for 2008 and 2009, respectively). The data on irrigation management (date and dose of each irrigation event applied in each plot) was provided by the Alconadre Irrigation District collective irrigation network managed with the Ador management software (Playán et al., 2007). The farmers fertilization management practices (nitrogen and phosphorus) were obtained from farmers interviews conducted in 2008 (16 farmers) and 2009 (17 farmers). The size of surveyed farms ranged from 4.3 ha to 23.5 ha with a total surveyed area of 185 ha in 2008 (16% of the irrigated area) and 176 ha in 2009 (15% of the irrigated area) covering the entire surface of the irrigated watershed. The main information collected from the surveys was: the type and the amounts of organic and inorganic fertilizers applied, the dates of application and the crop yields obtained.

2.3. Scenarios description

The BMPs tested in this study are related to nutrient management, irrigation management and tillage operations. Altogether, 20 BMP scenarios were tested. Six of the scenarios correspond to the individual BMPs while the other 14 scenarios consist of combinations of the first six individual BMPs (Table 2). In nutrient management, three BMPs were considered in regard to P fertilizer (incorporated, recommended, and zero), while nitrogen application (mineral and organic) was determined from farmers interviews and introduced in each simulation performed. The irrigation BMP consisted in applying an optimum irrigation management. The BMPs in relation to tillage were conservation tillage and no tillage practices. For the application of each BMP scenario, the related model parameters such as P fertilizer application rates, method of application, depth of till, amount of water applied, time of irrigation, or dose of irrigation were identified and modified in the corresponding SWAT input files such as management file, HRU file and crop database file (Santhi et al., 2006). The field conditions and the relevant modeling input parameters used in simulating each BMP are described in the following sections.

2.3.1. Nutrient management scenarios

Phosphorus fertilizer incorporation (P_INC): The direct incorporation of fertilizer into the soil is the main management practice applied for minimising and controlling the P transport induced by the surface runoff. With this practice, the fertilizer is incorporated directly into the soil by knifing, instead of being applied to the soil surface and later incorporated into the top 15 cm of the soil profile (the usual farmers' practices in the study area). The SWAT model assumes that surface runoff process interacts with the 10 mm of the top soil (Neitsch et al., 2005). Thus, only the P contained in the top 10 mm layer is available for transport to the main channel by this hydrologic process. As the study area farmers do not incorporate directly the fertilizers into the soil below the top 10 mm, the P_INC was considered in the simulation process by replacing the value of FRT_SURFACE parameter (fraction of fertilizer applied to top 10 mm of soil in SWAT; corresponding to 7% of P fertilizer in this case) in the SWAT management file (Neitsch et al., 2005) by zero. This means that all the amount of P fertilizer applied by the farmer was incorporated in the soil layer 10 – 150 mm under the P_INC BMP.

Recommended P fertilizer dose (P_REC): Farmers are required to limit P fertilizer applications to crop removal rates. Hence, nutrient management recommendations would be based on optimal crop agronomic requirements that would not reduce crop yields. For this BMP and each crop, P_REC was estimated considering the P harvested in crops (CFI, 1998; Fixen and Garcia, 2006, MAPA, 2007) and the average local crop yields gathered from field surveys. The P fertilizer recommended rates calculated represent 100, 46, 109 and 40 % of the baseline average rate for alfalfa, corn, sunflower and barley, respectively (Table 3). For alfalfa, the recommended P fertilizer rate was superior to the 2008 baseline rate and inferior to 2009 baseline rate. On the other hand, baseline mean P sunflower rate was slightly lower than the recommended mean rate.

Reduced P fertilizer dose (P_RED): This scenario was based on the result of soil surveys performed in DRW. according to the agronomic interpretation of soil P-Olsen concentrations proposed by López Ritas and López Melida (1978), all the surveyed fields sown to corn, alfalfa, sunflower and barley presented high P-Olsen concentrations in the layer 0 – 30 cm ($25 < \text{P-Olsen} < 34$ mg kg^{-1}). So, this scenario consists in setting the P application rate to 0 kg P ha^{-1} for all crops.

2.3.2. Irrigation Management Scenario

This scenario consists in using an optimum irrigation scheduling by adjusting irrigation water use (I_ADJ) to the crop net irrigation requirement (NIR). The usual estimate of NIR was increased by 10% in order to take into account possible losses, so that the daily NIR for corn, alfalfa, sunflower and barley was calculated according to:

$$\mathrm{NIR\ (mm)} = 1.1\,[(K_c \times ET_0) - Pr_{ef}] \tag{1}$$

where ET_0 is the reference evapotranspiration, K_c is the crop coefficient and Pr_{ef} is the effective precipitation. Daily values of Pr_{ef} were taken equal to precipitation (Pr) or calculated from crop evapotranspiration (ETc), the total soil available water (TAW) and the soil available water (AW) of each type of soil given by (Causapé, 2009):

$$Pr_{ef} = Pr \quad \text{if} \quad Pr < TAW + ETc - AW; \;\; \text{otherwise } Pr_{ef} = TAW + ETc - AW \tag{2}$$

Daily ETc was calculated from the duration of the crop development phases and K_c values were obtained from Martínez-Cob et al. (1998). The ET_0 was calculated using the FAO Penman-Monteith method described by Allen et al. (1998).

Once the daily NIR was calculated for each crop, the daily NIR values were added until the day on which the sum amounted to almost 20 mm; at that date the sum of the previous days NIR was introduced in SWAT as an irrigation event. The annual average depths of water applied with the I_ADJ BMP to corn, alfalfa, sunflower and barley are summarized in Table 3.

