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Advances in Water in Agroscience

Impacts of irrigation development on water quality in the San Salvador watershed (Part 2): Implementation of scenarios in SWAT

Impactos del desarrollo del riego en la calidad de agua en la cuenca del río San Salvador (Parte 2): Implementación de escenarios en SWAT

Impactos do desenvolvimento da irrigação na qualidade da água na bacia hidrográfica de San Salvador (Parte 2): Implementação de cenários no SWAT

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Abstract

Intensive agricultural activities pose a significant threat to water quality as critical non-point sources of pollution. Effective mitigation strategies demand understanding the causes and processes of water pollution. This study aimed to quantify the impacts of irrigation development on water quality and assess best management practices for sustainable agriculture intensification. Employing the calibrated SWAT model for the San Salvador watershed (baseline scenario), two scenarios were implemented and evaluated: the first one depicted irrigation development from a future reservoir, and the second integrated riparian buffer zones to minimize nutrient and sediment losses. Notably the baseline scenario did not achieve nutrient water quality objectives. Results revealed that irrigation development increases nutrient yields, driving the future reservoir toward eutrophication. Implementing riparian buffer zones reduced nutrient loss, but additional measures are necessary for sustainable environmental goals at the basin scale. This research contributes with valuable insights for formulating effective management strategies to minimize nutrient pollution in water and safeguard water quality and biodiversity in the basin.

Keywords: sustainable agriculture, water quality, supplementary irrigation, SWAT

Resumen

La intensificación agrícola representa una importante fuente de contaminación que amenaza la cantidad y la calidad del agua. Estrategias de mitigación efectivas requieren comprensión de las causas y los procesos de la contaminación del agua. Este estudio tiene como objetivo cuantificar los impactos del desarrollo del riego en la calidad del agua y evaluar las buenas prácticas de manejo para la intensificación agrícola sostenible. Se utilizó el modelo SWAT calibrado para la cuenca de San Salvador (escenario base), se implementaron y evaluaron dos escenarios: el primero representa el desarrollo de riego a partir de un futuro embalse, y el segundo incorpora zonas *buffer* ribereñas para minimizar las pérdidas de nutrientes y sedimentos. Se destaca que en el escenario base no se alcanzan los objetivos de calidad del agua. Los resultados revelaron que el desarrollo del riego aumenta la exportación de nutrientes, llevando al futuro embalse a un estado de eutrofización. La implementación de zonas *buffer* ribereñas redujo los nutrientes exportados, pero

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se necesitan medidas adicionales para alcanzar objetivos ambientales sostenibles en la cuenca. Esta investigación aporta conocimientos valiosos para formular estrategias de gestión eficaces que minimicen la contaminación por nutrientes y protejan la calidad del agua y la biodiversidad en la cuenca.

Palabras clave: agricultura sostenible, calidad de agua, riego complementario, SWAT

Resumo

A intensificação das atividades agrícolas é uma importante fonte de poluição que ameaça a qualidade da água. Estratégias eficazes de mitigação requerem compreensão das causas e processos da poluição da água. Este estudo visa quantificar os impactos do desenvolvimento da irrigação na qualidade da água e avaliar as melhores práticas de manejo para intensificação sustentável da agricultura. Utilizando o modelo SWAT calibrado para a bacia de San Salvador (cenário base), dois cenários foram implementados e avaliados: o primeiro representava o desenvolvimento da irrigaçãoa partir de um reservatório futuro, e o segundo integrava zonas de proteção ripária para minimizar as perdas de nutrientes e sedimentos. Note-se queocenário basenão atinge os objetivos de qualidade da água para nutrientes. Os resultados revelaram que o desenvolvimento da irrigação aumenta a exportação de nutrientes, levando o futuro reservatório a um estado de eutrofização. A implementação de zonas de proteção ripária reduziu a perda de nutrientes, masmedidas adicionais são necessárias para objetivosambientais sustentáveis na escala da bacia. Esta pesquisa fornece conhecimentos valiosos para a formulação de estratégias eficazes de gestãoparaminimizar a poluição por nutrientes na água e proteger a qualidade da água e a biodiversidade na bacia.

Palavras chave: agricultura sustentável, qualidade de água, irrigação, SWAT

1. Introduction

According to some projections, global crop production will need to at least double by 2050 to meet the projected food demand, leading to new concerns and stresses on the Earth's natural resources(1-2). To achieve global food security and environmental sustainability, FAO promotes climate-smart agriculture with three main objectives: sustainably increasing agricultural productivity and income, adapting and building resilience to climate change, and reducing or eliminating greenhouse gas emissions(3).

