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HYDROLOGICAL MODELING AND CALIBRATION WITH SWAT IN THE ARIT STREAM BASIN, TÜRKİYE

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Abstract

This study develops, calibrates, and validates a SWAT2012 hydrological model for the Arıt Stream sub-basin in Bartın Province, Türkiye, to provide a reproducible baseline for analyzing streamflow regime and basin water balance under current and changing climate conditions. The model was set up in QGIS using the QSWAT interface, supported by a 25 m DEM, CORINE 2018 land use/land cover data, and FAO-based soil information. Daily precipitation and maximum–minimum temperature records for 2010–2023 were used as meteorological forcing, and potential evapotranspiration was computed using the Penman–Monteith method. Simulations were performed at a daily time step for 2010–2023, with 2010–2011 reserved as a warm-up period and model evaluation carried out at a monthly scale. Monthly outlet discharge (FLOW_OUT) at the Darıören gauging station (DSİ D13A049) was compared with observations, and calibration/validation were conducted in SWAT-CUP using the SUFI-2 algorithm. To account for the small difference between the modeled drainage area (≈130 km²) and the reported gauge drainage area (137 km²), observed discharges were scaled by the area ratio 130/137 (=0.95). Model performance yielded NSE=0.79, R^2=0.84, KGE=0.71, RSR=0.46 and PBIAS=−16.9% for the calibration period (2012–2018), and NSE=0.78, R^2=0.83, KGE=0.70, RSR=0.47 and PBIAS=−20.9% for the validation period (2019–2023). The negative PBIAS values indicate a tendency to overestimate mean discharge; however, the model reproduces the observed seasonal pattern and provides a consistent basis for future scenario analyses and water resources assessments in the Bartın region.

Keywords: Bartın–Arıt, SWAT2012, QSWAT, SWAT-CUP, SUFI-2, streamflow, water balance, climate change

1. Introduction

Watershed-scale hydrological models are critical for water resources management, especially when climate change and land-use alterations increase pressure on river basins. Shifts in temperature and precipitation can change runoff generation, groundwater recharge, and the timing of peak flows and drought periods. Hydrological models allow researchers and decision-makers to simulate these processes and evaluate potential future scenarios. For example, Özdemir et al. (2024) used SWAT to examine how RCP4.5 and RCP8.5 scenarios may affect runoff and nitrogen loads in the Gördes Dam Basin, while Garcia et al. (2024) applied a SWAT-based framework to evaluate climate change impacts on hydropower production. Üneş et al. (2018) and Althoff and Rodrigues (2021) likewise highlight the role of modeling and performance assessment in supporting planning and decision-making.

Among available models, the Soil and Water Assessment Tool (SWAT) is one of the most widely used for watershed hydrology worldwide and in Türkiye. A review by Peker and Cüceloğlu (2022) documented many SWAT applications across Türkiye, indicating that the model can be applied under diverse Turkish conditions when supported by appropriate data preparation and calibration.

The classic SWAT version (SWAT2012) is a semi-distributed, process-based model that represents a watershed through sub-basins and hydrologic response units (HRUs).

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It solves a daily water balance and partitions precipitation into surface runoff, infiltration and percolation, lateral flow, groundwater contribution (baseflow), and evapotranspiration, and then routes flow through the channel network.

Because key processes are sensitive to local conditions and input uncertainty, calibration and uncertainty analysis are generally required before using the model for scenario studies. Model performance is commonly summarized with statistics such as Nash–Sutcliffe Efficiency (NSE), Kling–Gupta Efficiency (KGE), coefficient of determination (R^2), RMSE or RSR, and percent bias (PBIAS) (Moriasi et al., 2007).

The Arıt Stream sub-basin is located in the Western Black Sea Region of Türkiye, within Bartın Province. The catchment includes steep terrain and a humid climate, and streamflow is shaped by both rapid runoff during storm events and sustained baseflow contributions. These characteristics make the basin hydrologically responsive and relevant for local planning, and a calibrated model can support quantitative assessments of streamflow regime and basin water balance.

Accordingly, this study aims to (i) develop a SWAT2012 model for the Arıt Stream sub-basin using a GIS-based workflow, (ii) calibrate and validate monthly streamflow at the Darıören gauging station, and (iii) report model performance using standard statistical criteria. The resulting model is intended as a baseline for subsequent scenario analyses focused on streamflow regime and basin water balance in the Bartın region.