2.3.3. Tillage operations scenarios

The conservation tillage (CST) and the no tillage (NOT) BMPs were tested and compared with the conventional tillage (CVT), which represents the actual farmers' practices. These two practices increase the amount of residue on the surface after crop harvest and before planting of the next crop (Tuppad et al., 2010). In SWAT, the CST and NOT operations differ in terms of mixing efficiency (EFFMIX) which specifies the fraction of materials (residue, nutrient, and pesticides) on the soil surface that are mixed uniformly throughout the soil depth specified by DEPTIL (depth of mixing caused by the tillage operation). The DEPTIL and EFFMIX values for CVT, CST and NOT operations are presented in Table 4.

2.4. Best managements practices analysis

The simulation of the current conditions (baseline) and the 20 considered scenarios, using the calibrated and validated model SWAT-IRRIG, was performed during the hydrologic years 2008 and 2009. The simulation of the current conditions was based on the soil use distribution, soil characteristics, meteorological data and farmers' current management practices in the study area. This simulation provided the reference values of irrigation return flows (IRF, mm), total suspended sediments (TSS, ton), organic P (ORG_P, kg), soluble P (SOL_P, kg) and total P (TP, kg) for the current farmers' practices in the DRW. An overview on the used model input data is presented in the study area description section. For each BMP described above, the model was run for the same period (2008-2009) to calculate the IRF, TSS, ORG_P, SOL_P and TP after implementation of that BMP. The impact of BMP scenarios on water quality are presented as percent reductions in average annual losses of IRF, TSS, ORG_P, SOL_P and TP from the actual farmers' practices in the DRW according to:

$$\text{Reduction (\%)} = 100\left(\frac{\text{postBMP} - \text{preBMP}}{\text{postBMP}}\right) \quad (3)$$

where pre-BMP and post-BMP are SWAT-IRRIG outputs before and after implementation of the BMP, respectively. A negative value indicates that the BMP reduced the outputs compared to the current conditions; whereas a positive value indicates that the BMP results in increased losses. A paired *t* test (α = 0.05 and 0.10) (Walpole et al., 2002) was performed on the simulated monthly values of pre-BMP and post-BMP (for all variables IRF, TSS, ORG_P, SOL_P, and TP) to test the significance of the change induced by the application of each BMP.

2.5. Economic impacts of implemented BMPs

The implementation of the proposed BMPs could increase or decrease the total income and costs at plot scale. Therefore, for the economic sustainability of irrigated agriculture, it is important to consider the impact of the BMP scenarios on farmers' revenue, to identify those BMPs that enhance farmer profits and surface water quality. However, the greatest environmental improvements do not necessarily result in higher economic profits. For this reason, pre-BMP and the 20 considered post-BMP gross margins were estimated and analysed in this work for corn, alfalfa, sunflower, and barley.

The concepts used for the determination of total costs (water fees, fertilizers, tillage, phytosanitary, seeds, machinery, grain drying, and irrigation water) are shown in Table 5. Total revenue was calculated as the sum of crop revenue and subsidies for each crop (Table 5). The average crop yields used in the calculation of pre-BMP and post-BMP gross margins were obtained from the SWAT-IRRIG outputs corresponding to 2008 and 2009. Crop prices were obtained from the Barbastro agricultural cooperative located in Peralta de Alcofea village (Fig. 1). European Union subsidies resulting from the application of the Common Agricultural Policy were obtained from public databases (MARM, 2009). Gross margin for each crop was determined by subtracting total cost from total income for the evaluated crop. As no P fertilizer prices are available directly from any local sources (the P fertilizer was applied as commercial mixtures containing N, P and K), the price of P was calculated by multiple regression from the price of 15 fertilizer products and their percentage of active nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O). Prices of fertilizer products were obtained from public databases (MARM, 2010). The price of the fertilizer product is the dependent variable and the percentages of N, P_2O_5, and K_2O are the independent variables. The fitted model equation is:

$$\text{Price}\,(€) = 0.88 \times \text{N} + 1.25 \times \text{P}_2\text{O}_5 + 0.37 \times \text{K}_2\text{O}, \quad r^2 = 0.986 \text{ and adjusted } r^2 = 0.983 \qquad (4)$$

so that the estimated coefficient for P_2O_5 (1.25 €/kg P_2O_5) yields the unit price of P fertilizer (expressed as P_2O_5). The reduction in conservation and no tillage costs were calculated according to Pérez and Martínez (2007). As those practices often require less equipment operation time, this translates into a reduction in labor and equipment costs (especially when the farmers conserve the same equipment in the case of conservation tillage). In the case of no tillage practices, the machinery cost can be high due to need of new equipments. However, equipment renting or increasing the working time of the new purchased machinery may allow for reducing the machinery cost of no tillage. On the other hand, no tillage requires an increased herbicide use for weed control. Therefore, the cost of machinery used in the practice of no tillage is a little bit higher than that used in the case of conservation tillage (Table 6). The irrigation BMP scenario does not imply a reduction in water price (0.024 € m^{-3}) or water fees (66 € per irrigated hectare).

