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Assessing impacts of irrigation on flows frequency downstream of an irrigated agricultural system by the SWAT model

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Abstract. There are multiple conflicts between agronomic uses and environmental conservation. Environmental flows must be respected on basins with human interventions. The water regulation of Uruguay establishes a value of environmental flow per month for watercourses. For each month, the value corresponds to a 60 % probability of excess of the daily flows. However, the return flow of irrigation systems is not considered by current national regulations. The objective of this work is to assess the effect of irrigation downstream of reservoirs of agricultural basins. For this purpose, surface and subsurface water flow generation, and interactions between atmosphere, plant, water, and soil are quantified with the SWAT model. The model was implemented for a small basin in the north of Uruguay (Tala catchment, 120 km^2). The main crops are rice, soybeans, and corn, which are irrigated by pivots and border irrigation, where water is conducted by long dug channels. The water source is a reservoir with 1200 Hm^3 capacity, which is constructed with an earth dam and placed over vertisols soils. Water volumes in the reservoir and flows at the outlet of the catchment were validated with a moving window. Once the model was calibrated, it was used to simulate 30 years of irrigated agriculture and compared with simulations without human intervention. Results show the effect of return flow on the quantity and frequency of water fluxes through the basin. Flow duration curves show that the magnitude of low flows increases downstream on the irrigated system. On the other hand, high flows are attenuated by the storage capacity of the reservoir. The outcomes of this work could support new policies and water regulations, as they show that changes in the frequency of flows are associated with irrigation operations.

Keywords. UPH; UPH 19; Field observations; Modelling; SWAT; Irrigation return flows

1 Introduction

Water and soil resources support agricultural activity, which allows the economic development of the territory where it is carried out. However, some agricultural practices have effects on the flow frequency of flows downstream productive areas. To achieve sustainable production systems, it is necessary to minimize the impacts associated with each activity without compromising the performance of the system (Moltz et al., 2020). Irrigation return flows affect the flow regime of downstream rivers, being a key hydrological process that needs to be studied to achieve sustainable production (Song et al., 2020). For that purpose, hydrological modeling is a useful tool, especially on watersheds with scarce data (Gosain et al., 2005). The Soil Water Assessment Tool (SWAT) (Arnold et al., 2012) has been widely used to simulate the environmental impacts of land use, and land management practices. Irrigation return flows have also been simulated with SWAT, where the features of the model have allowed quantifying the dependence of return flows on different types of irrigation (Gosain et al., 2005). An approach to understanding the irrigation return flows was proposed by Kim et al. (2009) by means of SWAT modeling. These authors developed operating rules for reservoirs considering downstream environmental flow releases.

Uruguay is mainly an agricultural country with intensive use of water and soil resources, where assessing environmental conservation through hydrological modeling has been an attractive alternative (Mer et al., 2020). Models for better resource management, measuring economic benefits, and preserving water and environmental quality have been developed (Souto et al., 2021). National water regulation establishes reservoir operation using the probabilistic approach (AÑADIR REFERENCIA). Reservoirs must operate to guarantee an outflow greater than the flow with a 60 % probability of exceedance in the corresponding month. This approach gives a practical solution to estimate the water flow needed to preserve ecosystem services. However, local conditions such as irrigation or land use are not taken into account, even though they could have a significant effect on return flows (Ferencz and Tidwell, 2022).

The aim of this study is to assess the effect of irrigation downstream of a reservoir of a small agricultural basin in Uruguay. For that purpose, different scenarios will be modeled with the SWAT model. Additionally, to compare the effect of irrigation on flows with respect to the pristine condition, the flow frequency index (FFI) will be introduced and applied in several downstream sites of the irrigated system (analysis nodes).

2 Area of study and dataset

The study basin is located in the north of Uruguay in the department of Salto (Fig. 1). It has a humid subtropical climate (Cfa) according to the Köppen climate classification. Mean annual cumulative precipitation is 1430 mm with a slight seasonality, with mean daily temperatures around 10–15 °C for the winter and 20–30 °C for the summer. Soils are mainly brunisols and vertisols. The basin has an area of 120 km^2 and has been dedicated to rice, soybean, corn, and sorghum production since 1995 (Fig. 2). Water is supplied to crops through 40 km of canals from a reservoir with a volume of 12 Hm^3. This configuration makes the system efficient in soil use and conservation thanks to the agricultural rotations employed but inefficient in water use due to infiltration losses.