1.1 Study Area

Location and topography

The study area is the Arıt Stream (Arıt Çayı) sub-basin of the Bartın River Basin, located in Bartın Province in northern Türkiye within the Western Black Sea Region. The watershed outlet was defined at the DSİ Darıören streamflow gauging station (D13A049; 41.655833° N, 32.520556° E; elevation ~230 m), which was used as the control point for delineation and model evaluation. All spatial data sets were processed in the WGS 84 / UTM Zone 36N coordinate reference system (EPSG:32636). In the SWAT2012 model setup, the catchment was subdivided into 13 subbasins and 13 stream reaches.

Based on the 25 m digital elevation model (DEM) used in model setup, the modeling domain extends approximately between 32.35-32.89° E longitude and 41.54-41.87° N latitude. Elevations in the model domain range from approximately 304 m to about 1,380 m, indicating rugged topography. Slope values derived from the DEM reach up to about 73°, reflecting steep hillslopes and a dissected drainage network. The drainage area delineated to Darıören is approximately 130 km², while the official drainage area reported for the station is about 137 km² (a difference of roughly 5%).

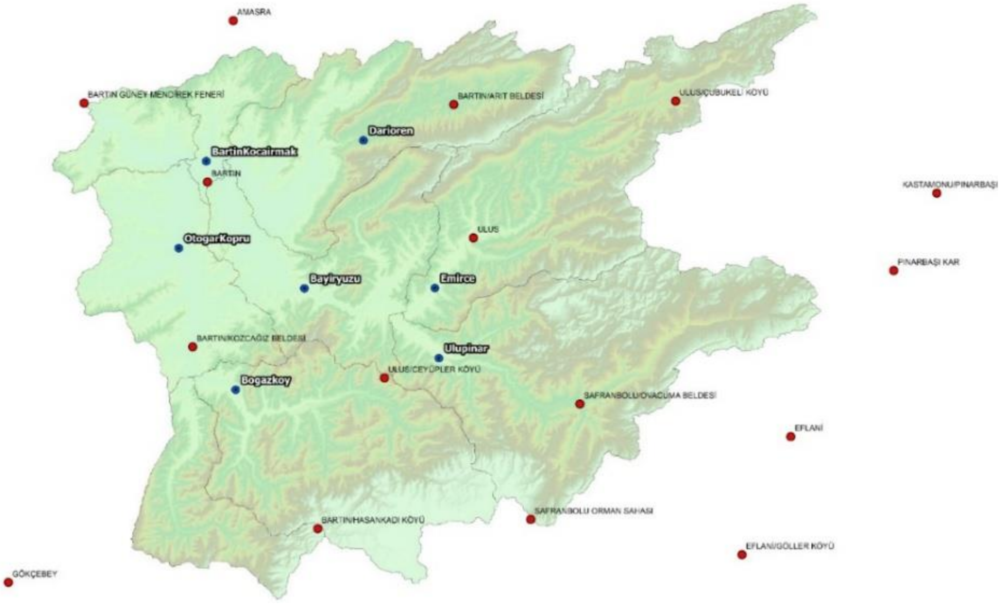


Figure 1. Study area map of the Arıt Stream Basin (Bartın, Türkiye), showing nearby Darıören.

Geological and hydrogeological setting

The basin exhibits spatially variable permeability controlled by lithology, fracture density, and weathering. Alluvial deposits in valley floors typically show relatively high permeability and storage, which can enhance recharge and support delayed groundwater contributions to streamflow. In contrast, less permeable hillslope units with finer-grained materials tend to promote a larger fraction of rainfall converting to surface runoff, potentially sharpening hydrograph peaks. Locally, more permeable interbeds may increase lateral flow and intermediate storage within the subsurface. Overall, the geological and hydrogeological framework is an important control on baseflow formation and should be considered when interpreting modeled water-balance components.