3. Result and discussion

Average irrigation water return flows (2008-2009), total suspended sediments, organic P, soluble P and total P simulated by SWAT-IRRIG considering current conditions (baseline) are 119.6 mm, 25.4 Mg, 30.6 kg, 197.0 kg, and 227.6 kg, respectively (Fig. 2). Monthly stream discharges ranged from 2.40 mm in January 2008 to 23.55 mm in April 2009. The maximum discharge took place during the irrigation season, mostly late spring and summer. Monthly TSS loads varied from 0.21 Mg in January 2008 to 8.85 Mg in August 2009. Higher TSS loads occurred in spring and summer 2009 under rainfall and irrigation conditions (e.g. 8.62 Mg in April 2009; 8.85 Mg in August 2009) whereas lower loads corresponded to low base flow conditions. In regard to TP, monthly loads ranged from 5.85 kg in January 2008 to 47.08 kg in April 2009. The highest TP loads occurred mainly during spring and summer months (months of fertilization) and occasionally during autumn. The highest TP concentrations (0.475 mg L^{-1}) were found mostly during the irrigation season of both years.

3.1. Nutrients BMPs scenarios

The direct incorporation of P fertilizer (scenario 1 in Table 7) leads to reduction of losses for all P forms. The impact of P incorporation is most significant for SOL_P and TP ($p < 0.10$) leading to percentage reductions of 4.7 and 4.0%, respectively, while no significant impact of P_INC scenario was found for ORG_ P. The impact of the incorporated P fertilization dose was related to the fact that the overland flow was not the main transport factor and that most of the TP yield was in the dissolved form (total dissolved P = 90% of TP) in the study area during 2008 and 2009 (Skhiri and Dechmi, 2012). As the aim of this BMP is to reduce and control the P transport induced by surface runoff, the impact will be major during the periods when rainfall-induced runoff is important.

The application of the recommended P fertilizer dose (scenario 2 in Table 7) and no P fertilization (scenario 3 in Table 7) BMPs presented similar reduction of ORG_P, SOL_P, and TP losses, compared to the initial conditions. On average, the implementation of P_REC and P_RED BMP scenarios reduced ORG_P, SOL_P and TP losses by 0.1, 5.8 and 5.1%, respectively. However, only losses of SOL_P and TP under P_REC and P_RED scenarios were significantly different ($p < 0.10$) from the initial conditions.

The implementation of nutrients BMP scenarios did not have any impact on IRF and TSS losses. This was due to the fact that the practice of these BMPs has the same effect on soil erosion processes than the current practices. Moreover, those scenarios did not impact significantly the ORG_P losses because almost all the P fertilizers applied in DRW were in mineral form. Also, these BMP scenarios did not have any impact on the average amount of crop P uptake (28.64 kg ha^{-1}) and crop growth (0% reduction in yield). This result is expected because the Olsen P measured in the soils of DRW was high (25 mg kg^{-1} < Olsen P < 34 mg kg^{-1}) according to López Ritas and López Melida (1978). Under this conditions of excessive Olsen P concentration (exceeding 20 mg kg^{-1}), extra P inputs by fertilization will increase only P runoff and leaching instead of crop production (Sharpley et al., 1999). With regard to the base line scenario, the application of the P_INC scenario increased the final amount of mineral P in the soil by 1.94%. This highlights that the amount of P fertilizer applied by farmers in the DRW was high, leading to an accumulation of P in the soil profile. However, the application of P_REC and P_RED scenarios decreased the final amount of P in the soil by 0.02 and 0.10%, respectively.

3.2. Irrigation BMP scenario

The annual average losses of IRF, TSS, ORG_P, SOL_P and TP under I_ADJ scenario were 82.0 mm, 16.9 Mg, 28.6 kg, 170.1 kg, and 198.5 kg and were significantly lower ($p < 0.05$) than those obtained under the initial conditions (scenario 4 in Table 7). The daily IRF simulated using the I_ADJ were significantly ($p < 0.001$) lower than those simulated under the current irrigation water management (82 mm $year^{-1}$ versus 120 mm $year^{-1}$ on average). If considering the principal irrigation period (considered here between April and September), the highest difference between daily I_ADJ and baseline scenario IRF was recorded at the end of August and September in both years (Fig. 3). Using this BMP, farmers could save 1950 and

1830 m^3 ha^{-1} of water for corn and alfalfa, respectively. This water saving is very important given the high extent of corn and alfalfa in the DRW.

Reducing irrigation water for corn and alfalfa, compared to the initial conditions, resulted in yield decreases of about 2.5 and 7.1%, respectively. However, this yield decrease was within the range of yield variation of such crops in the DRW. While in the case of sunflower and barley, for which more irrigation water was applied to meet crop water needs (showing that these crops are currently under-irrigated in DRW), yield increases of about 11.3 and 12.9%, respectively, were observed. The average sunflower and barley yield obtained with I_ADJ scenario were 3.95 and 6.77 Mg ha^{-1}, respectively.

The comparison between nutrient and irrigation BMPs impacts revealed that the management of the transport factor (irrigation water) was more efficient in reducing the losses of IRF, TSS, ORG_P, SOL_P, and TP than the management of the source factor (nutrients). The average percentage reductions in IRF, TSS, ORG_P, SOL_P and TP losses with the I_ADJ scenario were respectively, 100, 100, 98, 60 and 63% higher than those obtained from nutrient BMPs (scenarios 1, 2, and 3).

