



Research paper

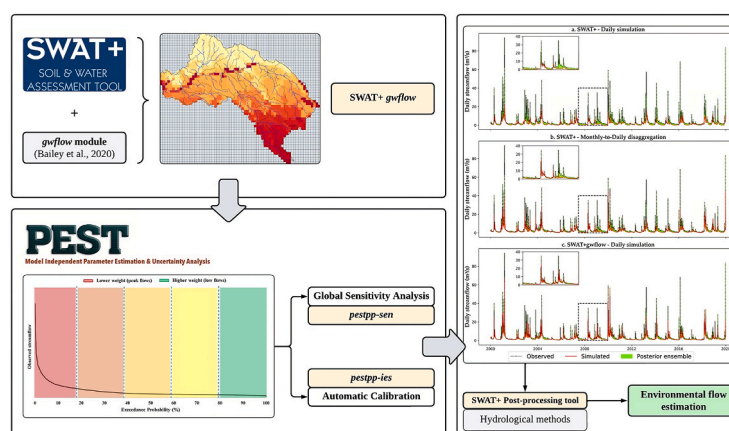
Assessing improvements in environmental flow estimation through the use of a coupled surface-groundwater model

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HIGHLIGHTS

- Groundwater representation in SWAT + model has been pointed out as an important limitation.
- Coupling with the new *gwflow* module enhances surface-groundwater interaction.
- A calibration approach based on FDC helps to accurately reproduce model's baseflow.
- Environmental flows are affected by the adjustment of surface-groundwater exchange.

GRAPHICAL ABSTRACT



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ABSTRACT

Environmental flow refers to the water required to maintain river ecosystems. Establishing methodologies to ensure these minimum flow rates is essential, particularly in highly anthropized regions, such as Spain. Hydrological models, including SWAT+, are used to simulate rivers in natural regime. However, accurately representing surface-groundwater interactions is crucial in groundwater-driven catchments, such as the Tagus River headwaters. Due to the standalone model limitations, we used the new coupled SWAT + *gwflow* model to appropriately represent surface-groundwater interactions in streamflow response. The calibration approaches of the (1) base SWAT+, and (2) SWAT + *gwflow* models focused on adjusting low flows, allowing for greater accuracy in daily flows to estimate environmental flows. In addition, (3) an experiment of monthly-to-daily disaggregation of the standalone model based on a daily flow pattern was conducted at two upstream

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stations. Our results indicated that the coupled model outperformed the standalone model across all statistical indicators, especially in low flows, where the Nash-Sutcliffe logarithm (LnNSE), an indicator of low flow performance, was inadequate for the standalone model because it underestimated of the simulated flows. This underestimation was also reflected in the environmental flow values, with variations ranging between -41% and -58% compared to the observed values. For the base model, a disaggregation experiment showed an improvement in environmental indicators, reducing their underestimation by half. Finally, the SWAT + *gwflow* model showed the best fit for environmental flows compared to observations, with average variations of $\pm 10\%$ in most cases, showing improvement in daily low flows due to a better representation of surface-groundwater interactions.

1. Introduction

Environmental flow is the water required to maintain a river ecosystem in a desired condition (Acreman and Dunbar, 2004). It delineates the optimal streamflow regime necessary to safeguard the environmental integrity of receiving water bodies (Poff and Zimmerman, 2010). However, the natural flow regime represents a fundamental assumption underlying the study of environmental flows that provides the optimal conditions for a river ecosystem (Poff et al., 1997). Establishing an environmental flow regime in a river is a complicated, challenging task with significant socio-economic and judicial implications. Currently, there is no consensus among scientific and technical communities regarding the criteria or methodology for this context (Senent-Aparicio et al., 2021b). During the last decades and due to the increasing impacts of human activity, some countries (e.g., South Africa, Australia, China, the United States, Finland, Portugal and Spain) have decided to include strategies based on environmental flows in their water laws to conserve natural ecosystems (Mezger et al., 2019). Its application is considered integral to achieving the environmental objectives proposed by the directives of each country. In Spain, a highly anthropized country influenced by numerous existing regulatory infrastructures (more than 70% of the surface area of Spain drains into a dam), legislation since 2001 has established the definition and application of environmental flows in basin management plans (Senent-Aparicio and Mulligan, 2024). The present study employed hydrological methods recommended by the Spanish Hydrological Planning Instruction (Orden ARM/2656/2008) (IPH, 2008), which are regarded as most suitable for the planning and management of water resources because they are the simplest, most directly applicable to environmental flow estimation (Tharme, 2003). The values of these environmental indicators are sensitive to the correct representation of the streamflow, in quantity and seasonality, and of the hydrological processes, making it essential to understand surface and groundwater processes that define the behavior of river flows.

To estimate environmental flows, the interaction between surface water and groundwater must be properly understood (Ntona et al., 2022; Sánchez-Gómez et al., 2024). Using or managing one flow component often affects the availability and temporal patterns of the other (Liu et al., 2020). However, geohydrological models can be categorized based on what they focus on simulating: models representing surface water or groundwater independently are referred to as single or standalone models. while models integrating surface water and groundwater are referred to as coupled models (Yimer et al., 2023b). Models traditionally applied to represent surface water processes often include a simplified representation of groundwater, as is the case with ensemble tools such as the soil and water assessment tool (SWAT), MIKE SHE, the variable infiltration capacity (VIC) model and, various surface water hydrology studies (e.g., Huang et al., 2017). Conversely, specific groundwater models, including the modular finite-difference groundwater flow (MODFLOW), typically require recharge data, which can be simulated from surface water models (Molina-Navarro et al., 2019), with the river stage as a boundary condition. However, these single models should be coupled when surface-groundwater interactions significantly influence streamflow generation and water movement

(Aliyari et al., 2019). The main advantages of coupling different models are notable pronounced on a regional scale, where the interaction between humans and environment are fully integrated (Barthel and Banzhaf, 2016). In rivers where a significant portion of the streamflow is baseflow, this interaction can strongly influence the overall flow and degrade the functioning of river ecosystems (Johansen et al., 2011). Therefore, given the need to accurately capture these interactions to manage environmental flows, models integrating surface and groundwater processes are necessary, particularly in basins where groundwater dynamics dominate.

When one analyzes environmental flows, a model's temporal resolution becomes critical. A daily time step is often preferred for certain modeling scenarios, including exploring crucial water system interactions (Khatami et al., 2019) and simulating scenarios associated with water management operations (Perera et al., 2005). One of the essential requirements for applying hydrological methods in the present study was the availability of daily streamflow in a natural regime and with a significant length to represent variations in the fluvial ecosystem (IPH, 2008). Given the difficulties of working on a daily scale (John et al., 2021), considering alternatives, such as a monthly scale followed by disaggregation, is sometimes necessary to avoid the uncertainties of daily fluctuations (Verma, 2021). Similarly, the naturalization of flows may affect the distortion of natural hydrological behavior in the analyzed river (Książek et al., 2019). Estimating naturalized streamflow, which reflects historical natural hydrology free from human influence, is crucial for addressing various aspects of river basin management (Wurbs, 2021b). Therefore, hydrological modeling is necessary for water resources planning, as it is an essential tool for simulating the water cycle's natural regime and predicting catchment dynamics (McMillan, 2021). The soil and water assessment tool (SWAT) (Arnold et al., 1998) has gained global acceptance and has been subjected to rigorous testing in numerous studies over the past few years at the basin scale (Janjić and Tadić, 2023). Furthermore, the SWAT model has demonstrated its efficacy in simulating various historical scenarios related to environmental flow regimes. (Kennen et al., 2009; Zeiger and Hubbard, 2018; Kumar et al., 2022). This study employed an entirely restructured updated version of this software, SWAT+ (Bieger et al., 2017), considering one of its main disadvantages and limitations: the accurate and detailed representation of the surface processes of the basin, but a simplified and homogeneous hypothesis of the groundwater processes and storage in the aquifer system (Molina-Navarro et al., 2019) that can lead to inadequate model performance, particularly in watersheds where groundwater dynamics predominate (e.g., Yimer et al., 2023a; Molina-Navarro et al., 2016). To address these challenges, in the present study, we turned to the new coupled SWAT + *gwflow* model (Bailey et al., 2020) to assess the streamflow response.

In this context, this study aimed to provide a methodology for improving environmental flow estimation. This objective was accomplished using the SWAT + *gwflow* model, which advantageously offered a simulation of groundwater-surface water interactions in a physically based manner in a river basin directly into the SWAT + code (Bieger et al., 2017). It incorporates essential hydrological characteristics, including groundwater saturation excess flow and groundwater transfer to soils, when the water table is situated in the soil profile. Additional

interactions encompass recharge from the soil profile to the water table and surface-groundwater exchange through the streambed (Yimer et al., 2023b). SWAT + *gwflow* is particularly suitable for catchments with unconfined aquifers (Bailey et al., 2020, 2023). Similarly, we compared the daily scale performance of the standalone SWAT + versus the coupled SWAT + *gwflow* to establish the best fit for estimating watershed environmental indicators. Following the hypothesis proposed in Castellanos-Osorio et al. (2023), monthly-to-daily disaggregation techniques based on a daily flow pattern were also applied using the water rights analysis pack (WRAP) modeling system (Wurbs, 2021a) as an alternative to environmental flows estimation. The methodology is demonstrated in the headwaters of the Tagus River Basin in Spain (HTRB), where the definition of environmental flows is crucial and influential in national political decisions. This methodology enabled the comparison and reduction of uncertainties associated with the hydrological modeling of the natural regime, highlighting the need to combine surface and subsurface processes in watershed representation. The methodology also provides various options for studying and preserving natural ecosystems under threat from ongoing environmental degradation. However, this preservation can only be achieved if the methodology is correctly applied and appropriate decisions are made regarding ecosystem management.