Globally, differences between observed and potential crop yields suggest the presence of 'yield gaps' where management constrained productivity; in recent decades, agricultural intensification (e.g., through the use of irrigation, fertilizers, biocides, and mechanization) has accounted for the majority of yield increases(1). Sustainable expansion of irrigation on rainfed croplands could close global yield gaps and secure food production to feed the world's population(4-6). For a sustainable irrigation expansion, water resources must not be depleted, and environmental flows must be maintained(7-8). Environmental flows refer to the quantity and quality of water required for ecosystem conservation and resource protection(9). Water infrastructure development is important as a long-term adaptation strategy to climate change(10); the irrigation demand can be sustainably satisfied through water storage infrastructure(11).

Agricultural cropland is considered a critical source of nutrients to nearby water bodies; high concentrations of total nitrogen (TN) and total phosphorus (TP) were associated with agricultural watersheds(12-13). Excessive nutrient levels can affect the health of water bodies by promoting rapid algal growth or eutrophication(14).

Riparian buffer zones represent a best management practice to protect waterbodies from diffuse nutrient, sediment, and chemical losses(15). A riparian buffer zone is an area adjacent to a water body where a combination of trees, shrubs, and /or other perennial plants grow. When a buffer zone is implemented, the soil is stabilized, fertilizers and pesticides are retained, and pollutants that are washed off with runoff are trapped by the vegetation and soil(15). Merriman and others(16) reported average nutrient reductions of 47% and 57% for riparian buffers for TN and TP, respectively. While Calvo(17) reported average reductions of nutrients of 25% to 78% for TP and -11% to 62% for TN, and suggested that a buffer zone composed of herbaceous and woody vegetation had the best overall efficiency.

Based on these considerations, this study used the Soil Water Assessment Tool (SWAT)(18) model to simulate and analyze the impact of irrigation development on agricultural production, water quantity, and water quality. SWAT is a physically based, continuous-time model at the watershed scale. It is widely used to predict the effects of land use and land management on nutrient loading and soil erosion in agricultural watersheds. Key components of the model include hydrology, weather, soil erosion, plant growth, nutrients, pesticides, land management, and stream routing.

This study represents the second part of a master's thesis aimed at developing a modeling tool to support sustainable land use and planning in an irrigation development scenario. The model implementation, calibration, and validation were reported in the paper “Impacts of irrigation development on water quality in the San Salvador watershed (Part 1): Assessment of current nutrient delivery and transport using SWAT”(19).

2. Materials and methods

2.1 Study area

The San Salvador watershed is located in the department of Soriano, Uruguay (Figure 1), and has an area of 2,413 km^2. The mean elevation is 79 m and ranges from 1 to 171 m, and the average slope is 2.3%. Land use (2018) is predominantly rainfed agriculture (62%) and native grassland (31%), while irrigated cropland accounts for only a small portion of the area (1.2%). The mean annual temperature and precipitation for the period 1961-1990 were 17.5 °C and 1100 mm, respectively(20).

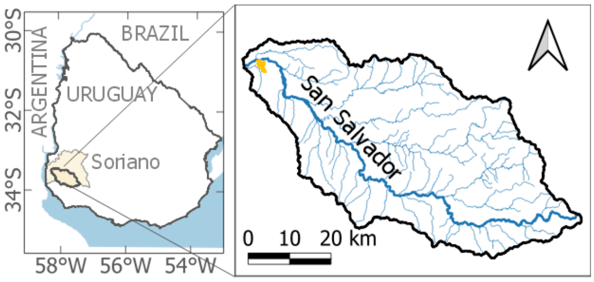

Figure 1. Location of San Salvador watershed (Soriano department, Uruguay). Coordinate Reference System: World Geodetic System 1984 (WGS84)

2.2 Brief model description

A model setup with land uses from 2018 and daily time step simulation 1992-2021 (and three years of warm-up 1989-1992) was considered. The model scheme included 13 sub-basins and 1354 hydrologic response units (HRUs), which are units with the same soil, slope, and land use. No filters were used in delineating the HRUs; this level of detail allows for the simulation of the hydrologic process using a semi-distributed approach (Figure 2). The model input data included a digital elevation model (DEM), land use, soil, management practices, and climatic data for the period 1990-2021; a detailed description of the input data can be found in Hastings and others(19).

The version of the model used in this study is SWAT 2012, including SWAT Editor (2020 Revision 681) and QSWAT interface (version 1.9), available for QGIS (version 2.6.1).