3.3. Tillage BMPs scenarios

For both tillage BMPs considered (scenario 5 and 6 in Table 7), the average decrease induced was about 5.2% for IRF, 20.8% for TSS, 12.2% for SOL_P and for 9.6% for TP. Nevertheless, only the yields of SOL_P ($P < 0.05$), TSS and TP ($P < 0.10$) were significantly different from those obtained under initial conditions. For IRF and TSS, NOT practice seems to be better than the CST since the calculated percent reductions were on average somewhat higher. Unexpectedly, the opposite was found for TP: the reduction in TP was 9% higher for CST than for NOT (the percent reduction from baseline were 10.0 and 9.1%, respectively). The highest differences between daily TP loads under both scenarios were recorded during the two dates with maximum IRF (226 L s^{-1} on 05/25/2008 and 941 L s^{-1} on 08/09/2009). However, the model calibration and validation showed a bad prediction ability for P loads during streamflow peaks (Dechmi et al., 2012) and therefore these results must be regarded with care. In spite of this difference, the decreases induced by CST and NOT on IRF, TSS, SOL_P, and TP losses can be considered similar. Other modelling results indicated that analogous SWAT performance was observed in reducing sediments and phosphorus loads when tillage BMPs were applied. However, some of those studies showed the same magnitude in sediment and phosphorus yield reduction (Kirsch et al., 2002; Tripathi et al., 2005) and others presented higher values than found in the Del Reguero watershed (Osei et al., 2003).

Otherwise, an average increase of 7.2% for ORG_P losses was observed under the tillage BMPs although erosion rate decreased. However, this increase was not similar under CST and NOT practices and not significantly different from the initial conditions for both cases. This result was mainly due to the fact that conventional tillage did mix the residues properly with the soil for a greater depth, where they finally decomposed. Therefore, attachment of ORG_P in sediments was poor and the resultant losses were lower than those of CST and NOT. The build up of easily removable ORG_P on the surface, due to the lack of soil inversion and mixing, enhanced the ORG_P loss under CST and NOT practices. Similar findings were also reported by Tripathi at al. (2005) in the Nagwan watershed (India) where the major grown crops are corn and rice. On the other hand, the decreasing tillage intensity resulted in an increase of baseflow by 2.9%, while surface runoff and total irrigation water return flows decreased by 25.4 and 4.7%, respectively.

3.4. Combined BMPs scenarios

In general, the combined BMPs scenarios (scenarios 7 to 20 in Table 7) were more efficient in reducing water, soil and phosphorus losses than individual BMPs. When the I_ADJ BMP was combined with the CST and NOT BMPs (scenarios 7 and 8 in Table 7, respectively), the predicted percentage reductions were greater than in the individual I_ADJ scenario. On average, the implementation of scenarios 7 and 8 resulted in reductions of 36.5, 54.6, 4.5, 24.8, and 22.0%, for IRF, TSS, ORG_P, SOL_P and TP losses from the initial conditions, respectively. The average percent reductions for IRF, TSS, ORG_P, SOL_P and TP losses resulting from scenarios 7 and 8 were on average 16.2, 62.8, 33.6, 80.7 and 71.9% higher than those obtained when I_ADJ BMP was applied individually. However, when I_ADJ scenario was combined with nutrient BMPs (scenarios 9 to 11 in Table 7), the percentage reductions of IRF remained the same as in I_ADJ. The TSS, SOL_P and TP percent reduction was lower and the percent reduction of P_ORG was higher. The combination of P_REC and P_INC BMPs (scenario 12) did not show significant differences with the individual BMP scenarios.

The SWAT-IRRIG model was also used to quantify the combined impact of fertilizer BMPs (P_REC and P_RED) simulated along with the tillage BMPs (CST and NOT) on the tested components (scenarios 13 to 16 in Table 7). In these cases, only the actual irrigation management was considered. The percentage reductions obtained with those scenarios were quite similar to those obtained with the individual CST and NOT scenarios. The combination of tillage (CST and NOT), irrigation (I_ADJ) and fertilizer (P_REC and P_RED) BMPs (scenarios 18 to 20 in Table 7) did not have significant additional benefits compared to the results from scenarios 7 and 8.

3.5. Economic impact of the BMPs scenarios

The economic impact of the BMPs scenarios on the gross margin is presented in Table 8 for the most representative crops. The gross margins resulting under initial conditions were 631.1

€ ha^{-1} for corn, 970.7 € ha^{-1} for alfalfa, 99.8 € ha^{-1} for sunflower, and 421.1 € ha^{-1} for barley. Negative values in Table 8 indicate that the BMP reduced the gross margin of the corresponding crop, compared to the initial conditions, whereas positive values indicate that the BMP increased the gross margin of the evaluated crop. The economic impact of the BMPs varied widely from scenario to scenario and from crop to crop.

The highest economic impact was found for corn (which occupied 41% of the irrigated area in the DRW). For this crop, the economic impact of the BMPs scenarios ranged from -27.4 € ha^{-1} (scenario 9 in Table 8) to 308.6 € ha^{-1} (scenario 15 in Table 8) with a coefficient of variation of 84.3%. However, the scenario 15 did not match with the highest percentage reduction of the TP losses from the DRW, mainly because scenario 15 includes the reduction of P application dose to 0 kg ha^{-1}. As shown in Table 5, the average total cost of the fertilizer applied to corn during 2008-2009 was about 558.2 € ha^{-1}. The reduction of P fertilizer dose to 0 kg ha^{-1} decreased the average total cost of corn fertilizer to 283.3 € ha^{-1}, what increased the gross margin sharply. On the other hand, the highest percentage reduction of the TP loss (-22.6%) corresponds to an increase of corn gross margin of 296.6 € ha^{-1} (scenario 19 in Table 8).