2. Background of study area

The Tagus River, the longest river in the Iberian Peninsula, crosses approximately 67% of Spanish territory, with the remaining portion flowing through Portugal (Valerio et al., 2021). The Spanish portion of the Tagus River is characterized by the significant regulation of and pressure from its water resources (CHT, 2021), including the supply of several significant urban populations, the management of nuclear power plants and water transfers to the Mediterranean coast. The present study, focused on the headwaters of the Tagus River basin (HTRB),

specifically in the subbasin that represents the main tributary to the Entrepeñas reservoir in the municipality of Trillo (Guadalajara, Spain). The HTRB has a surface area of 3274 km² and is located in central Spain, between 41°2'N – 40°19'N latitude and 2°36'W – 1°26'W longitude (Fig. 1). It is a mountainous area, with altitude variations ranging from 724 to 1893 m above sea level. This orography significantly influences rainfall distribution (Durán, 2016), with a mean annual precipitation of 630 mm for 2000–2019. The mean annual temperature is around 12.2 °C. Weather variables with these characteristics define the study area as a Mediterranean climate, which is one of the predominant ones in Spain (AEMET, 2011). This climate is rated as Csa/Csb according to Köppen-Geiger classification (Kottek et al., 2006).

The three main land cover types in the study area are forest-mixed (41%), range-grasses (18%) and agriculture (14%), obtained from the Corine Land Cover map of 2018. Due to the different bedrock of its mountain systems, the HTRB is characterized by significant heterogeneity in its geology, in which the main hydrological processes may vary according to the different geological zones (Sánchez-Gómez et al., 2022). In this area, carbonate and detrital rocks predominate (about 62% and 30% respectively) (Fig. 2), so a high relevance of baseflow is expected. The main soil classes, extracted from the Digital Soil Open Land Map (DSOLMap) (López-Ballesteros et al., 2023), are Inceptisols (81%) and Alfisols (18%), with a predominant loam and clay texture (Soil Survey Staff, 2022). The region is strategically significant for water resources because it supplies the Tagus-Segura water transfer (Lorenzo-Lacruz et al., 2010). Water allocation to the Mediterranean region involves national-level political decisions and has been a source of territorial disputes, particularly during drought periods (Garrote et al., 2007).

3. Methodology

Fig. 3 shows the methodology employed in this work, which is based

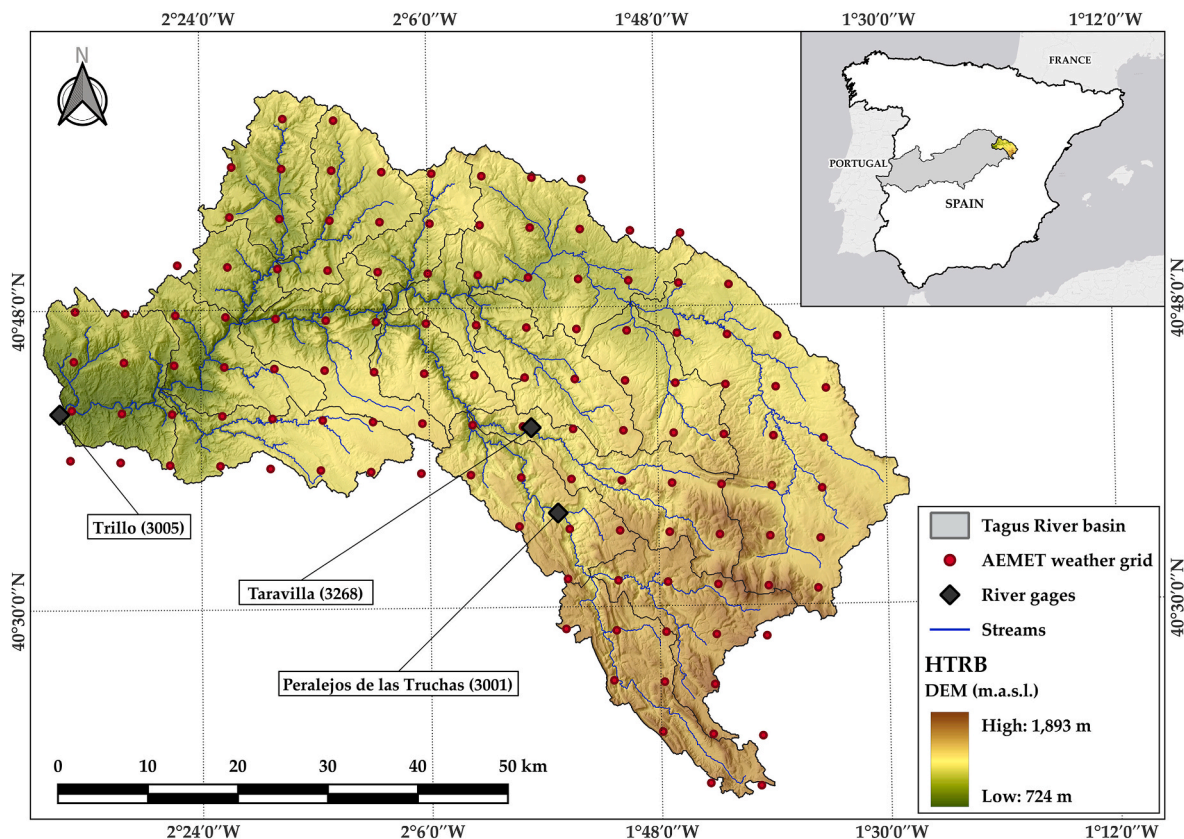


Fig. 1. Location, digital elevation model (DEM), river gauges and subbasin boundaries of the HTRB.

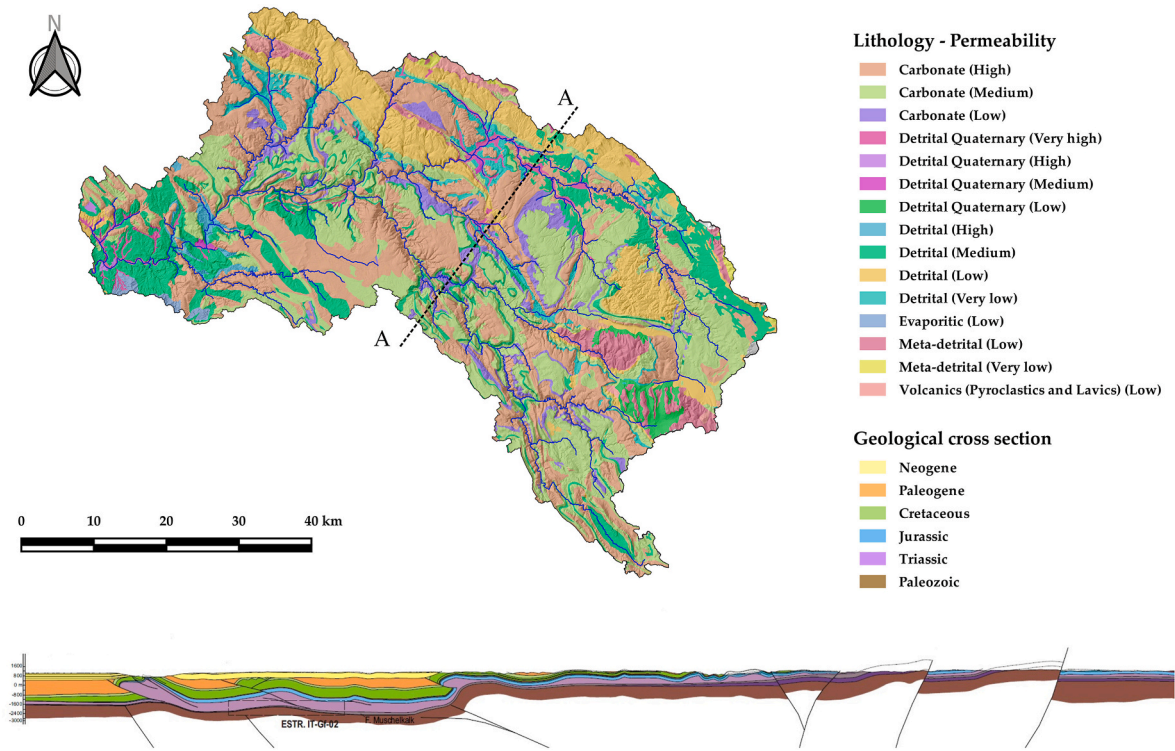


Fig. 2. Hydrogeological representation of the HTRB. Cross-sectional A-A view shows the geological zones (Spanish Geological Survey - IGME).

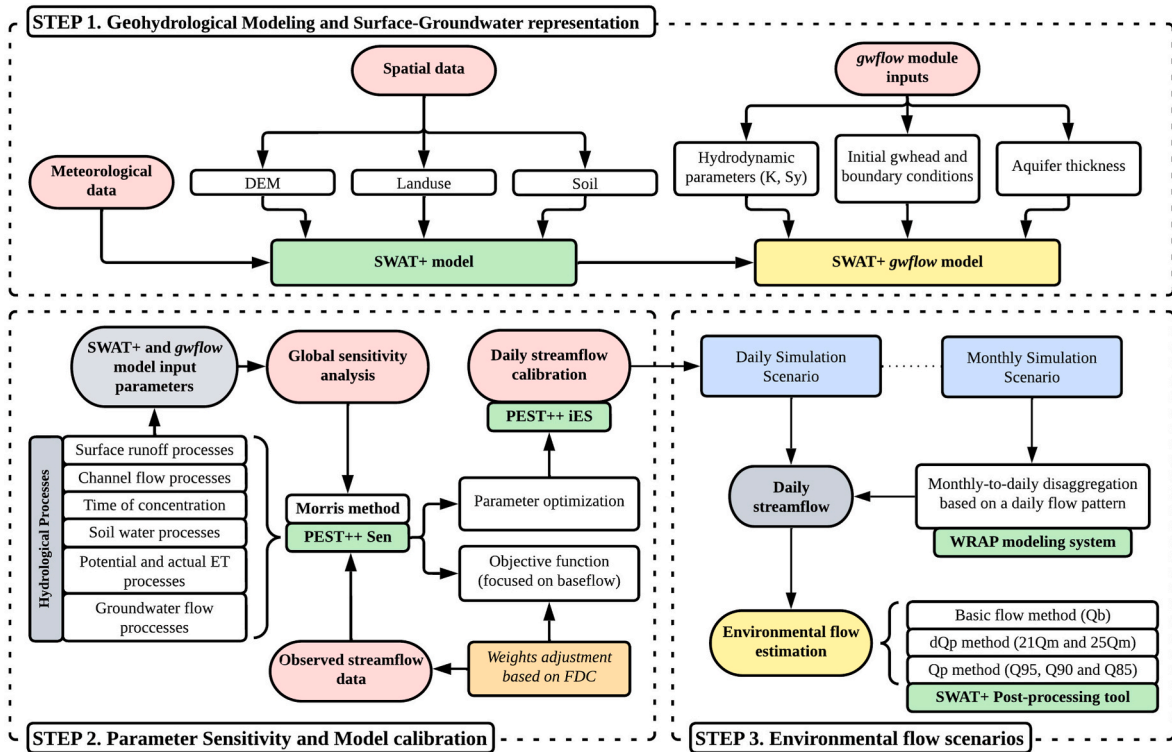


Fig. 3. Methodology flowchart.