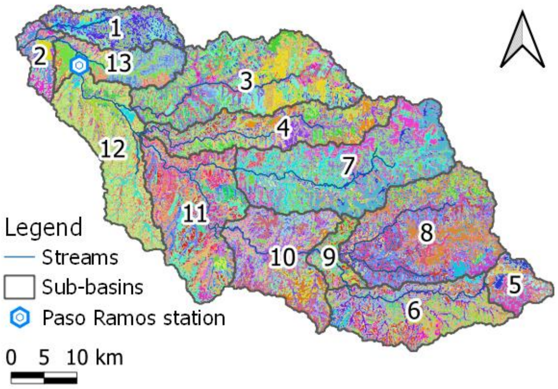

Figure 2. Sub-basins and hydrologic response unit (HRU) delineated in SWAT

2.3 Hard and soft model calibration

The calibration approach included hard and soft data(21). A detailed description of the procedures and results can be found in Hastings and others(19).

Time series of discharge at the Paso Ramos station were used as hard data for calibration and validation of hydrological processes. Calibration and validation were performed for the 1990-1998 and 1999-2000 periods, respectively. Particle swarm optimization (PSO)(22), available in the SwatPlusR tool(23), was used for model optimization and Nash-Sutcliffe efficiency (NSE)(24) was chosen as the objective function. Furthermore, percent bias (pbias) and Kling-Gupta efficiency (KGE) were calculated for model verification. According to Moriasi and others(25), calibration performance was satisfactory (NSE 0.55, pbias -9, and KGE 0.47); although NSE decreased to an unsatisfactory level during the validation period, KGE remained at a satisfactory level (NSE 0.37, pbias -12.5, and KGE 0.5). It was concluded that the performance of the hydrological model was adequate according to the available data.

Crop, sediment, and nutrient yields were verified using local data (observed crop yields and biomass 2010-2021, average annual sediment yield of Uruguay 2000-2020, and nutrient yields bibliographic review). Also, water quality (TN, TP, and total suspended solids, TSS) was soft-calibrated due to the low sampling frequency. Simulation averages were verified against observed averages at Paso Ramos station in the period 2014-2021.

2.4 Scenarios in SWAT

Two additional scenarios were implemented to compare to the baseline scenario representative of the current situation (1992-2021). The first scenario represents irrigation development (Scenario 1), and the second scenario adds riparian buffer zones to minimize export from diffuse nutrient, sediment, and chemical losses (Scenario 2).

2.4.1 Scenario 1: Irrigation development

The irrigation scenario implemented in this study consists of considering the construction of a reservoir on a tributary to the San Salvador River and the associated increase in irrigated croplands. The reservoir's location and size and the location and extent of irrigated cropland areas were determined by a previous study that considered economic, social, and environmental criteria to select the most interesting scenario for irrigation development in the Salvador basin(26).

The scenario provides water for the irrigation of 6,950 ha of summer crops through central pivots, representing a 2.5 times increase in the irrigated area compared to the baseline scenario. There are two irrigation zones simulated (Figure 4): the first is in sub-basin 3, where water from the reservoir is pumped to irrigate 2,100 ha near the lake; the second zone is in sub-basin 12, and water is transported 14.5 km downstream via Aguila Creek and then pumped to irrigate 4,850 ha.

The simulated reservoir, in sub-basin 3 (Figure 4), has a capacity of 26.5 hm^3, a lake of 587 ha, and a contributing watershed of 27,048 ha. Table 1 shows the volume and area of the projected reservoir, the volume to fill the emergency spillway is 5% greater than that of the principal spillway.

Table 1. SWAT input variables related to reservoirs

Variable	Value	Definition
RES_ESA	650	Area of the reservoir when filled to the emergency spillway (ha)
RES_EVOL	2783	Volume of water needed to fill to the emergency spillway (10^4 m^3).
RES_PSA	628	area of the reservoir when filled to the principal spillway (ha).
RES_PVOL	2650	Volume of water needed to fill to the principal spillway (10^4 m^3).

An environmental flow was assumed to be daily discharged from the reservoir, whose volume was calculated as the monthly discharge with a 60% probability of exceedance for the baseline scenario (Figure 3), in accordance with the requirements of Uruguayan law(27).

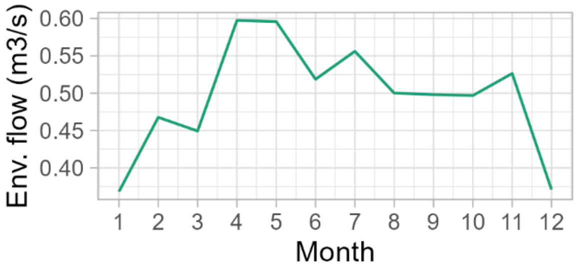

Figure 3. Monthly environmental flows

The SWAT model assumes the reservoir is completely mixed and the only transformation in the water body is sediment and nutrient settling. A mass balance is computed to calculate nutrient discharge. Settling losses of phosphorous and nitrogen are estimated as a mass flux proportional to the apparent settling velocity(28). Table 2 shows the settling velocities of phosphorus and nitrogen. Because reservoir water quality is very sensitive to these velocities and they are site-specific, default velocities and minimum and maximum values were used. In the case of sediment settling, the median particle diameter was set to 26 μm based on data from another local reservoir named Baygorria, located on Río Negro River(29). The equilibrium sediment concentration was set at 40 mg/L, resulting from an iteration until obtaining a mean concentration in the water body of 5.5 mg/L (mean TSS observed in a local reservoir named Paso Severino, located on Santa Lucía River(29)).