In the case of alfalfa, the economic impact of the BMPs scenarios ranged from -91.5 € ha^{-1} (scenario 9 in Table 8) to 188.5 € ha^{-1} (scenario 15 in Table 8) with a CV of 252.0%. In this ultimate case, the lower economic impact is due to 7.1% decrease in yield compared to the initial conditions. The reduction in the P fertilizer applied increased the gross margin of alfalfa under scenario 15. As for corn, the highest percentage reduction of TP losses was found for scenario 19, for which the alfalfa gross margin increased about 112.4 € ha^{-1}.

With regard to sunflower, the economic impact of the BMPs scenarios ranged from -21.1 € ha^{-1} (scenario 12 in Table 8) to 171.3 € ha^{-1} (scenario 19 in Table 8) with a CV of 81.2%. In this case, the scenario with the highest percentage reduction of TP (scenario 19 in Table 7) also leads to the highest sunflower gross margin. As the gross margin of sunflower was very low (99.8 € ha^{-1}), this crop was not important in the study area during 2008-2009 (only 9% of irrigated area). However, in 2010 the price of sunflower raised to 0.39 € kg^{-1} from 0.20 € kg^{-1} in 2008-2009. Considering the 2010 sunflower price, the gross margin for sunflower would increase to 754.0 € ha^{-1}. For barley, the scenario with highest percentage reduction of TP losses (scenario 19 in Table 7) also provided for the highest barley gross margin.

4. Conclusions

The first modified SWAT model version (SWAT-IRRIG) that simulates better the irrigation return flows was used to evaluate the impact of 20 best management practices on farmers' income and surface water quality in intensive irrigated systems. The tested BMPs showed differences in their environmental impact and gross margin and the most relevant conclusion is related to the use of several BMPs at the same time.

The BMPs targeting only the source factor (P in the soil or P fertilizer) lead to small reductions in TP (on average 4.7% reduction, compared to initial conditions). In terms of phosphorus losses, the conservation tillage practice seems to be better than no tillage, while the optimum irrigation management (irrigation according to crop net irrigation requirement), is the most appropriate BMP, as it decreased significantly the IRF, TSS, ORG_P, SOL_P, and TP. The combination between adjusted irrigation, reduced P fertilizer dose and conservation tillage showed the highest percentage reduction in TP losses from DRW (22.6%).

In the case of sunflower and barley, the combination between adjusted irrigation, reduced P fertilizer dose and conservation tillage scenario also resulted in the highest increase in their gross margin (171 and 307 € ha^{-1}, respectively). For corn and alfalfa, this scenario did not entail the highest increase in gross margin (some yield reduction). For corn and alfalfa, the highest increase in gross margin (309 and 188 € ha^{-1}, respectively) was obtained for the combination of reduced P fertilizer dose and conservation tillage. The optimum irrigation water applied in this case should be revised.

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Table 1.

Main crop parameters values for corn, alfalfa, barley and sunflower used in SWAT-IRRIG crop growth model.

Crop parameters	Main crop			
	Corn	Alfalfa	Sunflower	Barley
Biomass energy ratio (kg MJ^{-1})	39.00	29.00	20.00	23.00
Harvest index (Mg Mg^{-1})	0.57	0.90	0.28	0.42
Maximum leaf area index (m^2 m^{-2})	5.00	5.50	5.00	6.00
Optimum air temperature (ºC)	25.00	25.00	25.00	15.00
Base temperature (ºC)	8.00	2.00	6.00	0.00
Light extinction factor	0.50	0.67	0.90	0.65

Table 2.

Description of the Best Management Practices (BMPs) considered: phosphorus fertilizer incorporation (P_INC), recommended P fertilizer dose (P_REC), reduced phosphorus fertilizer dose (P_RED), adjusted irrigation dose (I_ADJ), conservation tillage (CST) and no tillage (NOT).

	BMP scenarios
Nutrient management	1. P_INC : Phosphorus fertilizer incorporation
	2. P_REC: Recommended P fertilizer dose
	3. P_RED: Reduced phosphorus fertilizer dose
Irrigation management	4. I_ADJ: Adjusted irrigation dose
Tillage operations	5. CST : Conservation tillage
	6. NOT : No tillage
Combined BMPs	7. I_ADJ + CST
	8. I_ADJ + NOT
	9. I_ADJ + P_INC
	10. I_ADJ + P_ REC
	11. I_ADJ + P_RED
	12. P_REC + P_INC
	13. P_REC + CST
	14. P_REC + NOT
	15. P_RED + CST
	16. P_RED + NOT
	17. I_ADJ + CST + P_ REC
	18. I_ADJ + NOT + P_ REC
	19. I_ADJ + CST + P_RED
	20. I_ADJ + NOT + P_RED

Table 3.

Farmers' phosphorus application rates baseline (kg P ha^{-1}), recommended P fertilizer dose BMP (P_REC) (kg P ha^{-1}), water irrigation depth baseline (mm) and irrigation management scenario BMP (I_ADJ) values considered for alfalfa, corn, sunflower, and barley.

	P application rates (kg P ha^{-1})				***Water irrigation depth (mm)***			
	Baseline			**BMP**	**Baseline**			**BMP**
	2008	**2009**	**Mean**	**P_REC**	**2008**	**2009**	**Mean**	**I_ADJ**
Alfalfa	32	68	50	50	796	864	830	699
Corn	100	95	98	45	898	898	898	787
Sunflower	25	20	23	25	474	473	474	620
Barley	41	59	50	20	241	189	215	421

Table 4.

Conventional tillage (CVT), conservation tillage (CST) and no tillage (NOT) scenarios parameters and their depth of till (DEPTIL) and mixing efficiencies (EFFMIX) values considered in SWAT-IRRIG simulations.