The basin is instrumented with a hydrometric station at the outlet, a water level station in the reservoir, and a complete climatological station (temperature, precipitation, wind, humidity, radiation). The simultaneous records of level, flow, and climatology are available for 2019–2020 agronomic year, in which the reservoir level is only available during the summer. The hydrometric station records instantaneous water levels and flow every 5 min. Then, the daily flow is calculated from instantaneous values.

3 Modelling scheme

SWAT is a semi-distributed model designed to predict the impact on water resources of various land management practices. It has a large number of parameters that serves to adjust biophysical processes in agricultural watersheds (e.g. runoff, infiltration, water storage, routing, crop yield, sediment transport, and nutrient cycles). To identify the important parameters, for the hydrological model, a sensitivity analysis was performed using the Fourier Amplitude Sensitivity Test (Reusser et al., 2011) . Then, a moving window calibration/validation routine was implemented for the 2019–2020 agronomic year. The routine uses a 7-month window for calibration and a 3-month window for validation. The windows are then scrolled to generate 8 independent calibrations and validations.

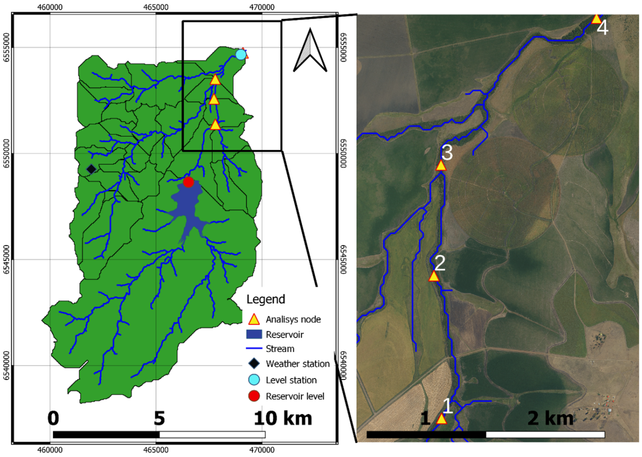

Figure 1. Tala basin and study area showing the location of the analysis nodes (Digital Orthoimagery: IDEUY, 2023).

Parameter optimization in each window is performed using Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992) with an objective function that quantifies the similarity of simulations and observations of flows and volume of water stored in the reservoir (Eq. 1).

$$\mathrm{OF} = 0.2\mathrm{KGE}_{\mathrm{res}} + 0.8\mathrm{KGE}_{\mathrm{reach}}, \tag{1}$$

where $\mathrm{KGE}_{\mathrm{res}}$ and $\mathrm{KGE}_{\mathrm{reach}}$ are Kling-Gupta efficiency (Gupta et al., 2009) for reservoir volume and river flow respectively. The coefficients 0.2 and 0.8 are weights assigned to reduce the effect of missing water levels on the reservoir, since during the winter water levels are not collected. These weights give priority to flow at the outlet, since it is the dataset with fewer missing values.

The impacts of irrigation were assessed with the Flow Frequency Index (FFI). The FFI index is introduced in this work to compare the frequency of flows of 2 scenarios. It is calculated as the ratio $Q_{\mathrm{i}}/Q_{\mathrm{o}}$, where Q is the flow rate for a certain frequency of occurrence, the subscript “i” is used for the irrigation case, and the subscript “o” for the basin without human intervention. To apply FFI, the simulation period was extended to 30 years. Climatological forcing was built with the data collected in a nearby climatological station. The

