A modeling approach to evaluate the impact of BMPs for minimizing the phosphorus transport under sprinkler irrigation system

Skhiri Ahmed[1,*] and Dechmi Farida[2]
[1] Département Hydraulique, Ecole Supérieure des Ingénieurs de Medjez el Bab, Université de Jendouba, Route du Kef Km 5, 9070 Medjez el Bab, Tunisie, ahmedskhiri2004@yahoo.fr
[2] Agrifood Research and Technology Centre of Aragon (CITA), Soil and Irrigation Department (EEAD-CSIC Associated Unit), Avda. Montañana 930, 50059 Zaragoza, Spain, fdechmi@aragon.es
* Corresponding Author: Ahmed Skhiri

Abstract
The SWAT (Soil and Water Assessment Tool) has been used to evaluate the impact of several best management practices (BMPs) on water yield (WYLD) and total phosphorus (TP) at the outlet of the Del Reguero stream watershed (Spain). In total, 6 individual scenarios and 14 combinations of various management practices including tillage (conservation and no-tillage), fertilizer (incorporated, recommended, and zero), and irrigation (adjusted to crop needs) were been tested. Results indicate that the best individual BMPs (adjusted irrigation water use BMP) reduced WYLD to 31.4% and TP loads to 12.8%, in comparison of the initial conditions. When individual BMPs were combined, the reductions of losses were increased. The BMPs combination between optimum irrigation application, conservation tillage and reduced P fertilizer dose was the best analyzed one with a TP loads reduction about 22.6%.
Keywords: SWAT, BMPs, Sprinkler irrigation, total phosphorus, water yield.

1. Introduction

Intensive agricultural practices (irrigation, fertilization and tillage) are identified to release significant amounts of nutrients, especially phosphorus (P) to receiving water bodies (Monaghan *et al.* 2005). To reduce nutrient losses from agricultural lands, many practices have been proposed, including on-farm nutrient management (rate added and method of application), tillage operations (conservation and no-tillage), and proper irrigation management (Sharpley *et al.* 2001).

Therefore, simulation models are necessary to evaluate best management practices (BMPs) performance in reducing non-point source pollutants from agricultural watersheds and for making watershed management recommendations (Chaubey *et al.* 2010). The SWAT model (Arnold *et al.* 1998) offers the greatest number of management alternatives for modeling agricultural watersheds (Arabi *et al.* 2007).

The SWAT model was modified (renamed as SWAT-IRRIG) (*Dechmi et al. 2012*), calibrated, and validated to improve its performance in intensive irrigation systems, and evaluate its prediction in modeling water flow and phosphorus loads. The objectives of this study were: (i) to identify and test the effectiveness of several BMPs scenarios using SWAT-IRRIG; (ii) to evaluate their effects on water quality in terms of total water yield, and phosphorus loads.

2. Materials and Method

2.1. Study zone

The Del Reguero watershed (DRW) belongs to the Alto Aragon Irrigation Scheme area located in the left bank of the middle Ebro River Basin in Spain (Figure 1). It has a total drainage area of 18.65 km^2 with elevations ranging from 208 to 502 m and an average land surface slope of 4.4‰.

The main cultivated crops in the two studied years (2008 and 2009) were corn (41%), barley (19%), alfalfa (15%), and sunflower (9%) and represent more than 84% of the watershed irrigated area.

The climate is semiarid with an average annual precipitation and reference evapotranspiration of 391 mm and 1,294 mm, respectively. The mean annual temperature is 13.1 °C, with a large temperature difference between winter and summer.

Irrigation practices began in 1982 using sprinkler irrigation systems (mainly solid-set sprinklers).

Two geomorphologic units are distinguished in the study area. The first unit corresponds to platform soils (locally called ‘‘sasos’’) that cover 38% of the total area. These soils are shallow, present calcareous horizons, and a high content of stones. The second unit covers the remaining of the watershed and corresponds to alluvial soils that are mostly stone-free and with soil depths varying from 0.6 m to more than 1.20 m.

The soil P-Olsen concentrations were very heterogeneous ranging from 5 to 137 mg kg^{-1} in the surface layer (0–30 cm) with an average of 28 mg kg^{-1} and an standard deviation of 19.32 mg kg^{-1}. The drainage waters were characterized by an annual average total phosphorus concentration of 0.112 mg L^{-1}.