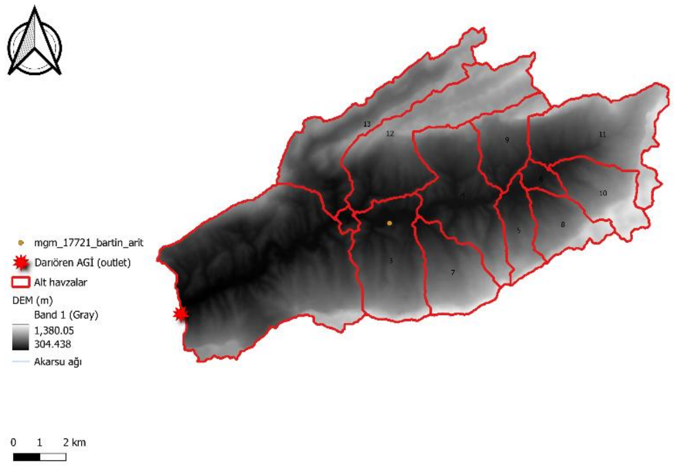


Figure 2. DEM hillshade map of the Bartın–Arıt sub-basin showing the delineated subbasins and stream network generated in QGIS using QSWAT (SWAT2012). The DSİ Darıören streamflow gauge (D13A049; outlet) and the MGM Arıt meteorological station (17721) are indicated. Projection: WGS 84 / UTM Zone 36N (EPSG:32636).

Climate

The catchment is under the maritime influence of the Black Sea and is characterized by generally humid conditions. Precipitation occurs throughout most of the year, typically increasing during autumn and winter and decreasing during summer. Orographic effects associated with the basin's rugged topography can lead to short-range spatial variability in precipitation. Temperatures are generally mild; however, the large elevation range enables snowfall and temporary snow accumulation in upper elevations during winter and transitional seasons. For model forcing, daily precipitation and maximum/minimum air temperature records from the MGM ARIT_MGM station (code 17721; 41.6872° N, 32.6156° E; elevation ~354 m) were used for the 2010-2023 period.

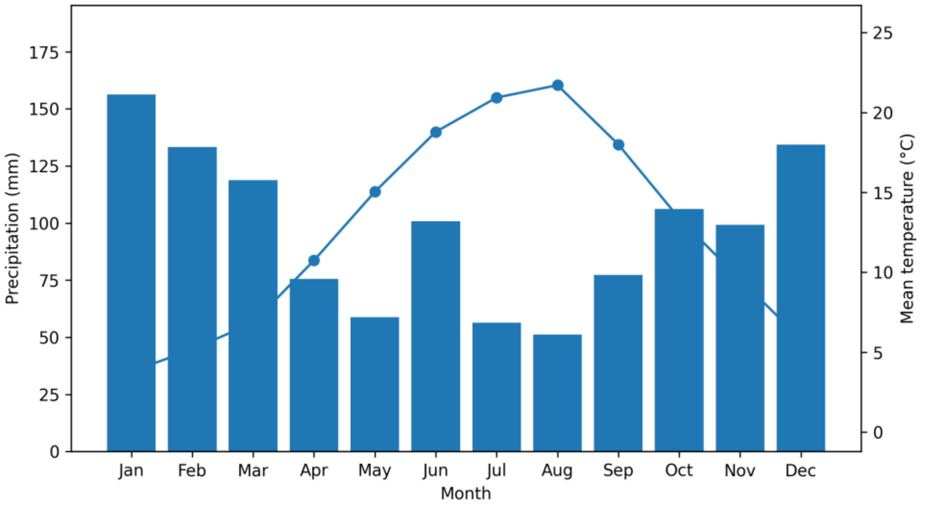


Figure 3. Monthly climate normals at the MGM Arıt station (code 17721), 2010–2023. Columns show precipitation (mm, left axis); the line shows mean temperature (°C, right axis). Warmest month: August (21.7 °C). Driest summer month: August (≈51 mm). Wettest winter month: January (≈156 mm). Classification: Cfb. Annual normals: ≈12.5 °C and ≈1168 mm.

Climate classification (Köppen–Geiger). Based on daily precipitation (PCP) and maximum–minimum air temperature (TMPmax/TMPmin) observations from the MGM Arıt meteorological station (17721) for 2010–2023, monthly climatological normals were computed by aggregating to monthly precipitation totals and monthly mean temperatures (Fig. 3). The climate of the Arıt Basin corresponds to Cfb (temperate; no dry season; warm summer): the warmest-month mean temperature is 21.7 °C (August; <22 °C) and at least four months exceed 10 °C, satisfying the "b" criterion, while the seasonal dryness thresholds are not met (P_driest_summer ≈ 51 mm in August; P_wettest_winter ≈ 156 mm in January), supporting an "f" precipitation regime. The resulting annual normals are approximately 12.5 °C for mean temperature and ~1168 mm for total precipitation.