Scenario	Tillage operation	DEPTIL (mm)	EFFMIX
CVT (baseline)	Moldboard plow	150	0.95
	Cultivator	100	0.25
	Roller packer	40	0.05
CST	Cultivator	100	0.25
NOT	Generic no tillage mixing	25	0.05

Table 5.

Description of the different concepts used to calculate gross margin (€ ha^{-1}) for corn, alfalfa, sunflower and barley during the period 2008-2009.

	Concept	Corn	Alfalfa	Sunflower	Barley
Costs (€ ha^{-1})	Water fees	66.0	66.0	66.0	66.0
	Fertilizers	558.2	272.1	198.3	328.9
	Labor	4.3	19.4	3.1	10.7
	Phytosanitary	81.8	32.5	81.8	8.2
	Seeds	228.9	12.0	59.8	59.1
	Machinery	158.6	223.9	148.5	138.4
	Grain drying	434.6	0.0	0.0	0.0
	Irrigation	199.2	215.5	113.8	51.6
	Total costs	1731.6	841.4	669.9	662.9
Income (€ ha^{-1})	Crop yield	2259.9	1812.2	717.5	1027.6
	Subsidies	102.8	0.0	53.6	56.4
	Total income	2362.7	1812.2	771.1	1084.0
Gross margin (€ ha^{-1})		631.1	970.7	99.8	421.1

Table 6.

Total cost of machinery (€ ha^{-1}) used for conventional tillage (CVT), conservation tillage (CST), and no tillage (NOT) for corn, alfalfa, sunflower, and barley.

Scenario	Corn	Alfalfa	Sunflower	Barley
Conventional tillage (CVT)	158.6	223.9	148.5	138.4
Conservation tillage (CST)	101.2	167.0	84.6	81.8
No tillage (NOT)	103.5	169.0	87.4	84.2

Table 7.

The SWAT-IRRIG model initial conditions (baseline scenarios) and the percentage changes resulted from each BMP application of total irrigation water return flows (IRF, mm), total suspended sediments (TSS, Mg), organic phosphorus (ORG_P, kg), soluble phosphorus (SOL_P, kg), and total phosphorus (TP, kg) average values. The considered BMPs are: phosphorus fertilizer incorporation (P_INC), recommended P fertilizer dose (P_REC), reduced phosphorus fertilizer dose (P_RED), adjusted irrigation dose (I_ADJ), conservation tillage (CST) and no tillage (NOT).

Baseline scenario	IRF	TSS	ORG_P	SOL_P	TP
	119.6	25.4	30.6	197.0	227.6
Percentage reduction from baseline (%)					
21. P_INC	0.0	0.0	–0.1	–4.7^{+}	–4.0^{+}
22. P_REC	0.0	0.0	–0.1	–5.8^{+}	–5.0^{+}
23. P_RED	0.0	0.0	–0.1	–5.9^{+}	–5.1^{+}
24. I_ADJ	–31.4*	–33.5*	–6.7*	–13.7*	–12.8*
25. CST	–5.0	–20.5^{+}	+5.3	–12.4*	–10.0^{+}
26. NOT	–5.4	–21.0^{+}	+9.1	–11.9*	–9.1^{+}
27. I_ADJ + CST	–36.3*	–54.3*	–5.9	–24.9*	–22.3*
28. I_ADJ + NOT	–36.7*	–54.8*	–3.0	–24.6*	–21.7*
29. I_ADJ + P_INC	–31.4*	–33.5*	–6.7*	–14.1*	–13.1*
30. I_ADJ + P_ REC	–31.4*	–33.5*	–6.7*	–13.6*	–12.6*
31. I_ADJ + P_RED	–31.4*	–33.5*	–6.8*	–19.7*	–17.9*
32. P_REC + P_INC	0.0	0.0	–0.1	–5.9^{+}	–5.1^{+}
33. P_REC + CST	–5.0	–20.4^{+}	+5.3	–12.7*	–10.3^{+}
34. P_REC + NOT	–5.4	–21.0^{+}	+9.1	–12.1*	–9.2^{+}
35. P_RED + CST	–5.0	–20.4^{+}	+5.3	–12.7*	–10.3^{+}
36. P_RED + NOT	–5.3	–21.0^{+}	+9.1	–12.1*	–9.2^{+}
37. I_ADJ + CST + P_ REC	–36.3*	–54.3*	–5.8	–24.9*	–22.3*
38. I_ADJ + NOT + P_ REC	–36.7*	–54.8*	–3.0	–24.7*	–21.7*
39. I_ADJ + CST + P_RED	–36.3*	–54.3*	–5.9	–25.2*	–22.6*
40. I_ADJ + NOT + P_RED	–36.7*	–54.8*	–3.0	–24.8*	–21.9*

* Significantly different from the initial conditions ($\alpha = 0.05$)
$^{+}$ Significantly different from the initial condition ($\alpha = 0.10$)

Table 8.

Average calculated gross margin (€ ha^{-1}) of baseline scenario during the period 2008-2009, and its changes (€ ha^{-1}) for corn, alfalfa, sunflower, and barley in applying various BMPs. The considered BMPs are: phosphorus fertilizer incorporation (P_INC), recommended P fertilizer dose (P_REC), reduced phosphorus fertilizer dose (P_RED), adjusted irrigation dose (I_ADJ), conservation tillage (CST) and no tillage (NOT).