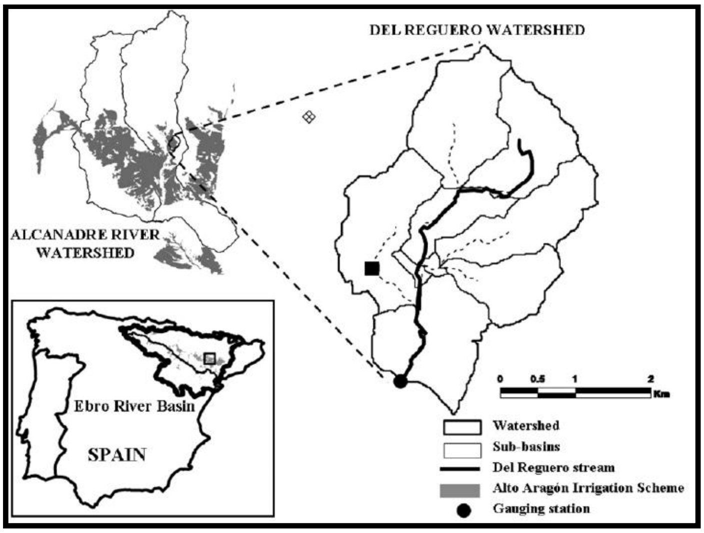

Figure 1. Del Reguero watershed (DRW) localization

2.2. SWAT model description

SWAT is a continuous time, spatially semi-distributed, physically based model (*Arnold et al. 1998*). The watershed is divided into multiple sub-watersheds, which are then further subdivided into specific soil/land use characteristic units that are called hydrologic response units (HRUs).

The water balance of each HRU is represented by 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 each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet.

The soil profile is subdivided into multiple layers that consider several soil water processes including infiltration, evaporation, plant uptake, lateral flow, and percolation. The soil percolation component of SWAT uses a storage routing technique to simulate flow through each soil layer in the root zone.

Crop evapotranspiration 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 using a similar approach to that in the Erosion Productivity Impact Calculator (EPIC) model (*Williams, 1990*).

The surface runoff from daily rainfall was estimated using the modified SCS curve number and the potential evapotranspiration (PET) was determined using the modified Penman–Monteith approach.

Phosphorus can be lost in both particulate and dissolved forms (*Arnold et al. 1998*). The loss of dissolved phosphorus in surface runoff is estimated based on the concept of partitioning phosphorus into the solution and sediment phases as described by Leonard and Wauchope (1980) for pesticides.

2.3. SWAT input data

All the components of the landscape were integrated into the model. For that purpose, a digital elevation model (DEM), a soil map, and a land use/land cover (LULC) map were required for delineating the basin into subbasins and hydrological response units HRUs. The topographic parameters (slope, slope length, drainage network, watershed delimitation and number of subbasins) were obtained from the digital elevation model (DEM) of the Ebro River Basin (20x20 m grid size). The land use and soil data were obtained from the special crop and soil distribution maps prepared during the study years.

The weather input data, including maximum and minimum daily air temperature, solar radiation, wind speed and relative humidity, were obtained from the Huerto meteorological station.

Regarding irrigation management, dates and amounts of water applied to each crop during each irrigation event were obtained from the databases facilitated by the Alconadre Irrigation District.

Parameters of farmers' current management operations as tillage, planting dates, fertilization, and irrigation and harvesting were provided as inputs to the model.

The amounts of organic and inorganic fertilizers applied to each crop grown in DRW were determined through farmer's interviews performed during the 2008 and 2009 agricultural seasons.

2.4. Scenarios description

The BMPs considered in this study were grouped into three categories: (i) nutrient management (incorporated, recommended and reduced fertilizer); (ii) irrigation management; and (iii) tillage operations (conservation tillage and the no tillage). In present study, a combination set of these categories were considered to assess their effect on water quality, as simulated by SWAT.

2.4.1. Nutriments management scenarios

Three levels of phosphorus fertilizer were considered:

1. Incorporated P fertilizer dose (P_INC): in SWAT the incorporation of fertilizer is possible by adjusting of the fraction of fertilizer applied to top 10 mm of soil;
2. Recommended P fertilizer dose (P_REC): the P fertilizer recommended rates are calculated for each crop considering the P harvested in crops and the average local crop yields gathered from field surveys;
3. Reduced P fertilizer dose (P_RED): the P fertilizer dose was reduced to 0 kg P.ha^{-1} for each crop.

2.4.2. Irrigation management scenario

This scenario consists in using of an optimum irrigation scheduling by adjusting irrigation water use (I_ADJ) considering the crop net irrigation requirement (NIR). The daily NIR for each crop were calculated using equation 1:

$$NIR = (Kc \times ETo) - Peff$$

2.4.3. Tillage operations scenarios

The conservation tillage (CST) and the no tillage (NOT) scenarios were tested and compared with the conventional tillage (CVT), which represents the actual farmers' practices. CST and NOT practices are practically absent in the study area.

2.4.4. BMPs analysis

In total, 20 BMPs scenarios were tested. Six of the scenarios correspond to those previously described while the other 14 scenarios consist of combinations of the first six BMPs. The impact of BMPs scenarios on water quality are presented as percent reductions in average annual losses of water yield (WYLD, mm) and total P (TP, kg) from the actual farmers' practices in the study zone. The calibrated SWAT-IRRIG model, considering the actual farmer practices, was run for 2 years period from 2008 to 2009 to calculate WYLD and TP actual values. For each previously described BMPs, SWAT-IRRIG model was run for the same period (2008-2009) and the percent reduction was calculated as:

$$Reduction\ (\%) = \frac{PreBMP - PostBMP}{PreBMP} \times 100$$

Where pre-BMP and post-BMP are SWAT-IRRIG outputs before and after implementation of the BMP, respectively. A paired t test ($\alpha = 0.05$ and 0.10) was performed on the simulated monthly values of WYLD and TP losses at Del Reguero Watershed (DRW) outlet to test the significance change in the BMPs application. STATGRAPHIC version 5 was used.