1.2 Data Sets

This study developed a SWAT2012 hydrological model of the Arıt Stream sub-basin using the QSWAT interface in QGIS. Model setup required spatial layers (terrain, land use/land cover, and soils) and time-series inputs (meteorological forcing and observed streamflow). All spatial datasets were prepared in WGS84 / UTM Zone 36N (EPSG:32636) and aligned to a common ~25 m grid prior to import. The simulation period spans 01/01/2010–31/12/2023 at a daily time step; the first two years (2010–2011) were used as a warm-up period (NYSKIP=2) and excluded from model evaluation. Daily precipitation and temperature from the MGM Arıt meteorological station (17721) provided the primary climate forcing, while observed discharge at the DSİ Darıören gauging station was used for streamflow evaluation. A summary of datasets and key preprocessing steps is provided in Table 1.

1.3 Terrain

A Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was obtained from USGS EarthExplorer. The DEM was mosaicked and clipped to the study domain, reprojected to EPSG:32636, and resampled to ~25 m resolution for consistency with other layers. Sink filling was applied to remove spurious depressions, and flow direction and flow accumulation rasters were derived to generate the drainage network. The stream definition threshold was selected by trial (approximately 20 km²) to balance drainage density and model complexity, yielding 13 reaches and a watershed outlet snapped to the Darıören gauge. DEM statistics indicate elevations from ~25 to ~1384 m, reflecting rugged topography. Slope was derived from the DEM and classified into four bands (0–5%, 5–10%, 10–20%, and >20%) for HRU definition.

1.4 Land Use/Land Cover

Land use/land cover (LULC) was represented using the CORINE 2018 dataset (100 m). The CORINE layer was reprojected to EPSG:32636, clipped to the basin boundary, and reclassified to SWAT land-use codes using a lookup table. For spatial consistency with the DEM, the processed LULC layer was rasterized and resampled to ~25 m. LULC was assumed constant over the simulation period. Forest and agricultural classes dominate the basin and exert first-order control on interception, evapotranspiration, and runoff generation.

1.5 Soils

Soil information was derived from a global FAO-based soil dataset and prepared for SWAT2012 via QSWAT. The soil layer was reprojected to EPSG:32636, clipped to the basin, and rasterized to ~25 m. Soil codes were linked to the SWAT2012 soil database (usersoil) through the QSWAT reference database. In the final soil layer, a single dominant soil unit (soil code 3003) covers the model domain, reflecting the coarse scale of global soil products. While this provides a first-order representation suitable for a baseline model, higher-resolution soil surveys would improve parameter realism and reduce uncertainty.

1.6 Meteorological Forcing

Daily precipitation (PCP, mm) and maximum/minimum air temperature (TMPmax/TMPmin, °C) were obtained from the MGM Arıt meteorological station (code 17721; 41.6872° N, 32.6156° E; elevation ≈354 m) for 2010–2023. The Arıt station record served as the primary forcing dataset. Prior to model use, time series were checked for date continuity, unit consistency, physically plausible ranges, and missing values. Where gaps or suspicious records occurred, they were treated using the thesis data-preparation procedure (including, when required, support from nearby station records and/or SWAT's missing-data coding approach) to ensure continuous daily inputs. In QSWAT, meteorological inputs were assigned to subbasins using the default nearest-station approach.

Climate classification procedure. MGM daily observations (2010–2023) were aggregated to monthly mean temperatures and monthly precipitation totals to compute climatological normals (Figure 3). Köppen–Geiger classification was determined from these normals following standard rules for "C" climates: the a/b/c subtype is set by the warmest-month mean temperature (a if ≥22 °C; otherwise b if ≥4 months >10 °C; else c), and the f/s/w symbol is set by seasonal dryness tests (s if the driest summer month <40 mm and <1/3 of the wettest winter month; w if the driest winter month <1/10 of the wettest summer month; otherwise f). For the Arıt station, T_warmest = 21.7 °C (August), P_driest_summer ≈ 51 mm (August), and P_wettest_winter ≈ 156 mm (January), yielding Cfb. Annual normals are approximately 12.5 °C and 1168 mm.