Baseline scenario (€ ha^{-1})	Corn	Alfalfa	Sunflower	Barley
	631.1	970.7	99.8	421.1
Changes from baseline: € ha^{-1}				
1. P_INC	-15.5	-15.5	-15.5	-15.5
2. P_REC	148.0	12.8	-5.6	84.6
3. P_RED	274.9	141.0	64.8	141.0
4. I_ADJ	-11.9	-76.0	69.8	112.4
5. CST	33.7	47.5	36.6	53.8
6. NOT	14.6	38.8	17.1	49.8
7. I_ADJ + CST	21.7	-28.5	106.5	166.2
8. I_ADJ + NOT	2.6	-37.2	87.0	162.2
9. I_ADJ + P_INC	-27.4	-91.5	56.7	96.9
10. I_ADJ + P_ REC	136.1	-63.2	64.2	197.0
11. I_ADJ + P_RED	263.0	64.9	134.7	253.3
12. P_ REC + P_INC	132.5	-2.7	-21.1	69.1
13. P_ REC + CST	181.7	60.3	31.0	138.4
14. P_ REC + NOT	162.6	51.6	11.5	134.4
15. P_RED + CST	308.6	188.5	101.4	194.8
16. P_RED + NOT	289.5	179.8	81.9	190.8
17. I_ADJ + CST + P_ REC	169.7	-15.7	100.9	250.8
18. I_ADJ + NOT + P_ REC	150.6	-24.5	81.4	246.8
19. I_ADJ + CST + P_RED	296.6	112.4	171.3	307.2
20. I_ADJ + NOT + P_RED	277.5	103.7	151.9	303.2

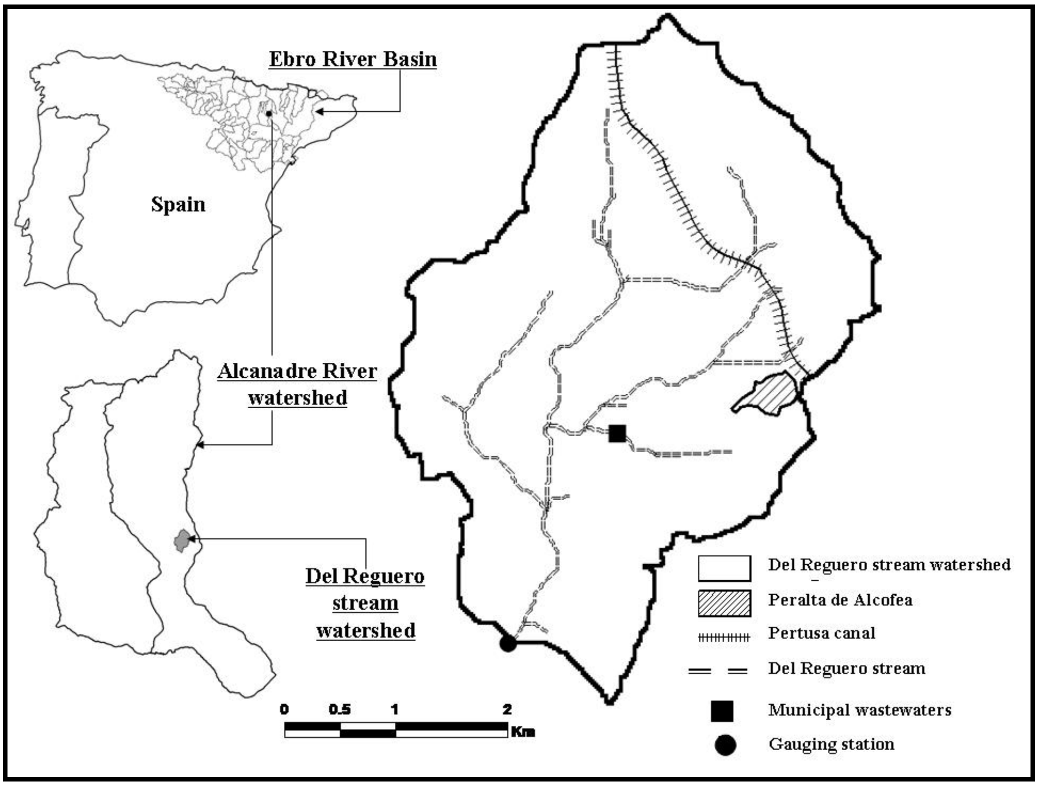

Figure 1. Location of Del Reguero watershed (DRW).