on three main steps. First, hydrological modeling of the Tagus River headwaters basin was conducted using the SWAT + model with a subsequent coupling of the model with the new gwflow subsurface module. The second step is based on conducting a global sensitivity analysis of parameters related to various hydrological processes in the SWAT+ and

SWAT + gwflow models using the Morris screening method included in the PEST++ sensitivity module (White et al., 2020). Once the most sensitive parameters were determined, the models were calibrated and validated using an iterative ensemble smoother (iES) included in PEST++ (White, 2018) as a technique for uncertainty quantification and

parameter estimation, providing computational efficiency for a large number of parameters. In both processes, weights were assigned to observations to define their objective functions and emphasize the model's low flow. In the third and last step, environmental flows were estimated by applying hydrological methods using the SWAT + post-processing tool from the daily calibrated flow series obtained in Step 2. An extra daily streamflow from a monthly-to-daily disaggregation of a monthly simulation using the WRAP modeling system was also included.

3.1. SWAT + model description and setup

The soil and water assessment tool (SWAT) (Arnold et al., 1998) is a semi-distributed basin-scale hydrologic model widely used to simulate the impact of land use management practices on water quantity and quality in watersheds worldwide (Janjić and Tadić, 2023). The SWAT model applies the concept of hydrologic response units (HRU) to connect each subbasin's zones with the unique characteristics of slope class, land use and soil type (Neitsch et al., 2009). The water balance equation used in the SWAT is as follows:

$$SW_t = SW_o + \sum (R_{day} - Q_{surf} - ET_{\alpha} - W_{seep} - Q_{gw}),$$

where all of its components are related to the hydrological processes used for the production of the quantity of water available in the watershed. SW_t and SW_o are the final and initial water content, respectively, at a given time (t) (days). Q_{surf} is the surface runoff produced by the precipitation on a given day (R_{day}). ET_{α} is the evapotranspiration, W_{seep} is the percolation and Q_{gw} is associated with the quantity of baseflow on a day (mm).

SWAT+ (Bieger et al., 2017), the most recent version of the SWAT model, represents a re-structuring of the original code that allows the user greater configuration flexibility and a realistic representation of watershed systems. SWAT is limited to the simulation of a single channel per subbasin. In contrast, the SWAT + model can simulate the movement of sediment, water and nutrients through various channels in a watershed landscape (Bailey et al., 2023). Hydrologic objects include HRUs, channels, aquifers, reservoirs, routing units and wetlands where users can specify how water, nutrients and sediment move from one object to another (Bieger et al., 2017). To separate upland and flood-plain processes, SWAT + also works with the smaller-scale subdivisions of the subbasins: landscape units (LSUs).

The model input maps to construct the SWAT + model (Table 1) were prepared using the new MapSWAT tool (López-Ballesteros et al., 2024), which was integrated as a plug-in to the open-source quantum geographical information system (QGIS) interface and is connected with Google Earth Engine (GEE). The digital elevation map (DEM), used for estimating flow accumulation, has a resolution of 25 m per grid cell. In accordance with the Food and Agriculture Organization (FAO, 1980) criteria, the SWAT + model was constructed using three slope range groups, which were classified as follows: 0–8%, 8–30% and greater than 30%. The land use data were extracted from the Corine Land Cover of 2018. Finally, the soil property map was obtained from the new Digital Soil Open Land Map with finer spatial resolution (250 m), and a detailed soil profile divided into six soil horizons (López-Ballesteros et al., 2023).

To ensure the accuracy of the SWAT + model, it is necessary to input data pertaining to meteorological conditions, specifically the total precipitation experienced on a daily basis and the minimum and maximum temperatures recorded. It can be reasonably assumed that these variables may influence flow rate variations (Zaman et al., 2018). We obtained this data from the Spanish National Meteorological Agency (AEMET) grid with a 5-km spatial resolution from 1951 to 2021 (Senent-Aparicio et al., 2021a). The Hargreaves equation (Hargreaves, 1994) was used as potential evapotranspiration (PET) calculation method. Observed streamflow data were collected from the Spanish Hydrographical Studies Center (CEDEX). The following three gauging stations were used (Fig. 1): 3005 at Trillo, 3001 at Peralejos de las

Table 1

SWAT+ and SWAT + gwflow inputs.

	Data	Description	Source
SWAT+	Digital Elevation Map (DEM)	25 m spatial resolution map	Spanish National Geographic Institute (IGN)
	Streamflow gauging stations	3005: Trillo (flow pattern) 3001: Peralejos de las Truchas 3268: Taravilla	Spanish Hydrographical Studies Center (CEDEX)
	Land use map	100 m spatial resolution map	2018 Corine Land Cover Program (CLC2018) - Copernicus
	Soil properties map	250 m spatial resolution map and six soil horizons	Digital Soil Open Land Map (DSOLMap)
	Climate data	Precipitation, minimum and maximum temperature	Spanish National Meteorological Agency (AEMET)
gwflow	Aquifer thickness	Absolute depth to bedrock - 250 m spatial resolution	ISRIC – World Soil Information
	Permeability zones	Global aquifer permeability units – vector polygons	GLobal HYdrogeology MaPS (GLHYMPS)
	Groundwater head	Piezometric data – Vector points	Spanish Monitoring Network (Tagus River Basin District)

Truchas and 3268 at Taravilla. Trillo station, which is the downstream station, was used as the daily flow pattern (or “donor station”) for the disaggregation technique used in this study's methodology.

3.2. SWAT + coupling with the gwflow module

The gwflow module (Bailey et al., 2020), a new groundwater sub-routine for SWAT+, describes the spatial distribution of groundwater storage and flow in unconfined aquifers hydraulically linked to surface water features (channels, lakes and reservoirs). The model is discretized using a set of cells (Fig. 4a), with each cell representing a control volume of the aquifer for which groundwater storage, groundwater head and saturated thickness are computed using a water balance of groundwater inflows and outflows (Fig. 4c). Groundwater components include recharge from HRUs, lateral flow between cells, groundwater evapotranspiration (GWET), discharge to channels, channel seepage into the aquifer, pumping for either irrigation or municipal water supply, transfer to the HRU soil layers if the water table is within the soil profile and saturation excess flow if the water table reaches the ground surface. Based on the current storage at time n and the groundwater inflows and outflows for each grid cell (i, j), the gwflow module uses the groundwater storage equation to modify the amount of groundwater storage (V in m^3) for each grid cell at each time step (daily, from time n to time $n + 1$):

$$V_{ij}^{n+1} = V_{ij}^n + (sources_{ij}^n + sinks_{ij}^n \pm lateral\ flow_{ij}^n)(t^{n+1} - t^n)$$

where *sources* and *sinks* relate to groundwater inflows and outflows, and *lateral flow* reflects the Darcy flow between the cell and the four neighboring cells (west, east, north and south). Recharge and seepage (from streams and lakes) represent inflows, pumping, GWET, saturation excess flow to streams, groundwater discharge to lakes and tile drainage represents the outflows. This new gwflow module replaces the standard SWAT + groundwater module (*aquifer.aqu*) since one of its main limitations is the simulation of groundwater fluxes under the assumption of aquifers with homogeneous properties, excluding the exchange of water between neighboring aquifer systems (Abbas et al., 2024a).