Table 2. SWAT input variables that control settling in the reservoir. The minimum and maximum values are given in parentheses

Variable	Default value	Final value	Definition
PSETLR	10 (2-20)	10 (2-20)	Phosphorous settling rate (m/yr).
NSETLR	5.5 (1-15)	5.5 (1-15)	Nitrogen settling rate (m/yr).
RES_D50	10 (0-10^5)	26	Median particle diameter of sediment (mm).
RES_NSED	4000 (1-5000)	40	Equilibrium sediment concentration (mg/l).

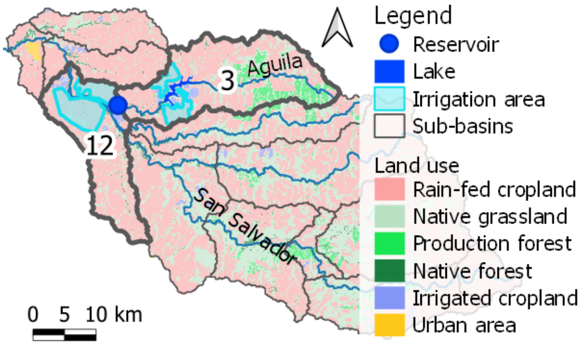

Figure 4. Irrigation scenario: location of the proposed reservoir and irrigated area

This scenario entails a change in land use with respect to the baseline scenario: most (84%) of the projected irrigated area (6,950 ha) is converted from rain-fed agriculture to irrigated agriculture, while the remaining area (16%) is converted from native grassland to irrigated agriculture. An irrigated crop rotation of three years was considered: two years of soybeans and one year of corn (with a cover crop between summer crops). Simulated fertilizer applications per season were 215 kg N/ha for corn and 79 and 24 kg P/ha for corn and soybeans, respectively. Irrigation of crops in the model was based on crop demand during the season; irrigation occurs whenever the plant reaches a stress level of AUTO_WSTRS=0.9 (this value ranges from 0 to 1, where 1 means that plant growth is not affected by water stress). Once the irrigation scenario was implemented, the SWAT model was run using the 30-year climate database (from 1992 to 2021 and considering a warm-up period from 1989 to 1992).

2.4.2 Scenario 2: Riparian buffer zones

The second scenario consists of incorporating riparian buffer zones into Scenario 1 for the entire watershed. In this study, the design of the riparian buffer zones followed the guidelines proposed in the Santa Lucía River Protection Action Plan(30). That plan proposes riparian buffer zones to mitigate nutrient delivery from agricultural areas in another Uruguayan watershed. The riparian buffer zones proposed have a width of 40 m in the main river, 20 m in streams with a minimum watershed of 10 km^2, and 100 m around reservoirs. Quantum GIS was used to delineate watersheds with a minimum size of 10 km^2 and their drainages. Buffer zones of 20, 40, and 100 m were then drawn. In the Plan(29), a buffer zone is defined as an area without crop cultivation and agrochemical application, with the purpose of containing the transport of soil contaminants to water and restoring the hydromorphological condition of the river. The native forest, defined as a natural buffer zone due to its inherent characteristics, was not considered part of the buffer zone scenario if it overlapped with the buffer area delineated in GIS (at a fixed distance from water courses). Finally, the buffer area of the Scenario was uniformly distributed among all HRUs with land use in agriculture, livestock production, or urban areas. This calculation was performed on a sub-basin basis.