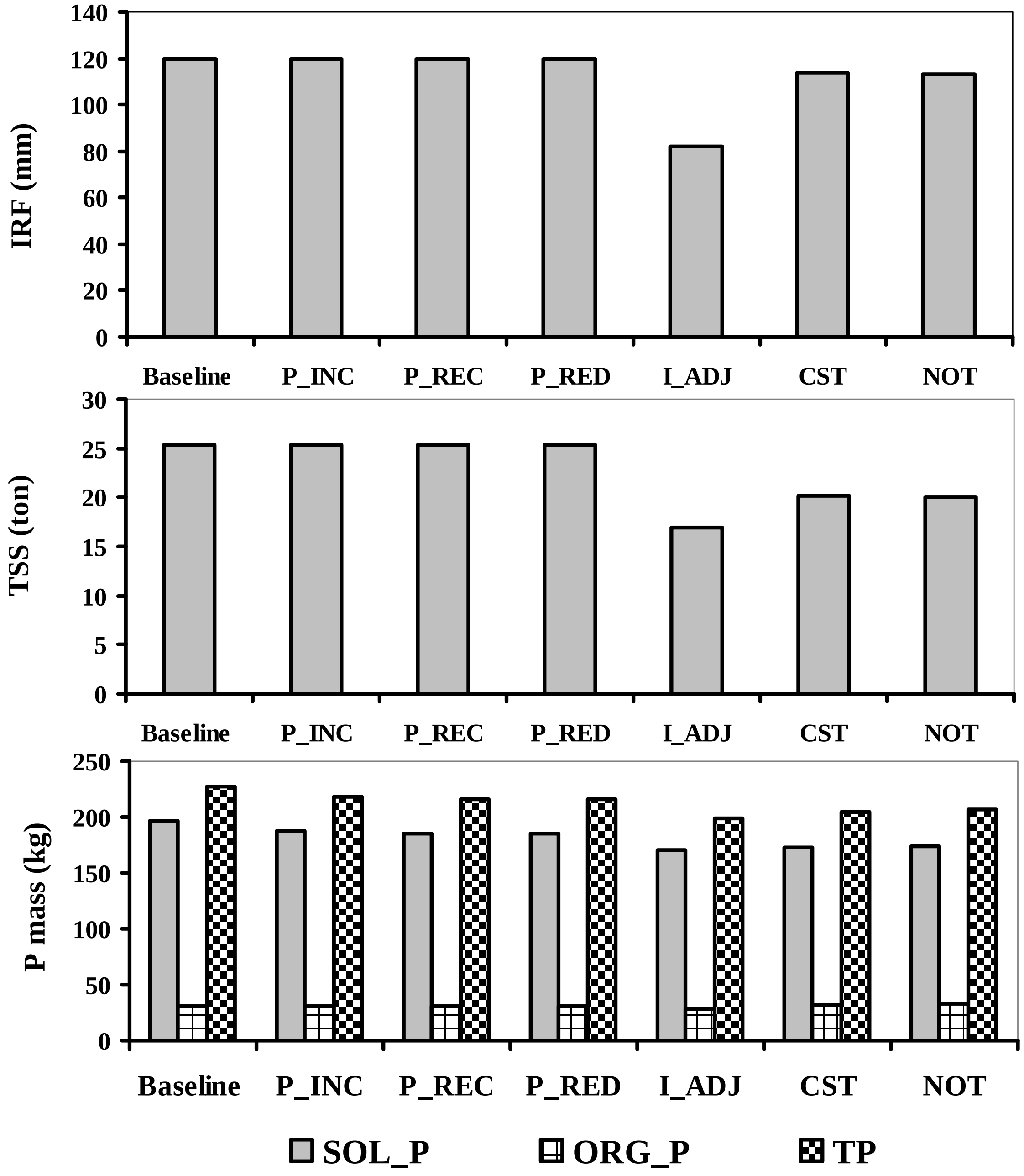

Figure 2. The simulated irrigation return flow (IRF, mm), total suspended sediments (TSS, ton), total phosphorus (TP, kg), mineral phosphorus (SOL_P) and organic phosphorus (ORG_P) average values under baseline, phosphorus fertilizer incorporation (P_INC), recommended phosphorus fertilizer dose (P_REC), reduced phosphorus fertilizer dose (P_RED), adjusted irrigation water (I_ADJ), conservation tillage (CST) and the no tillage (NOT) scenarios.

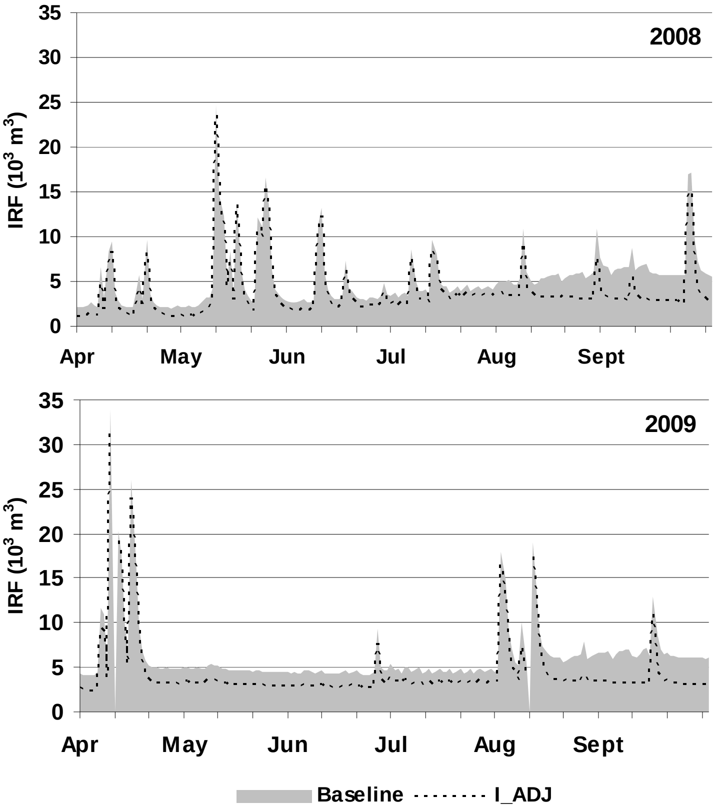

Figure 3. Daily simulated irrigation return flow (IRF, 10^3 m^3) under current condition (baseline scenario) and irrigation BMP (I_ADJ scenario) during the main irrigated months (April to September) of the study period (2008 and 2009). For better visualisation of the daily data during 2009, the very high IRF recorded on 4/11/2009 and 8/09/2009 (182 and 189 10^3 m^3, respectively) were not presented in the figure.