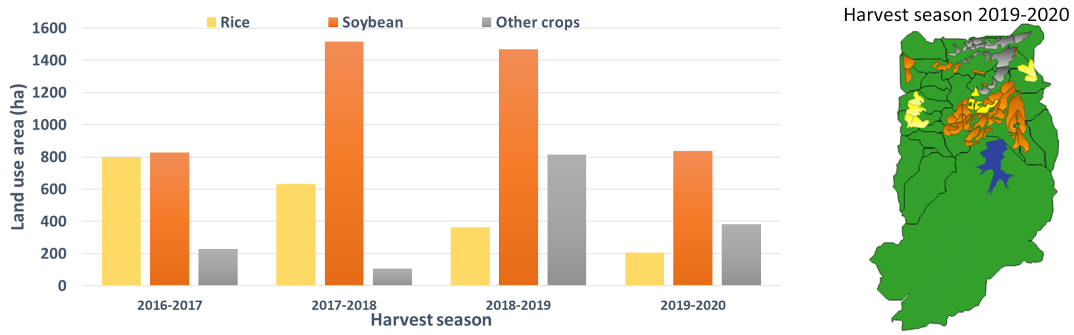

Figure 2. Areas of the different land use of the farms within the Tala watershed. The map shows the distribution of crops in the 2019–2020 harvest.

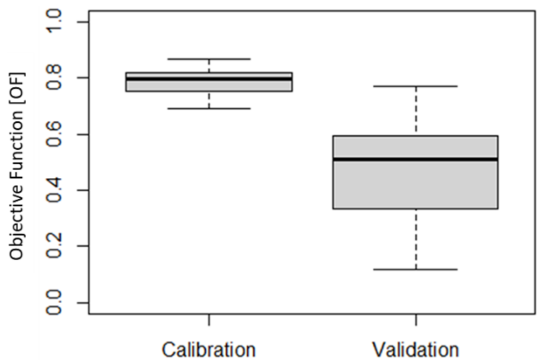

Figure 3. Objective Function values for the calibration and validation of the model.

pristine basin was simulated by eliminating the reservoir and incorporating natural herbaceous as the unique land use.

4 Results and discussion

The moving window calibration/validation showed objective function values between 0.6 and 0.8 for calibration (Fig. 3). The hydrographs show that good predictions are obtained for low flows and underestimates for high flows (Fig. 4). The slight degradation of the objective function between the calibration and validation periods may be due to the difference in size between the two windows as well as the climatic differences between the two periods (Ekmekcioğlu et al., 2022).

Figure 4 shows the simulated volumes of the irrigation reservoir are highly sensitive to the calibration/validation windows. One notable example of this sensitivity is evident when comparing the results obtained during the September–October–November validation window (Fig. 4a and b) with the November–December–January validation window (Fig. 4c and d). In the first period, a better fit is observed for reservoir volumes where more observed data is available for calibration (Fig. 4b). In contrast, the second period shows a slight degradation of the model fit, however, it still captures the depletion of the reservoir (Fig. 4c). On the other hand, the hydrographs, do not show significant changes (Fig. 4a and c).

The FFI was applied at four points downstream of the irrigated system. Values lower than 1 mean flow reduction for a given frequency. Figure 5 shows that the impact is different at each site. For example, a reduction of flows is obtained near the reservoir (Fig. 5a, b), where the return flow is supposed to be small as there are no large irrigated lands upstream. The reduction for higher non-exceedance probabilities (high flows) is explained by the storage effect of the reservoir, while the reduction for lower non-exceedance probabilities (low flows) is due to the detour and transfer of water to other irrigated lands. The impact is quite similar in winter/summer with small differences that may be due to the change in land use from natural grassland to agricultural rotations. In contrast, an increase of low flows is obtained in the analysis nodes 3 and 4 (Fig. 5c, d). The reason for these results is that the irrigation water losses are incorporated into the channel as return flows. The contribution of return flows to the main channel is greater for nodes 3–4 than nodes for 1–2 because nodes 3–4 have larger irrigated lands.

In future works, there are several aspects that can be addressed to enhance the study's findings. Firstly, extending the observation period would provide a more comprehensive dataset for model training and validation, ultimately leading to improved prediction accuracy. Secondly, a crucial area for improvement lies in refining the representation of groundwater-surface water interaction within the SWAT model. Currently, the model employs a simplified approach, which may not fully capture the complexities of this relationship. Considering a coupling with more sophisticated models would be beneficial in such cases, allowing for a more robust and accurate analysis of this interaction (Guzman et al., 2015).