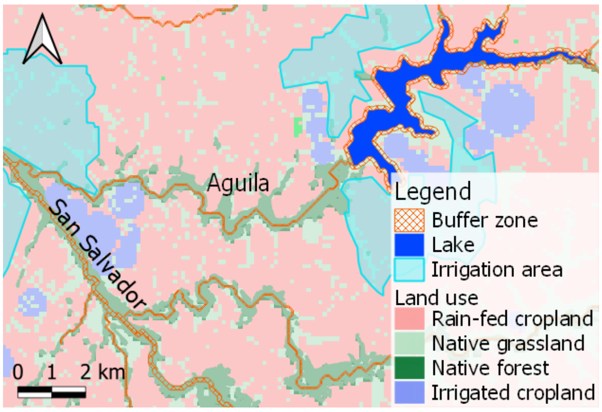

Figure 5. Scenario 2: Location of the riparian buffer zones implemented

The delineated buffer covers an area of 2,703 ha and represents 1.1% of the total watershed area. Figure 5 shows the different widths of the riparian buffer zones in Scenario 2: 100 m around the reservoir, 40 m in the San Salvador River, and 20 m in Aguila Creek. The riparian buffer zones scenario entails a change in land use and/or management compared to the baseline scenario, where half (50%) of the buffer zone area is currently native grassland, 28% is native forest (which is already considered a buffer zone), 21% is rainfed agriculture, and the remaining 1% is production forest. Table S3 shows the buffer area per sub-basin and its current land use.

In SWAT, the filter strip algorithm (VFS) is used to model riparian buffer zones; it reduces sediment and nutrients without affecting surface runoff. The VFS is based on 22 publications of measured data collected by researchers in several countries(31). The algorithm includes three parameters: FILTER_RATIO, which was calculated for each sub-basin as the ratio of the sub-basin area to buffer area and varied from 42 to 148 (Table S3); FILTER_CON, where the default value of 0.5 was used, meaning that 50% of the HRU drains into the most concentrated 10% of the buffer; FILTER_CH, where the default value of 0.5 was used, meaning that there is no fully channelized flow(32).

3. Results and discussion

After implementing the scenarios in SWAT, daily simulations (1992-2021) were compared to the baseline scenario. Sub-basins 3 and 12 were selected for analysis because that is where the projected irrigated area develops. For inland processes, changes in crop yields, irrigation volume, and sediment and nutrient yields were evaluated. In addition, the construction of the reservoir changes the flow regime and affects water quantity and quality. Therefore, streamflow, TN, TP, and TSS were evaluated at the outlet of sub-basin 3 (in Aguila Creek, at the location of the reservoir) and the outlet of sub-basin 12 (after the confluence of Aguila Creek with the San Salvador River) (Figure 4). SWAT assumes that the reservoir is fully mixed so that water quality in the water body is equivalent to water quality at the outlet of sub-basin 3. Local water quality objectives (TN < 0.65 mg/L and TP < 0.05 mg/L)(33) were considered to evaluate the simulated water quality.

3.1 Scenario 1: Irrigation development

The implementation of the irrigation development scenario showed that the flow of sub-basin 3, at the location of the reservoir, changed. Figure 6 compares the flow duration curves for the irrigation and baseline scenarios, and Table S1 shows some flow percentile values. In the irrigation scenario, the flow duration curve has a flattened middle portion attributable to environmental flow discharge (with a 60% exceedance rate). The interquartile range (IQR), which explains the spread of 50% of the data, has also decreased from 1.9 m^3/s to 0.4 m^3/s. Downstream (sub-basin 12), flow impacts are lesser as Aguila Creek joins the mainstream. However, low flows (q10 and q25) seem slightly increased, again likely due to environmental flow requirements.

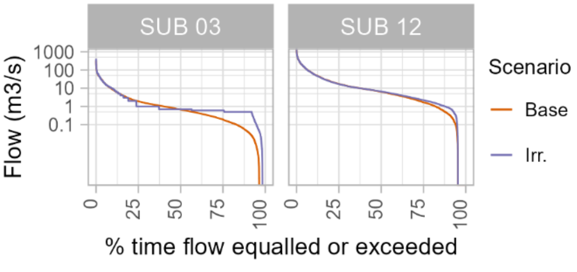

Figure 6. Flow-duration curve for the baseline and irrigation scenarios, 1992-2021

Table 3 presents rainfall, irrigation, and irrigation deficit statistics for soybeans and corn during each growing season. Irrigation supplements precipitation but is highly variable; for example, simulated soybean irrigation averaged 115 mm but varied from 20 to 244 mm per season (1992-2021), while cumulative seasonal precipitation varied from 297 to 1,272 mm. These results are consistent with the observed irrigation average for 2016-2019(34) which was 133 and 183 mm for soybean and corn, respectively, and with a local study(35) that reported a simulated irrigation average of 204 mm for soybean and 225 mm for corn (1984-2007). The irrigation deficit is the difference between the amount irrigated with an unlimited water source and the amount with the reservoir as the water source. The average irrigation deficit is about 10% of the irrigated water.