3. Results and discussion

Average water yield losses (2008-2009) and total P simulated by SWAT-IRRIG considering initial conditions (baseline) are 119.6 mm of irrigation return flow (IRF) and 227.6 kg of total phosphorus (Table 1).

Table 1. 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) and total phosphorus (TP, kg) average values.

Baseline scenario (initial conditions)	IRF	TP
	119.6	227.6
1. P INC	0.0	-4.0**
2. P REC	0.0	-5.0**
3. P RED	0.0	-5.1**
4. I ADJ	-31.4*	-12.8*
5. CST	-5.0	-13.7*
6. NOT	-5.4	-10.0**
7. I_ADJ + CST	-36.3*	-9.1**
8. I_ADJ + NOT	-36.7*	-22.3*
9. I_ADJ + P_INC	-31.4*	-21.7*
10. I_ADJ + P_REC	-33.5*	-12.6*
11. I_ADJ + P_RED	-31.4*	-17.9*
12. P REC + P INC	0.0	-5.1**
13. P_REC + CST	-5.0	-10.3**
14. P_REC + NOT	-5.4	-9.2**
15. P_RED + CST	-5.0	-10.3**
16. P_RED + NOT	-5.3	-9.2**
17. I_ADJ + CST + P_REC	-36.3*	-22.3*
18. I_ADJ + NOT + P_REC	-36.7*	-21.7*
19. I_ADJ + CST + P_RED	-36.3*	-22.6*
20. I_ADJ + NOT + P_RED	-36.7*	-21.9*

* Significantly different from the initial conditions ($\alpha = 0.05$).

** Significantly different from the initial condition ($\alpha = 0.10$).

3.1. Nutrients BMP scenarios

The results indicate that P fertilizer incorporation scenario leads to reduction of TP by 4.0%. The application of the recommended P fertilizer dose and no P fertilization BMPs presented similar reduction of TP losses, compared to the initial conditions. On average, the implementation of P_REC and P_RED BMPs scenarios reduced TP losses by 5.1%. These losses of TP under P_REC and P_RED scenarios were significantly different ($P < 0.10$) from the initial conditions.

The application of these scenarios did not have any impact on the average amount of crop P uptake (28.64 $kg.ha^{-1}$). In the other hand, 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 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 results indicate that the adjustment of the irrigation water dose to the crop water requirements reduced WYLD and TP losses at the outlet of the study zone. The annual average losses of WYLD and TP under I_ADJ scenario were 82.0 mm of water and 198.5 kg of phosphate and were significantly lower ($P < 0.05$) than those obtained under the initial conditions.

The comparison between nutrient and irrigation BMPs impacts revealed that the management of transport factor (irrigation water) was more efficient in reducing the losses of WYLD and TP than the management of source factor (nutrients). Therefore, impacts of I_ADJ scenario on WYLD and TP losses were, respectively, 100% and 63% higher than average percentage reductions obtained from nutrient BMPs scenarios.

3.3. Tillage BMPs scenarios

Results indicate that on average, both tillage BMPs considered induced a decrease of WYLD (5.2%) and TP losses (9.6%). However, the values of WYLD losses, under CST and NOT BMPs, were not significantly different from the initial conditions. With less intensive tillage practices the yields of TP ($P < 0.10$) were significantly different from those obtained under initial conditions. The CST practice was a little bit better than NOT in terms of TP losses.

3.4. Combined BMPs scenarios

In general, the combined BMPs scenarios were more efficient in reducing water and phosphorus losses than individual ones. When the I_ADJ BMP was combined with the CST and NOT BMPs, the predicted percentage reductions were greater in comparison with the individual I_ADJ scenario. On average, this combination resulted in reductions of 36.5 and 22.0%, for WYLD and TP losses from the initial conditions, respectively.

4. Conclusion

The environmental impact variability between the considered 20 BMPs was observed. When the BMPs only targeting the source factor (P in the soil or P in fertilizers), the resulting percentage of reduction of TP will be low (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 and the optimum irrigation management, according to crop net irrigation requirement, is most appropriate because it decreases significantly the losses of WYLD and TP. However, the most relevant conclusion is related to the use of several BMPs at the same time. The combination between adjusted irrigation practices, reduced P fertilizer dose, and conservation tillage BMPs showed the highest reduction of TP losses in the study zone

(22.6%). The new knowledge acquired from this work should help scientists, policy makers, and farmers to take optimal decisions for a sustainable management of agricultural irrigated watersheds under similar environmental conditions.

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