5 Conclusions

This work evaluated the impact of irrigation downstream of reservoirs in agricultural basins. For this purpose, the SWAT model was used and the FFI was proposed. It was found that

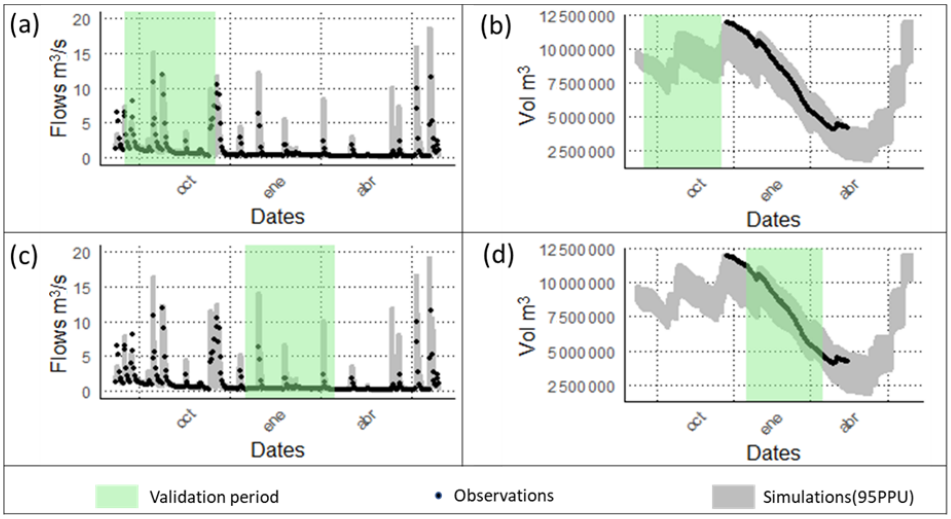

Figure 4. Comparison of two moving window calibration and validation periods for flow **(a, c)** and reservoir volume **(b, d)**.

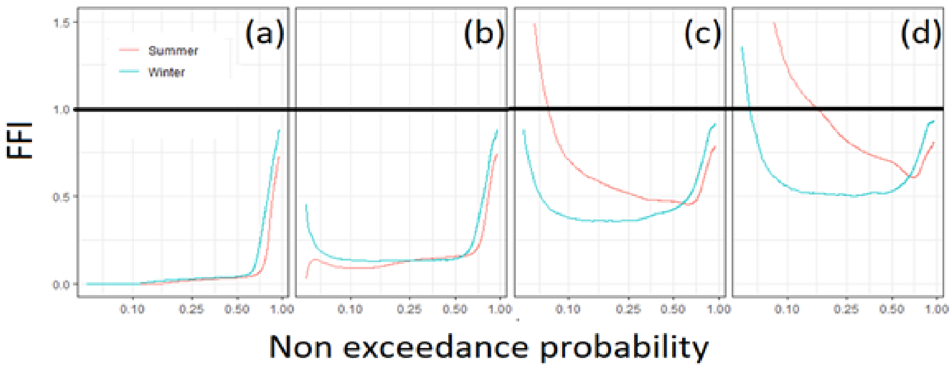

Figure 5. Flow Frequency Index as a function of non-exceedance probability on sites 1 **(a)**, 2 **(b)**, 3 **(c)** and 4 **(d)** (analysis node).

the impact of irrigation due to return flows is not homogeneous across the stream and also varies between seasons. The results of the model indicated that although the general effect of the operation of the reservoir is the reduction of the flow in the channel, this effect can be partially reversed under certain conditions: particularly during the dry season and in sections with significant accumulation of irrigation return flows.

The spatio-temporal heterogeneity of return flows limits the application of the probabilistic approach to define optimal reservoir operations since local conditions (e.g., irrigation type, land use, soil type) are not considered. The results of this work can provide new tools for defining policies and water regulations. This is extremely relevant given the worrying scenarios of increasingly accentuated droughts linked to climate change.

Code availability. The model is available at https://doi.org/10.5281/ZENODO.5708713 (Saracho, 2021).

Data availability. Observed flow, volume and climate data are available from the corresponding author on request.

Author contributions. AS: working on data processing, methodology, evaluation of the results, writing the paper; RN: conceptualization, methodology, supervision; PG: resources and review; AE: Evaluation of the results and discussion, review and editing.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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