Table 3. Precipitation (Pcp.), irrigation (Irr.), and irrigation deficit (Deficit) (mm) per cropping season, 1992-2021, average of sub-basins 3 and 12

	Soybean				Corn			
	mean	**sd**	**min.**	**max.**	**mean**	**sd**	**min.**	**max.**
Pcp.	710	243	297	1272	579	243	215	1306
Irr.	115	61	20	244	118	61	40	224
Deficit	14	20	0	81	13	26	0	105

In this scenario, irrigation had a positive effect on crop yields and reduced the coefficient of variation compared to the baseline scenario (Table 4). The results showed a 39% and 32% increase in average yields for corn and soybeans, respectively. The coefficient of variation also decreases by more than half. This decrease in the coefficient of variation suggests that production is more stable over time under irrigation; similar results are reported by Rosas and others(36). In absolute terms, considering all crops in the rotation, the average yield in sub-basins 3 and 12 increased by 13% under the irrigation scenario (from 164,155 Mg/yr to 185,316 Mg/yr).

Table 4. Average yields (kg/ha), standard deviation, and variation coefficient, 1992-2021, of sub-basins 3 and 12

	Rain-fed		Irrigated	
	Corn	**Soybean**	**Corn**	**Soybean**
Mean	6683	2551	10980	3753
Std.	1011	992	809	498
CV (%)	15%	39%	7%	13%

As a result of the land use change, there was an increase in sediment, nitrogen, and phosphorus yields in this scenario compared to the baseline. Table 5 shows the results of the annual mean values of sediment, nitrogen, and phosphorus yields and their standard deviation. Sediment, nitrogen, and phosphorus yields increased by 2.3%, 5.6%, and 2.4%, respectively.

Table 5. Annual sediment (SYLD), nitrogen (NYLD), and phosphorus (PYLD) yields, 1992-2021, sub-basins 3 and 12

	SYLD (Mg/ha/yr)(M		**NYLD (kg/ha/yr)**		**PYLD (kg/ha/yr)**	
Scenario	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
Base	4.34	2.29	11.49	5.97	2.65	1.45
Irr.	4.44	2.36	12.14	6.34	2.71	1.49
Irr. Buff.	1.17	0.85	5.89	3.35	1.14	0.69

The construction of the reservoir changed hydraulic conditions and nutrient transport. As mentioned before, there was an increase in sediment, nitrogen, and phosphorus yields, some of which were trapped in the reservoir. The mean sedimentation rate for 1992-2021 was 19,845 Mg/yr with a trapping efficiency of 94%. The mean sedimentation rate of nitrogen was 44 Mg/yr when NSETLR = 5.5 m/yr and varied from 15 to 66 Mg/yr when NSETLR varied between 1 and 15 m/yr. Nitrogen trapping efficiency was 17% and ranged from 5% to 25%. The mean phosphorus sedimentation rate was 17 Mg/yr when PSETLR = 10 m/yr and varied from 6 to 25 Mg/yr when PSETLR varied from 2 to 20 m/yr. Phosphorous trapping efficiency was 25% and ranged between 8% and 37%.

For nitrogen, phosphorus, and sediment loads transported by water (Table 6), total amounts were lower for the irrigation scenario (Irr.) than for the baseline scenario (Base) for sub-basins 3 and 12. Results for loads of TN and TP varied in magnitude as PSETLR and NSETLR varied, but the trend was the same.

Water quality was affected by changes in the streamflow and nutrient loads. Figure 7 shows the daily nutrient and sediment duration curves in the water for the baseline and irrigation scenarios at the outlets of the sub-basins 3 and 12. Significant changes were observed at the discharge of the reservoir (sub-basin 3); while there were slight changes at the outlet of sub-basin 12 as Aguila Creek flows into the San Salvador River. In sub-basin 3, the median concentration of TN increased from 0.47 to 1.63 mg/L and the median concentration for TP increased from 0.10 to 0.36 mg/L. In the case of TSS, the median concentration at the outlet of sub-basin 3 decreased from 35.1 to 1.6 mg/L (Table S2).

Based on these results, conservation measures would be needed to reduce nutrient concentrations in the reservoir (water quality in the fully mixed reservoir is equivalent to water quality at the outlet of sub-basin 3). It would be desirable to reduce TP to at least mesotrophic levels (TP < 0.04 mg/L, classification by Salas & Martino(37)). Measures may include practices that minimize nutrient inputs to surface waters, such as establishing riparian buffer zones and limiting nutrient loading upstream through less intensive agriculture, practices to reduce erosion, and moving cropland downstream.