Additional maps (Table 1) beyond those of the standard SWAT + model were necessary to build the SWAT + gwflow model. The

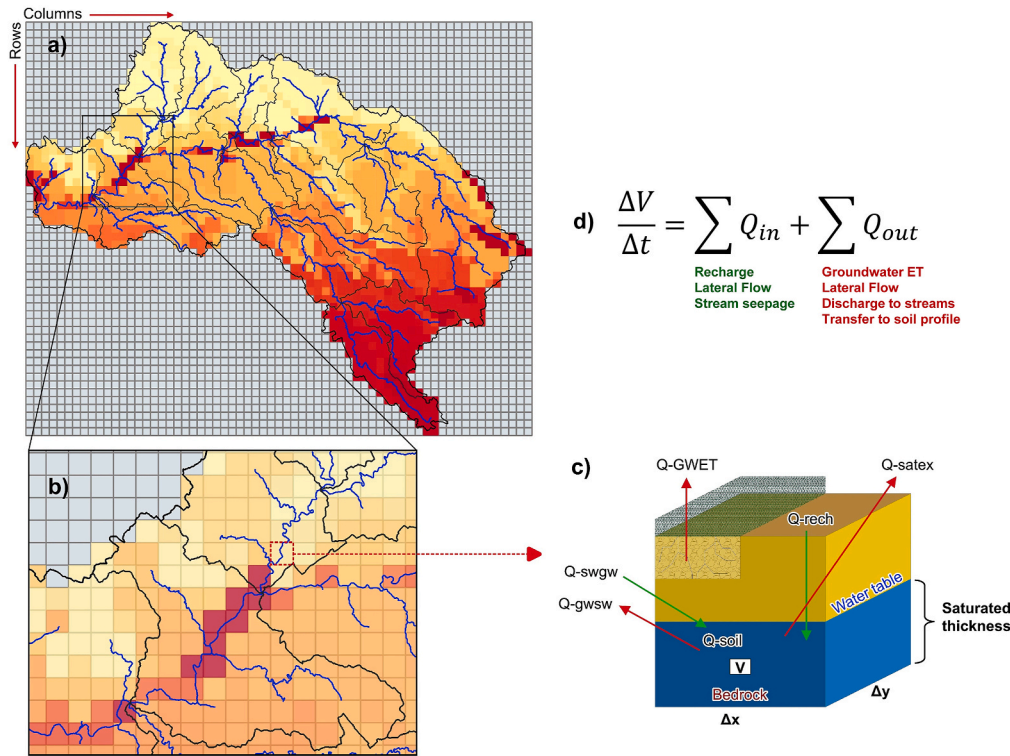


Fig. 4. Conceptual framework and computation method of the SWAT + gwflow. (a) Model grid cells, watershed and streams for the Upper Tagus River Basin; (b) zoomed-in section of channels and grid computation and (c) control volume for each cell to represent the system's (d) water balance.

MapSWAT tool allowed for obtaining maps of aquifer thickness and permeability zones from GEE in the study watershed. This dataset provided vertical distance to bedrock, hydraulic conductivity (K) and porosity (S_y) values for the initial model setup. Similarly, an interpolation was made based on the piezometric data of the wells distributed along the basin to define the initial groundwater head for all the active cells in the grid. In this study, the grid cell size for the HTRB was set at 500 m due to the larger spatial extension of the watershed. We note that the gwflow module is included in the official published SWAT + code.

3.3. Global sensitivity analysis

The SWAT + model, and in this case, SWAT + gwflow, has a large number of calibration parameters; thus, a prior selection process is necessary to avoid over-parameterization during model calibration (Arnold et al., 2012a). Therefore, we performed a sensitivity analysis to identify the impact of each parameter on the model streamflow using PEST++ (White et al., 2020). The sensitivity module of PEST++ (pestpp-sen) was used to employ the Morris screening method (Morris, 1991), also commonly known as the Elementary Effects Test, that is a specialized randomized One-At-a-Time Global Sensitivity Analysis (GSA) approach which is effective for identifying significant variables in a model (Campolongo et al., 2007). This approach assumes that the variable most affecting output when the same relative amount modifies all other variables is the most significant (King and Perera, 2013).

In this study, adjusting the model's low flows was a major essential for the subsequent estimation of environmental flows, in which minimum flows are integral to their definition. To focus on this adjustment, we separated and classified the observed flow data into five groups based on their position in the flow duration curve (FDC) and their probability of exceedance (0–20%, 20–40%, 40–60%, 60–80% and 80–100%). From this approach, we were able to obtain the most sensitive parameters from the Morris screening method for each zone of the FDC, identifying the parameters controlling the low flows of the model

with greater precision. We performed this sensitivity analysis for the calibration period (2000–2009) with a five-year warm-up period (1995–1999).

3.4. Calibration, testing and model evaluation criteria

A calibration process is necessary to minimize the uncertainty of the parameters (Arnold et al., 2012b) that comprise the SWAT+ and SWAT + gwflow models. In this study we employed an iterative ensemble smoother (IES) method for parameter estimation and calibration process using the software pestpp-ies included in PEST++ (White, 2018). The IES method, introduced by Chen and Oliver (2013), enables the estimation of both prior and posterior uncertainty of model parameters within defined calibration ranges. This approach is based on the original ensemble kalman filter (EnKF) (Evensen, 1994). The EnKF is a data assimilation technique leveraging correlations between state variables and measurements to incorporate observed data into model predictions. This approach emphasizes the variability and possible range of outcomes due to model structure, initial conditions and parameters uncertainties before the integrating data (Abbas et al., 2024a).

Regarding the objective function, parameter estimation software (PEST) is based on reducing the squared differences between the observed and model-simulated flows. As we did during the sensitive analysis, we focused the calibration on the model's low flows. To do so, we modified the objective function by manually altering the influence of the observed peak and low flows. Based again on the FDC and quantiles, we assigned greater weights to the low flows (Q80%) and reduced weights as the quantiles decreased. Thus, we ensured that the peaks' dominant values did not bias the model, and that the parameter estimation resulted in a balanced reproduction of the model streamflow with higher accuracy in the lowest part of the hydrograph. It is important to note that in this study we focused on the improvement of low flows because they are essential to environmental flows. However, emphasizing on the different types of flow varies according to the

objectives or the hydrological problems of each study area, such as climate and land use change, or the prediction of extreme events, such as floods and droughts events, for river management (Pfannerstill et al., 2014). For example, peak flows (below Q20%) are critical for flood risk management, while mid-range flows (between Q40%-Q60%) may be priorities in water supply planning.

Pestpp-ies automatic calibration was performed from 1995 to 2009 using the first 5 years as warm-up period (10 years for the calibration period) in the downstream Trillo-3005 gauging station (See Fig. 1). This step was executed for three iterations of the iterative ensemble smoother algorithm and 500 realizations (i.e. 2096 model runs). For testing, we used the following 10 years of available data (2010–2019) in the two river upstream gauges (Taravilla-3268 and Peralejos de las truchas-3001) and in the objective gauge for calibration downstream. To calibrate the streamflow response in the watershed we included parameters emphasizing the main hydrological processes: surface runoff, potential and actual evapotranspiration, soil water storage, time of concentration, channel and groundwater flow. To evaluate model performance, the Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), the percent bias (PBIAS), the Kling–Gupta efficiency (KGE) (Gupta et al., 2009), and the coefficient of determination (R^2) were used as indicators to measure the accuracy of the flow series, following the criteria proposed by Moriasi et al. (2015). We also included the Nash–Sutcliffe logarithm (LnNSE) as a statistic to improve low flows performance interpretation and to avoid the uncertainty produced by peak values (Krause et al., 2005). This parameter's transformation has been employed in previous studies with similar objectives (Castellanos-Osorio et al., 2023).

3.5. Monthly streamflow disaggregation based on a daily flow pattern

The disaggregation of monthly flow data to a daily scale is critical for accurately assessing environmental flows, as many ecological processes and water management decisions depend on daily flow variability (Slaughter et al., 2015). While monthly data may be sufficient for general water resource planning, they often lack the temporal resolution to capture critical ecological events, affected by daily flow variability (Kim, 2015). Access to daily hydrological data can be valuable for water resource planning efforts (John et al., 2021). This, in turn, broadens the scope for using the model data in a multitude of potential applications. Thus, the disaggregation of monthly SWAT + output to a daily scale is a fundamental step in exploring alternatives in the study of environmental flows (Castellanos-Osorio et al., 2023). The water rights analysis pack (WRAP) modeling system (Wurbs, 2021a), which has been employed in many studies (e.g., Verma, 2021; Wurbs, 2021b) to simulate an array of water-use planning scenarios, was utilized in this study to disaggregate naturalized monthly flows into daily flows. The software is available for free download on the Texas A&M University website.

The daily simulation program SIMD (Wurbs, 2021a), included in the WRAP modeling system, was used. This module includes all the modeling features of the monthly time step module (the SIM program), as well as a number of additional significant features made possible by disaggregating to a daily time scale. Streamflow on a monthly scale is processed and disaggregated by the SIMD module according to one of the four possible disaggregation techniques that users specified. Uniform distribution is the first and the simplest method, where monthly flow is divided evenly across the number of days in the month. Linear interpolation, the second method, connects daily flows at the beginning, middle, and end of each month using splines, producing smoother sequences but often unrealistic daily flow variations. The third method, adjustment based on variability, refines the linear interpolation by incorporating daily flow variation patterns and adjusting the daily flow volumes accordingly. Finally, the fourth method, replicating a daily flow pattern, is most often recommended and uses a pre-existing daily flow series as input. Monthly volumes are proportionally distributed based on the ratio of the daily flow pattern to its monthly total.

In this study, the flow pattern replication technique (4), the most

realistic approach for relying daily flow data from an existing gauging station, was employed for disaggregate the monthly flows of the SWAT + model. This technique is the one recommended by default in the SIMD program and has shown good results in related studies with similar topics (Castellanos-Osorio et al., 2023) when compared with the other three methods. Using this approach, the monthly flow volumes were disaggregated to the daily step including an extra input of the daily flow pattern in the SIMD setup window. In the present study, we used the downstream station (Trillo-3005) as daily flow pattern or “donor station” to disaggregate the other two upstream stations (See Fig. 1). The Trillo station provides the main contribution of the HTRB, thus, it was selected as a flow pattern to represent the entire basin's general behavior.

3.6. Environmental flow estimation

Hydrological methods are among the most common ways of estimating environmental flows. They are based on the idea that hydrological conditions reflect ecological demands (Książek et al., 2019). In accordance with daily time series, they are considered the most appropriate for water resources planning because they are the simplest and most direct methods for environmental flow estimation (Senent-Aparicio et al., 2021b). This study applied the hydrological methods recommended by the Spanish Hydrological Planning Instruction (IPH, 2008), which are defined below. These indicators are included in the SWAT + post-processing tool, in the QSWAT + interface in Step 4 after model building and simulation. More detailed information about the tool's functionality can be found in Senent-Aparicio et al. (2021b).