Table 6. Annual mean loads (Mg/yr) of nitrogen, phosphorus, and sediment transport by water, 1992-2021. Values in parentheses are the results when NSETLR and PSETLR vary, as indicated in Table 2

Sub	**Scenario**	**TN**	**TP**	**SED**
3	Base	294	76	21,316
	Irr.	258 (237-288)	60 (52-71)	1,516
	Irr. Buff.	120 (110-133)	25 (22-29)	1,516
12	Base	1,849	490	170,664
	Irr.	1,787 (1,768-1,813)	463 (456-473)	169,474
	Irr. Buff.	855 (846-867)	196 (193-200)	103,299

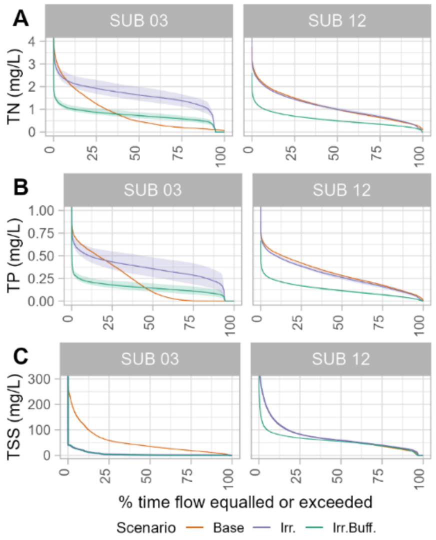

Figure 7. Daily duration curves in water for the baseline (Base), irrigation (Irr.), and irrigation with riparian buffer zone (Irr.Buff.) scenarios, 1992-2021. (A) Total nitrogen concentration, (B) total phosphorus concentration, and (C) total suspended solids. Ribbons represent the results of considering that PSETLR and NSETLR vary in a range of 2-20 m/yr and 1-15 m/yr

3.2 Scenario 2: Riparian buffer zone

Implementing the riparian buffer zone resulted in a high reduction in nutrient and sediment yields compared to the irrigation scenario. Table 6 shows the results (Irr. Buff. scenario) of annual mean sediment, nitrogen, and phosphorus yields in sub-basins 3 and 12, and their standard deviation. Sediment, nitrogen, and phosphorus yields decreased by 74%, 51%, and 58%, respectively.

As a result, nutrient and sediment loads in water (Table 6) decreased compared to the irrigation scenario. The buffer zone has an overall retention efficiency of 52%, 57%, and 46% for TN, TP, and sediment, respectively, evaluated at the watershed outlet (sub-basin 2). These results are comparable with a study at the Paso Severino reservoir (Uruguay), where nutrient retention was measured within riparian buffers of different compositions (herbaceous, shrublands, and woodlands). In this study, nutrient retention efficiency ranged from 25% to 78% for TP, and from -11% to 62% for TN(17).

Figure 7 shows the daily nutrient and sediment concentration duration curves for the baseline, irrigation, and riparian buffer zone scenarios at the outlets of the sub-basins 3 and 12. At the reservoir outlet (sub-basin 3), the median concentrations of TN and TP decreased from 1.63 to 0.72 mg/L and from 0.36 to 0.14 mg/L, respectively. There was no change in TSS because its concentration was very low after settling in the reservoir. Although the median TP concentration decreased by 61% in the buffer scenario compared to the irrigation scenario, the water body remains classified as eutrophic.

It is crucial to note that achieving and maintaining the retention efficiency of riparian buffer zones requires proper design, including the selection of appropriate plant species, as well as effective management, which may involve harvesting products(17). If not properly designed and managed, the buffer can be saturated and become a nutrient source rather than a sink, particularly during high-flow events(17). Another related conservation practice is preventing animal access to water bodies, a measure observed to result in the revegetation of banks and the re-establishment of forested buffers(38-39).

4. Conclusions

The evaluation of the scenarios allowed us to understand the main processes affecting the export, transport, and transformation of nutrients, and to quantify the impact at the watershed level, which is crucial for evaluating and proposing best management practices consistent with sustainable agricultural intensification.

The results of the irrigation development scenario showed increased sediment, nitrogen, and phosphorus yields compared to the baseline scenario. Additionally, heavy sedimentation occurs in the reservoir, with 17%, 25%, and 94% retention of the upstream of TN, TP, and sediment, respectively. As a result, the average load of nutrients and sediment in water would decrease compared to the baseline scenario. However, the reservoir would be classified as eutrophic due to the predicted median concentration of TP. Therefore, conservation measures would be required to reduce nutrient concentrations in the reservoir and achieve an environmentally sustainable scenario.