3.6.1. Basic flow method (Q_b)

Proposed and established in Spain by Palau and Alcázar (2012), the basic flow method determines the minimum flow that should exist in a river. Several studies have tested this method (Efstratiadis et al., 2014; Asadi et al., 2024), which is significant to Spanish hydrological planning. This method applies the moving averages for a specific interval in which uninterrupted daily flow data are available, ranging from 1 to 100 values. The use of 100 days is justified by the need to include the periods in which the lowest flows occur annually, represented by the water levels observed during the summer months. Therefore, this would comprehensively represent the daily flow rates over slightly more than three months (Camargos et al., 2018). The final Q_b value will be the average of the Q_b value of each year. In this case, we used the most recent 20 years of data (2000–2019) as the Spanish planning instruction recommended.

3.6.2. Methods based on moving averages (dQ_p)

The fundamental principle underlying these methodologies is the calculation of the mean flow rates over a specified duration (days) that are not exceeded within a given probability (percentiles) of years. Likewise, Baeza Sanz and García de Jalón (2005) proposed a methodology in which percentiles are not sorted and the mean values are considered: 25Qm methodology. Like the previous method, this method uses the moving averages of the 25 consecutive days of each year of study, choosing the lowest value. The series will be, at least, of the same size as the selected study years and represents the environmental flow, as determined by the arithmetic mean. Notably, the mean rather than the percentile is used. In this study, we estimate the 25Qm and 21Qm indicators, which are the most widely used in Spain.

3.6.3. Methods based on percentiles (Q_p)

These methods focus on the analysis of the frequency of the series., which is approached through the analysis of percentiles associated with the daily flow duration curve (FDC). To relate it to the two previous methods, in this case the moving average would correspond to a specific day (1 day) associated with a probability Q of non-exceedance p . The most common percentiles are the 95th and 90th percentiles (Efstratiadis

et al., 2014). In the present study, we have included the Q95, Q90 and Q85 percentiles, which are also used in the Tagus River Basin Management Plan.

4. Results and discussion

4.1. Sensitivity analysis

The results of the Morris screening method for parameter influence conducted for the HTRB are shown in Fig. 5. These results were used to select the most sensitive parameters in both base SWAT+ and coupled SWAT + *gwflow*, before the calibration process. Based on the position of the parameters within the scatter plot, relating its mean sensitivity (μ^*) and its deviation (σ), we were able to determine the most influential hydrological processes throughout the study watershed. According to Morris (1991), parameters with relatively small values of both μ^* and σ are characterized by non-influential effects. These low values indicate that the parameters has an insignificant effect on the overall model output. These non-influential parameters are typically clustered closer to the origin. However, depending on μ^* and σ relative values, the interaction or effect of the parameters could vary linearly or non-linearly. Large values of μ^* and small values of σ it indicates that for the perturbations in the parameter space, the magnitude of the impact itself is consistently significant, while the variety of elementary effects is minimal. The opposite case occurs when we have small values of μ^* and large values of σ , where the effect is seemingly small but the variation of the effect is large. The magnitude of the effect may vary based on the other parameter values at which the model is assessed. This approach was conducted qualitatively, presenting a standard parameter classification based on a visual assessment of elementary effect statistics (Vitullo et al., 2023).

Sensitivity analysis reveals that for the standalone SWAT + scenario the most influential groups are the aquifer, soil and hydrology and evapotranspiration processes. The recharge to deep aquifer (*rchg_dp*) and depth from mid-slope surface to bottom of aquifer (*dep_bot*) were the most sensitive aquifer parameters, highlighting the influence and need to represent in a more accurate way the groundwater processes in continental Mediterranean basins (Senent-Aparicio et al., 2021c). In the same way, both models were strongly influenced by parameters related to hydrological processes, mainly the potential and actual evapotranspiration components (*esco*, *epco* and *can_max*), which was to be expected in Mediterranean climate with high evapotranspiration rates (Molina-Navarro et al., 2014). The percolation coefficient (*perco*), which is a coefficient that allows adjusting soil moisture for percolation to occur, was sensitive in both cases. This makes sense in watersheds where groundwater processes are dominant (Yimer et al., 2023a). In keeping with the soil processes group, soil available water capacity (*awc*) was sensitive in common model classes. For the *gwflow* case, surface runoff lag coefficient (*surq_lag*), related with the time of concentration, and Manning's *n* (*ch_n*) for channel processes, were sensitive to streamflow response. The significant influence of streambed and aquifer hydraulic conductivity (*bed_k* and *kaqu*), and aquifer specific yield (*syaqu*), highlighted their potential impact on groundwater-channel exchange and water table gradients (Abbas et al., 2024b).

4.2. SWAT+ and SWAT + *gwflow* model performance

4.2.1. Calibration and validation

Table 2 presents the calibrated parameter values for both SWAT+ and SWAT + *gwflow*. Highlighting the variability of the values obtained in the calibration due to the different interactions and construction of the two models (Yimer et al., 2023a), although the values typically follow the same trend. The plant uptake compensation factor (*epco*) and the soil evaporation compensation factor (*esco*) showed a reduction with respect to their default values in both cases, resulting in an increase in

the model's evapotranspiration. Other studies in the upper Tagus employed similar values for *esco* and *epco* (Molina-Navarro et al., 2014; Castellanos-Osorio et al., 2023). The extensive vegetation covering the study area may explain to the observed increase in the maximum canopy storage (*can_max*) value. Similarly, the available water capacity (*awc*) of the soil layer increased in all soils, indicating a reduction in the water movement through soil profiles (Qiu et al., 2012). The infiltration process was reduced because of the decrease in Manning's roughness value (*ch_n*). This contributes to further groundwater entering and remaining in the main river channel (Abbas et al., 2024a). The increase in the surface runoff lag time (*surq_lag*) regarding to the default value indicated a decrease in available temporary storage (Neitsch et al., 2002), directly affecting the time of concentration of the basin. Regarding to groundwater processes, the recharge to the deep aquifer (*rchg_dp*) in SWAT + reached a value close to 0, which means a very low water loss to an eventual deep aquifer and matching with the hydrogeological configuration of the study area. Likewise, the value obtained for the baseflow recession constant (*alpha_bf*) is very similar to those used in the work of Molina-Navarro et al. (2014) in areas close to the study area. This parameter serves as a direct indicator of groundwater flow response to recharge variations, and the calibrated value ranging from 0.1 to 0.3 suggests that the catchment exhibits a slow response to recharge (Smedema and Rycroft, 1983). However, in SWAT + *gwflow* the groundwater contribution to streamflow was directly influenced by the aquifer hydraulic (*kaqu*) conductivity and specific yield (*syaqu*), whose value adjustment allows for controlling the fluctuation of groundwater levels due to a change in groundwater storage (Bailey et al., 2023). The increase in streambed hydraulic conductivity (*bed_k*) is attributed to the relatively shallow groundwater levels compared to the ground surface and channel elevation (Abbas et al., 2024b), directly affecting the surface-groundwater exchange and baseflow.

Fig. 6 shows the daily statistical values and graphical performance of both models for the calibration (2000–2009) and testing (2010–2019) period in the downstream gauging station (Trillo-3005). In this case, a simple visual inspection indicated that the coupled model improved the reproduction of the observed flows, showing higher accuracy in simulated peaks and baseflow. According to Moriasi et al. (2015) criteria, the SWAT + *gwflow* scenario performed very good for the calibration period, with a NSE value of 0.86 and a PBIAS value very close to 0%. In contrast, statistical values for the standalone SWAT + showed a satisfactory performance with a NSE of 0.57 and a PBIAS around 15%. With SWAT + *gwflow* simulation, the good performance remained stable for the remainder of the simulation period, while the standalone model was still satisfactory despite showing a slight worsening in model volumes with an increase in the PBIAS value. Furthermore, KGE performance was identified as satisfactory based on Kouchi et al.'s (2017) criteria, with values above 0.50 in both cases for the simulation period, even surpassing 0.85 in some cases for the *gwflow* module. Finally, we evaluated the LnNSE indicator with additional emphasis to determine the low-flows model performance, as it is fundamental to the objectives of the present study. Despite the good statistical results for both cases, an underestimation of the low flows of the SWAT + model is observed for most of the simulation period. Daggupati et al. (2015) determined that this visual analysis between simulated and observed streamflows was crucial for two reasons. Firstly, relying solely on metric values to assess the model may be deceptive, leading to the generation of scenarios that may appear statistically satisfactory but lack realism in terms of the desired outcomes. Secondly, the incorporation of visual analysis allows to provide a more thorough assessment of the model's performance. For this statistical indicator (LnNSE), the SWAT + *gwflow* model showed very good performance with values of 0.87 and 0.84 for the calibration and testing period, and a trend of low flows similar to those observed. Furthermore, for SWAT + *gwflow* model validation, the same statistical values were calculated for the upstream stations. Daily performance for station 3001-Peralejos de las Truchas showed a very good fit compared to the observed flows, reaching NSE values of 0.79 and 0.75 and PBIAS

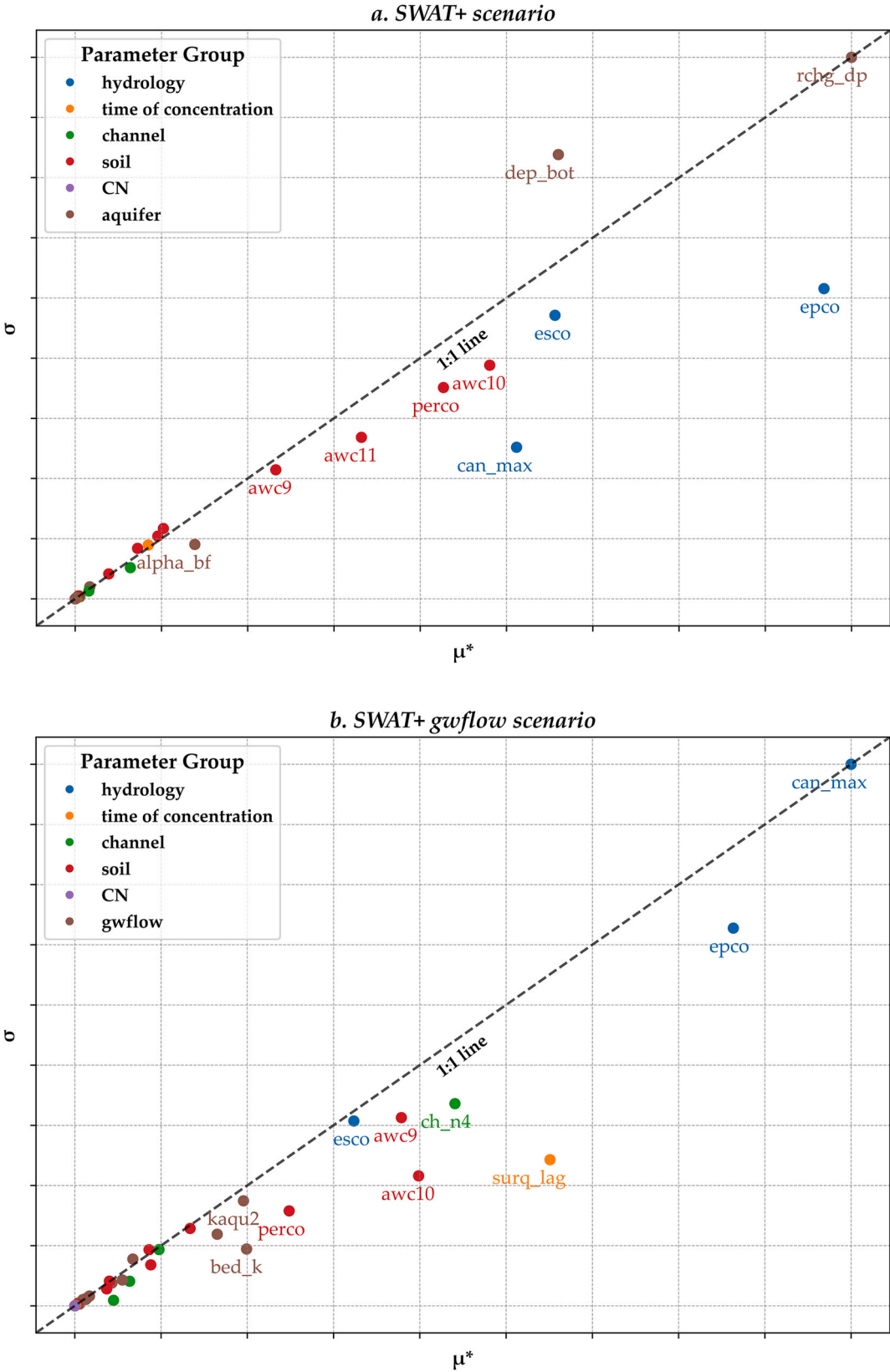


Fig. 5. Parameter sensitivity analysis based on the Morris screening method for a) standalone SWAT+ and (b) SWAT + *gwflow* in the Upper Tagus River Basin. μ^* represents the mean sensitivity and σ the standard deviation of sensitivity. Each color represents a different hydrologic process.

Table 2
Selected parameters and calibration values for the SWAT+ and SWAT + *gwflow* models.

Hydrologic Process	Parameter	Description	Fitted value	
			SWAT+	SWAT + <i>gwflow</i>
Potential and actual ET	epco	Plant uptake compensation factor	0.1833	0.0481
	esco	Soil evaporation compensation factor	0.6681	0.5542
	can_max	Maximum canopy storage (mmH ₂ O)	2.4667	21.8434
Soil	awc # (3 classes)	Available water capacity of the soil layer (mmH ₂ O/mm soil)	3.87–18.08%	9.65–11.42%
	perco	Percolation coefficient	0.17	0.36
Channel flow	ch_n # (1 class)	Manning's "n" for the main channel	–	0.018
Time of concentration	surq_lag	Surface runoff lag time (days)	–	21
Aquifer	rchg_dp	Recharge to the deep aquifer (percolation factor)	0.0431	–
	dep_bot	Depth from mid-slope surface to bottom of aquifer	10.956	–
	alpha_bf	Alpha factor for groundwater recession curve	0.2559	–
Groundwater flow	bed_K	Streambed hydraulic conductivity (m/day)	–	1.5e ^{−4}
	Kaqu # (1 class)	Aquifer hydraulic conductivity for a specific zone (m/day)	–	1.65
	Syaqu # (1 class)	Aquifer specific yield for a specific zone	–	0.18

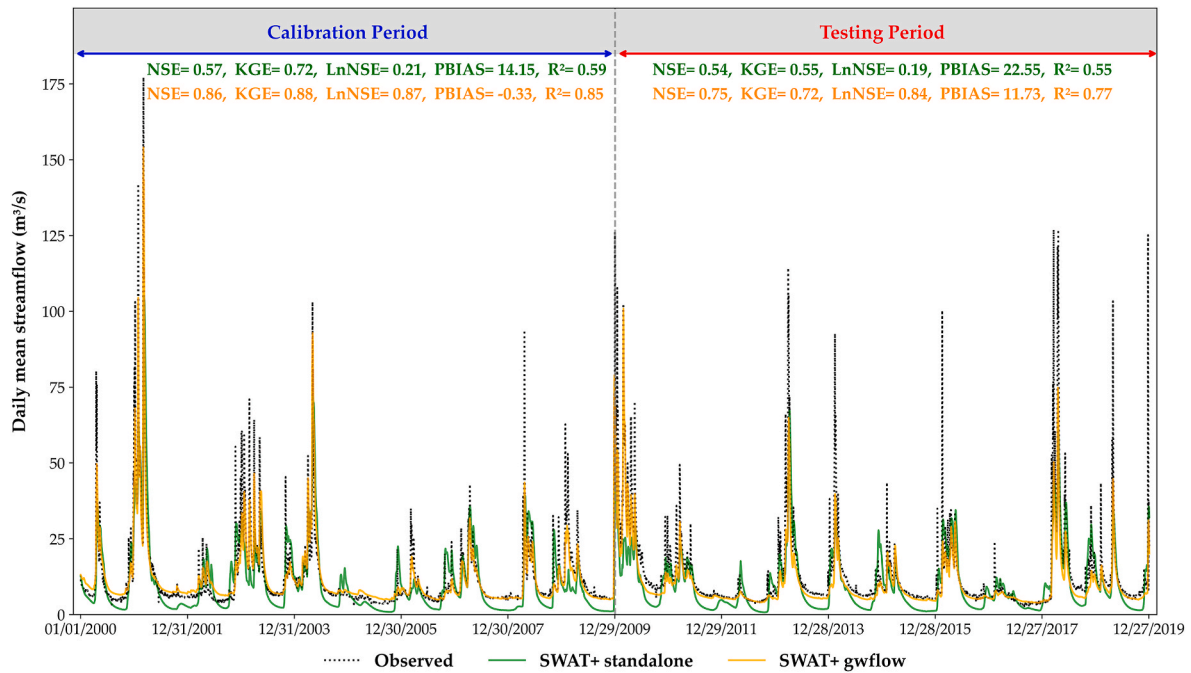


Fig. 6. Daily observed and simulated streamflow for standalone SWAT+ (green) and SWAT + *gwflow* (orange) in the downstream station (Trillo-3005).

between −4% and 13% for the calibration and testing periods. As for low flows, the LnNSE values for this station were 0.82 and 0.73, and the KGE was higher than 0.80 in all cases. Finally, the station 3268-Taravilla performance was satisfactory according to Moriasi et al. (2015), slightly worsening in the statistical indicators (NSE values of 0.59 and 0.51 and PBIAS around −17%) but corresponding to the same visual trend of the observed flow rates. The LnNSE values were 0.56 and 0.49, and the KGE ranged from 0.61 to 0.65, maintaining a satisfactory fit of the model's mean and low-flows.

4.2.2. Water balance

Fig. 7 displays the monthly hydrologic processes in the upper Tagus watershed for the simulation period (2000–2019). Plot (a) shows the entire watershed system from the surface processes and (b) from the aquifer and groundwater systems. Positive values refer to system inputs, mainly precipitation and boundary inflows in the surface water balance and recharge in the groundwater balance. In contrast, system outputs are represented by negative values, including surface ET, surface runoff and soil lateral flow, with the latter two contributing to streamflow. The seasonal pattern revealed by the inflows and outflows makes sense for the overall watershed balance. Similarly, as a highly groundwater-

dominated catchment, a significant portion of the total water yield produced is soil lateral flow, originating from groundwater (Fig. 6b) in areas of shallow groundwater levels, with its volume an significantly contributing to streamflow. Molina-Navarro et al. (2014) also highlighted the importance of the lateral flow component in a basin geographically close to the current study area. In the same way, the slopes of the studied watershed (higher than 8% in about 65% of the basin) also contribute to the importance of the lateral flow increase as established by Samper et al. (2011). In general, soil lateral soil flow serves as a pathway for groundwater to reach the stream network, which and can be considered part of the baseflow (Yimer et al., 2023a).