Implementation of the scenario with riparian buffer zones resulted in reduced nutrient and sediment loads in water with overall retention efficiencies of 52%, 57%, and 46% for TN, TP, and sediment, respectively. These results are consistent with local studies. Although the average concentration of TP in the reservoir has decreased by 58%, it remains classified as eutrophic. On the other hand, the riparian buffer zone improves the overall water quality of the watershed. In sub-basin 12, the concentrations of TN and TP decreased by 52% and 58%, respectively, compared to the baseline scenario. This means that the median concentration of TN is 0.49 mg/L and meets the water quality objective ($TN < 0.65$ mg/L), while the median concentration of TP is 0.11 mg/L and does not meet the water quality objective ($TP < 0.05$ mg/L).

Although the riparian buffer zone improves water quality in the watershed, additional conservation measures would be required to achieve an environmentally sustainable scenario. It is worth noting that in the current situation (baseline scenario), the nutrient water quality standards are not accomplished, as the median concentrations in Paso Ramos (sub-basin 12) were 0.99 mg/L and 0.51 mg/L for TN and TP, respectively. However, the construction of the reservoir involves transitioning from a lotic water body to a lentic one, accompanied by high nutrient availability, which could potentially increase the risk of algae growth.

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Transparency of data

The models with the scenarios implemented in this work are freely available on the OSF platform: https://osf.io/ytn9g/

Author contribution statement

HF: Methodology, software, validation, formal analysis, investigation, data curation, writing - original draft, visualization, funding acquisition.

PBM, NR and GA: Conceptualization, methodology, writing - review and editing, supervision, funding acquisition.

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Supplementary material

Table S1. Flow (m3/s) quantiles and averages for the baseline and irrigation scenarios, 1992-2021

Sub	Scenario	mean	q10	q25	q50	q75	q90
3	Base	4.3	0.1	0.2	0.8	2.1	9.2
	Irrigation	4.4	0.5	0.6	0.7	1.0	10.0
12	Base	30.4	0.9	2.7	7.6	19.1	67.0
	Irrigation	30.2	1.4	3.4	7.8	18.4	65.6

Table S2. Total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS) concentrations quantiles and averages for the baseline and irrigation scenarios, 1992-2021

Sub	Scenario	mean	q10	q25	q50	q75	q90
			TN (mg/l)				
3	Base	0.82	0.13	0.20	0.47	1.25	2.08
	Irr.	1.60	1.04	1.38	1.63	1.92	2.19
	Irr. Buff.	0.72	0.45	0.58	0.72	0.87	1.03
12	Base	1.11	0.40	0.63	0.99	1.50	1.96
	Irr.	1.09	0.43	0.67	1.00	1.44	1.89
	Irr. Buff.	0.55	0.23	0.34	0.49	0.69	0.93
			TP (mg/l)				
3	Base	0.209	0.001	0.005	0.099	0.399	0.571
	Irr.	0.351	0.205	0.285	0.357	0.432	0.506
	Irr. Buff.	0.144	0.078	0.11	0.143	0.179	0.216
12	Base	0.301	0.098	0.175	0.282	0.42	0.527
	Irr.	0.278	0.091	0.161	0.262	0.386	0.493
	Irr. Buff.	0.125	0.039	0.07	0.114	0.169	0.225
			TSS (mg/l)				
3	Base	49.8	9.9	18.8	35.1	58.3	117.4
	Irr.	5.5	1.0	1.0	1.6	4.1	16.8
	Irr. Buff.	5.5	1.0	1.0	1.6	4.1	16.8
12	Base	70.4	20.0	35.9	59.0	83.4	136.2
	Irr.	71.6	25.7	39.6	59.2	82.7	134.8
	Irr. Buff.	55.2	22.7	37.2	55.0	68.0	85.0

Table S3. Riparian buffer zone design, projected area per sub-basin, and current land use

Sub.	Sub. Area (ha)	Current (2018) land use of the GIS delineated buffer zone						GIS delineated buffer area (ha)	Scenario buffer area (ha)	FILTER RATIO*
		Rain-fed cropland (ha)	Native grassland (ha)	Production forest (ha)	Native forest (ha)	Irrigated cropland (ha)	Urban area (ha)			
1	10198	34	34		34	1		103	69	148
2	4848	43	24		60		4	131	71	68
3	31713	181	279	8	66	5		539	473	67
4	19303	13	126	4	59			202	143	135
5	5880	35	106					141	141	42
6	20431	80	311	7	58			456	398	51
7	34132	45	211	1	47			304	257	133
8	31992	72	195	4	25			296	271	118
9	4717	19	57	2	75			153	78	60
10	20004	17	189	13	151			370	219	91
11	25654	68	221		219			508	289	89
12	21145	97	82		183	2		364	181	117
13	10744	75	38		51			164	113	95
Total	**240761**	**779**	**1873**	**39**	**1028**	**8**	**4**	**3731**	**2703**	**89**

*FILTER RATIO = Sub. Area (ha) / Scenario buffer area (ha)