4.3. Environmental flow estimation

Once the SWAT+ and SWAT + *gwflow* were calibrated, the daily flow series from these models were used to estimate environmental flows. The daily simulations of these models correspond to scenarios (a) and (c). Regarding scenario (b), we used the flow rates from a monthly simulation as input to the WRAP model to extract an extra daily flow series from disaggregation based on a daily flow pattern. Obtaining daily streamflow from monthly-to-daily disaggregation techniques as an

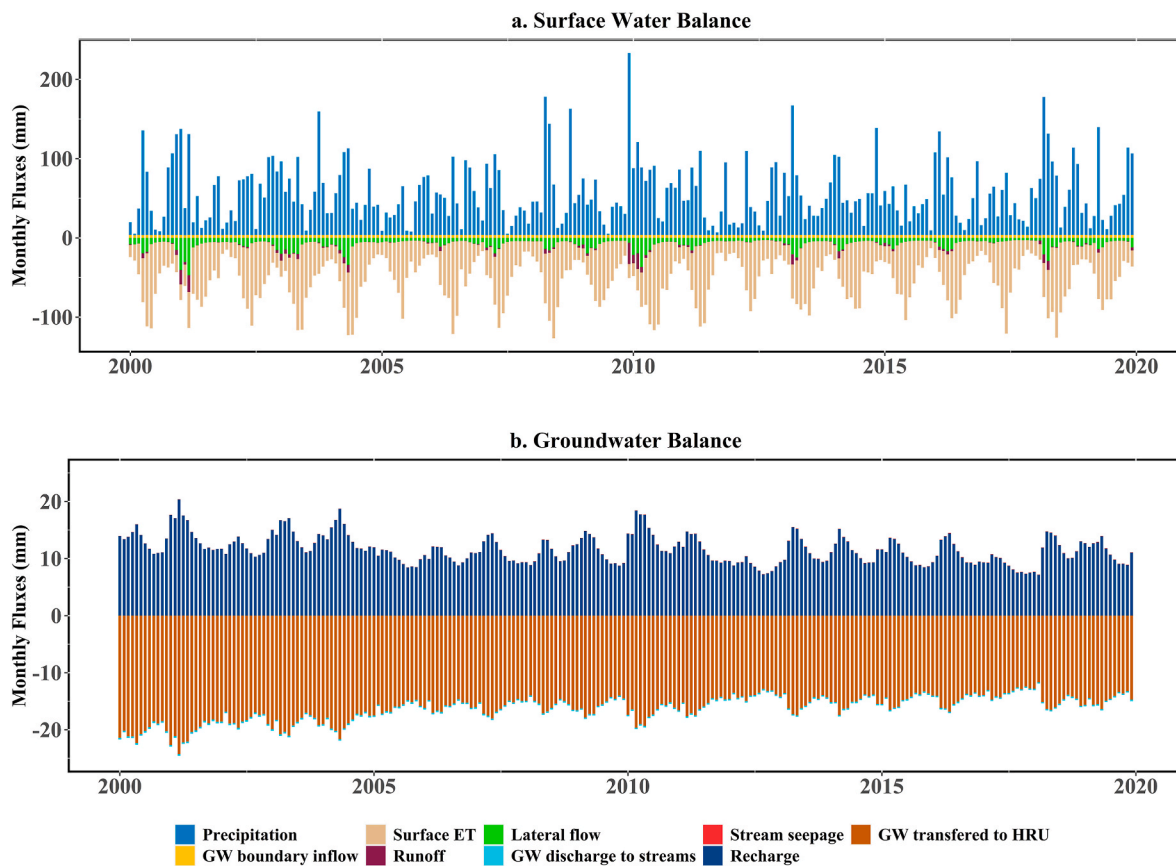


Fig. 7. Monthly (a) surface water fluxes and (b) groundwater fluxes for the simulation period 2000–2019 in the HTRB.

alternative for environmental flow estimation provides continuity for the hypotheses proposed by Castellanos-Orsorio et al. (2023), allowing for analysis of the uncertainty associated with the flow series employed to calculate environmental flows. In relation to this, Fig. 8 shows the differences found according to the series of daily flow rates used (a, b or c), highlighting the necessity of effectively reproducing the minimum flows for the aforementioned objectives. Each hydrograph includes a zoomed-in window to show a specific period, allowing for a detailed comparison between the calibrated and observed flows at one of the upstream validation stations (3001-Peralejos de las Truchas). A simple visual inspection revealed the differences for each of the three compared scenarios, with green highlighting. Daily simulation from the standalone SWAT+ (a) shows a general alignment with the observed data, particularly during mean and high flow events. However, discrepancies are evident during low flow periods, as the significant amount of green area indicates. The zoomed-in section reveals that the model often underestimated baseflow, possibly due to the parameterization of the model or its inherent limitations in accurately capturing low flow dynamics (Yimer et al., 2023b). The disaggregated SWAT + scenario (b) demonstrated better performance in simulating low flows than the daily simulation scenario (a). The green shaded area is narrower, indicating a decrease in uncertainty and an improvement in model timing. The zoomed-in window shows a closer match between observed and simulated flows during low flow periods, suggesting that the disaggregation approach enhanced the model's capacity to capture baseflow variations more accurately (Castellanos-Orsorio et al., 2023) than the previous scenario. Finally, coupled SWAT + gwflow (c) exhibited the best performance among the three scenarios in simulating peak flows and baseflow. The discrepancies, indicated by the green shaded area, are minimal, and the zoomed-in section highlights a strong concordance between observed and simulated flows. The ability of the gwflow module to integrate groundwater flow dynamics significantly improves its

accuracy in representing baseflow conditions (Bailey et al., 2023).

Environmental flow indicators were calculated for the downstream (3005-Trillo) and upstream (3001-Peralejos de las Truchas and 3268-Taravilla) stations from the daily streamflow data of the three proposed scenarios using the SWAT + post-processing tool. Table 3 shows the variations of the environmental flow indicators in % calculated with simulated flows related with those calculated with the observed flows. Station 3005-Trillo had indicator values only for scenarios (a) and (c), corresponding to the daily simulations of the SWAT+ and SWAT + gwflow models, since the monthly-to-daily disaggregation scenario (b) provided the daily flow pattern (donor station) for the upstream stations. In general terms, the standalone SWAT + scenario (a) showed an underestimation of low flows at all stations, generalizing the associated uncertainty shown in Fig. 8. This underestimation, quantitatively, ranged from 46% to 58% at the downstream station and is around 50% and 40% for stations 3001 and 3268, respectively. In any case, despite showing satisfactory results in the overall model performance, the standalone SWAT + daily flows showed a marked deterioration in the environmental indicators, which are directly associated with low flow rates. When we applied flow pattern-based disaggregation techniques to SWAT + monthly flow rates (b), we observed that the relative difference of the indicators was reduced, even by half for some indicators, for both upstream stations. The indicator that best reflected this improvement was the basic flow (Qb), which, based on the 100-day moving average, allowed for highlighting the low flow performance by considering the seasonal component (Palau and Alcázar, 2012). Overall, station 3268-Taravilla was most positively affected by the disaggregation based on the 3005-Trillo daily flow pattern. Finally, the best performance associated with the environmental indicators was shown in the third scenario associated with the SWAT + gwflow daily flows (c). The improved representation and parameterization of the groundwater component is directly reflected in the reproduction of the model

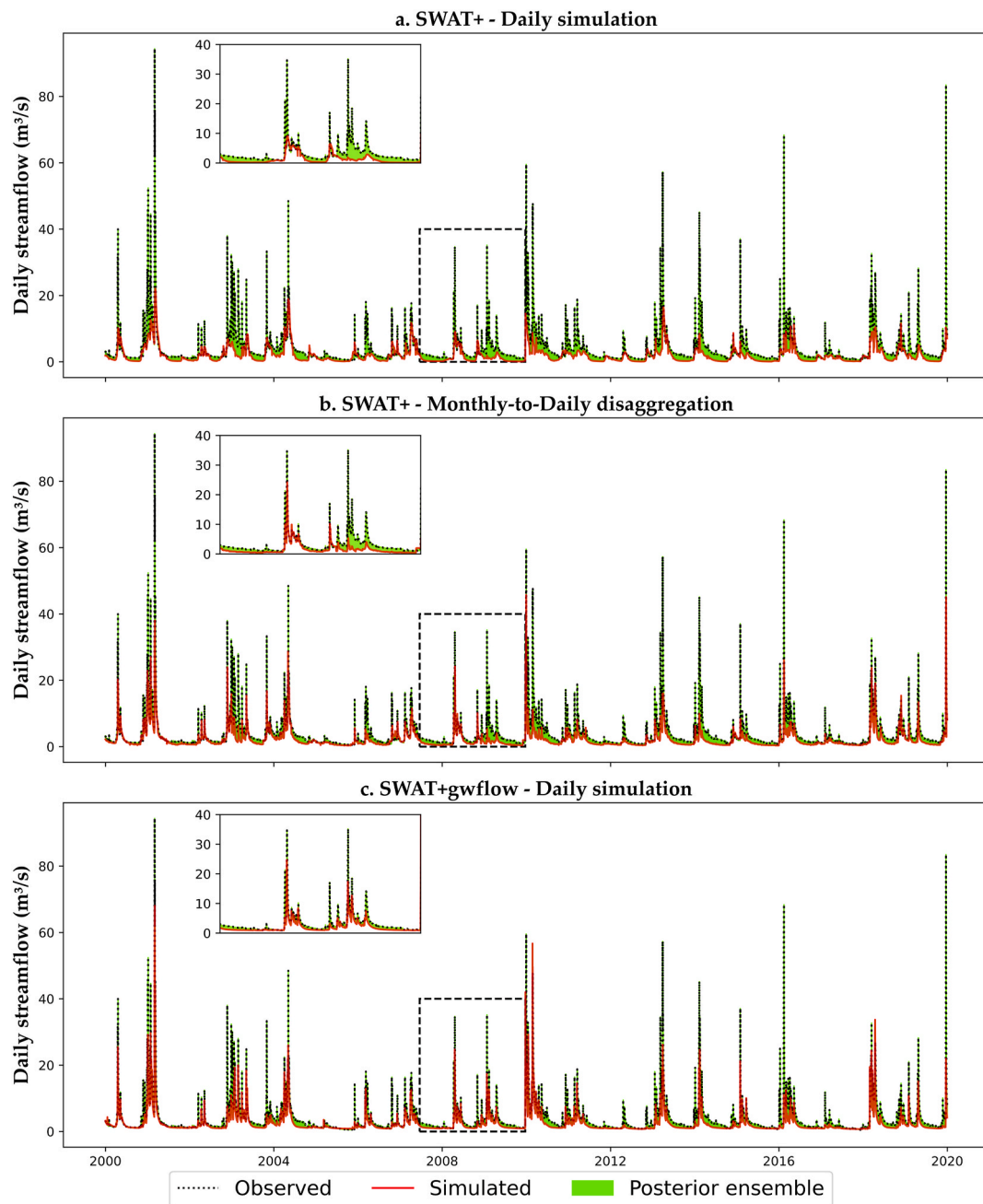


Fig. 8. Daily observed and simulated streamflow for (a) SWAT+ and (c) SWAT + *gwflow* posterior ensemble at station 3001-Peralejos de las Truchas. Monthly-to-Daily disaggregation from a daily flow pattern (3005-Trillo) is shown in (b).

Table 3

Relative variation (%) of simulated environmental flow indicators with respect to observations in the downstream and upstream stations. Scenarios (a) and (c) correspond to daily standalone SWAT+ and SWAT + *gwflow*, respectively. Scenario (b) corresponds to monthly standalone SWAT + disaggregated.

Station	Scenario	Qb	Q95	Q90	Q85	25Qm	21Qm
3005 (Trillo)	(a)	−46.33	−58.74	−57.36	−55.28	−57.38	−56.40
	(c)	−8.04	−13.07	−11.84	−10.12	−14.11	−13.86
3001 (Peralejos de las Truchas)	(a)	−52.46	−54.05	−53.64	−51.45	−49.74	−49.69
	(b)	−28.12	−30.26	−32.73	−30.85	−22.86	−22.28
	(c)	−6.86	−6.05	−9.27	−11.73	−10.95	−9.61
3268 (Taravilla)	(a)	−41.02	−42.50	−42.12	−41.65	−46.08	−46.21
	(b)	−7.81	+26.04	+16.67	+11.47	+1.40	+1.06
	(c)	−1.02	+4.90	+3.92	+2.15	+2.45	+2.82

baseflow. The accuracy in low and maintenance flows significantly reduced the discrepancy in the calculation of environmental indicators, reaching values closest to zero for most of them across all three gauging stations. The underestimation observed in the other scenarios was significantly reduced, even showing a slight underestimation at the upstream station 3268-Taravilla, where the average flows were considerably lower than those of the other two stations.

Adjusting weights during the model calibration was crucial for reducing uncertainty in environmental indicators estimation. This approach, combined with a higher valuation of low flows, allowed for greater accuracy in baseflow conditions. This improvement, mainly for the SWAT + *gwflow* scenario, can be seen in the flow duration curves (FDC) shown in Fig. 9. To consider a complete analysis hydrograph's high and low flow phases, we divided the flow duration curve into five segments based on the flow exceedance probability (Qp%) (U.S. Environmental Protection Agency, 2007). Previous studies have performed this characterization in zones for a more detailed analysis of the simulated flow behavior (Jimeno-Sáez et al., 2018; Pfannerstill et al., 2014). In this study, we considered flows greater than Q10% as high flow, between Q10% and Q40% as moist conditions, between Q40% and Q60% as medium flow, between Q60% and Q90% as dry conditions, and finally, flows smaller than Q90% as low flow. We have also identified the percentiles 85, 90 and 95 (in red) in the figure. We used them as environmental flow indicators in Table 3 to observe performance in that range. The standalone SWAT + model (green) exhibited limitations in simulating streamflow in different flow conditions.

Despite showing a good representation of the flow rates in high flow and wet conditions, the standalone SWAT + model revealed a higher deviation from medium to low flow conditions. This discrepancy justifies the underestimation of environmental flows based on percentiles, and the model's deficit in simplified representations of hydrological processes during these low flow conditions. In contrast, the SWAT + *gwflow* coupled model (orange) revealed consistent improvement and satisfactory performance across the five zones. The enhanced representation of groundwater processes allowed the model to reproduce a better behavior of the HTRB, mainly in low flow and drought conditions. In observing the trend of the coupled model's curve, we expected this scenario's would show the smallest deviations when estimating environmental flows, highlighting the significant improvement over the single SWAT + model, daily and monthly disaggregated, under the same conditions.

4.4. Drawbacks and future research

SWAT + *gwflow* offers a valuable tool for simulating groundwater-surface water interactions, outperforming the standalone SWAT+ in all respects according to this study's objectives; however, its application has requirements. One of the main challenges was the need for piezometric data to better define the initial boundary conditions and comprehensive geohydrological information on the study area, which could vary significantly. An accurate simulation of the hydrology depends on this data. Disaggregation techniques also require a daily streamflow pattern ("donor station") with sufficient data length, which is not always available. If available, it can be useful for simulating scenarios in non-gauged basins. Another potential handicap is the computational demand these coupled models mainly require for their calibration and simulating scenarios. The extension of the watershed and the number of parameters directly chosen influenced the latter, making prior optimization of the study area essential to expedite the model processes. However, despite these challenges, SWAT + *gwflow* proved highly effective in this study and thus has the potential for numerous applications. Future research could explore its use in regional water management scenarios, following the methodology applied to Mediterranean basins analyzed in this work, such as simulating the impact of agricultural practices, assessing climate change scenarios and investigating the hydrological responses to land use changes or extreme events. These applications demonstrate the model's flexibility and utility in hydrological research and planning.

5. Conclusions

Overall, this study highlights the significance of coupling surface and groundwater models to improve the accuracy of the reproductions of a basin's hydrological regime. This is particularly crucial in highly regulated rivers, where a detailed understanding of geohydrological processes is necessary for sustainable water management and environmental conservation. The development and application of tools, such as SWAT + *gwflow*, can provide a realistic basis for assessing environmental flows and long-term hydrological representation. We concluded the following from the results.

- The coupled SWAT + *gwflow* model demonstrated significant improvements over the standalone SWAT + model in estimating

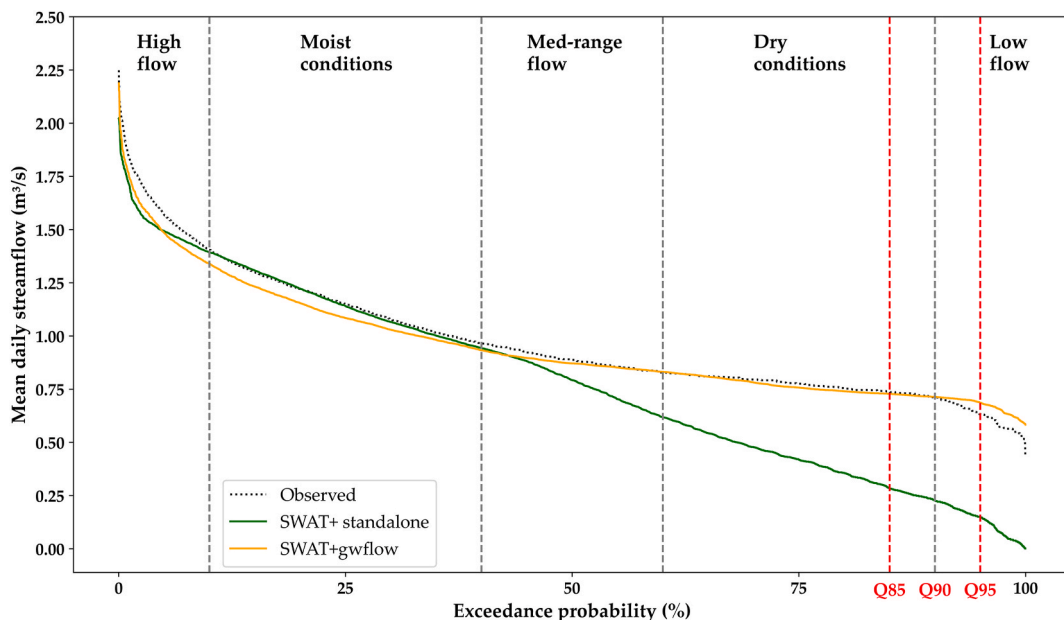


Fig. 9. Comparison of estimated daily streamflow from SWAT+, SWAT + *gwflow*, and observed data at downstream 3005-Trillo station.

environmental flows, particularly in low flow conditions. This coupling enhanced the representation of surface-groundwater interactions, effectively capturing groundwater contributions. The SWAT + *gwflow* model was especially suited for basins with complex hydrological regimes where groundwater is crucial, making it a reliable, accurate tool for daily flow simulation and environmental flow management.

- The sensitivity analysis and calibration approach, with its focus on low flows, was essential for reducing model uncertainty and improving performance in environmental flow estimation. By prioritizing the Q80 streamflow in the calibration process, the results showed that parameter sensitivity was effectively captured, enhancing the estimation of low flow-related environmental indicators. This enhancement was particularly evident in the SWAT + *gwflow* scenario, which benefited most from these adjustments, resulting in improved model accuracy.
- Even after automatic calibration and applying monthly-to-daily flow disaggregation methods, the standalone SWAT + model struggled to simulate low flows in the HTRB accurately. While disaggregation improved the fit of low flows, this method had limitations, notably due to the need for accurate daily-scale data from donor stations representing the broader watershed's behavior. This introduces uncertainties, highlighting the challenges of adjusting a model that does not consider groundwater contributions in a basin where such processes dominate.
- The coupled SWAT + *gwflow* model exhibited superior accuracy across the hydrograph, capturing high, medium and low flow conditions with greater precision than the standalone model. Including groundwater dynamics through the *gwflow* module significantly improved the baseflow simulation, resulting in a realistic representation of the basin's water balance. Thus, the SWAT + *gwflow* model is a powerful tool not only for environmental flow estimation but also for hydrological planning and decision-making in basins where groundwater processes are critical.

CRedit authorship contribution statement

Gerardo Castellanos-Osorio: Writing – original draft, Methodology, Conceptualization. **Salam A. Abbas:** Validation, Methodology, Formal analysis. **Eugenio Molina-Navarro:** Writing – review & editing, Supervision. **Ryan T. Bailey:** Writing – review & editing, Supervision. **Javier Senent-Aparicio:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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