PET data rationale. Potential evapotranspiration (PET) was computed using the Penman–Monteith method to provide a physically based estimate for the daily water balance. Because radiation, relative humidity, and wind observations were unavailable, SWAT2012's weather generator module (WXGEN) was used to generate these variables from long-term climate statistics. Weather generator statistics (WGEN_Bartin) were prepared using the WGN Statistics tool and written to the model's .wgn file, allowing Penman–Monteith PET to be calculated consistently with the available precipitation and temperature records.

Pre-processing checks. All rasters (DEM, LULC, soils, and slope) were overlaid to verify alignment and to ensure that each HRU was uniquely defined by one land-use class, one soil class, and one slope band.

HRUs were created using threshold values of 5% for land use, 5% for soil, and 10% for slope to reduce model complexity while preserving dominant landscape characteristics.

1.7 Streamflow Observations

Observed streamflow at the basin outlet was obtained from the State Hydraulic Works (DSI) Darıören streamflow gauge (D13A049) located on the Arıt Stream (41.655833° N, 32.520556° E; approximately 230 m a.s.l.). Model performance was evaluated using the monthly mean discharge series (m^3/s) for 2012–2023, with 2012–2018 used for calibration and 2019–2023 for validation.

Before model evaluation, the monthly discharge record was checked for (i) continuity and correct Jan–Dec ordering, (ii) unit consistency (m^3/s), (iii) missing months and potential measurement/transcription errors, and (iv) outliers. To keep the model–observation comparison physically consistent, a drainage-area adjustment was applied because the QSWAT delineation yielded an outlet drainage area of approximately 130 km^2, whereas DSI reports 137 km^2 for the Darıören station. Accordingly, observed discharges were scaled by 130/137 (≈0.95) prior to comparison. The adjusted observations were then matched to the corresponding outlet-reach simulations (FLOW_OUT) for monthly performance assessment in SWAT-CUP.

Table 1. Summary of input datasets used in the SWAT2012 (QSWAT) model setup and SWAT-CUP evaluation for the Bartın Arıt sub-basin (2010–2023), including data sources, spatial/temporal resolution, and key GIS/time-series preprocessing steps.

Data set	**Source / institution**	**Resolution / time step**	**Key preprocessing (summary)**
Digital Elevation Model (DEM)	USGS SRTM (EarthExplorer)	25 m	Mosaic; reproject to EPSG:32636; set NoData (-9999); clip to basin; grid alignment (DEM as reference).
Land Use / Land Cover (LULC)	Copernicus CORINE Land Cover 2018	100 m (adapted to 25 m grid)	CRS conversion; clip to basin; geometry/topology fixes; assign SWAT2012 LULC codes via lookup; rasterize to 25 m (snap to DEM).
Soil map	FAO DSMW / HWSD-based soil layer (project dataset)	Vector to 25 m raster	CRS conversion; clip to basin; define SOIL_CODE; rasterize to 25 m (snap to DEM); link to SWAT soil database via soil_lookup and usersoil.
Climate forcing (PCP / TMP)	MGM stations (primary station) + nearby station (selective completion)	Daily (2010–2023)	Calendar/unit checks; selective completion of missing/suspicious periods; convert to SWAT2012 format; assign stations in QSWAT.
Weather generator statistics (WGEN_Bartin)	Derived from station climatological statistics	WGEN parameter table	Schema/field-name checks; import to Access; define using SWAT Editor “Weather Data Definition”; generate .wgn for TxtInOut.

Data set	Source / institution	Resolution / time step	Key preprocessing (summary)
Observed streamflow (Q_obs)	DSI Darıören gauge (D13A049)	Monthly mean (2012–2023), m³/s	Time/unit checks; missing-month screening; drainage-area correction (×0.95); export to SWAT-CUP observation format.

Pre-processing checks. All spatial layers were projected to WGS84/UTM Zone 36N (EPSG:32636) and aligned to the 25 m DEM grid to avoid pixel mismatch during HRU creation. CORINE land-cover polygons were cleaned for geometry/topology errors and reclassified to SWAT2012 land-use codes using the QSWATRef2012 database. To control model complexity, HRU threshold values were set to 5% for land use, 5% for soil, and 10% for slope. Slope bands were defined as 0–5%, 5–10%, 10–20%, and >20%. Daily climate series were screened for date continuity, units, and missing records; where necessary, gaps were addressed using nearby-station support and SWAT's missing-data coding approach so that the model ran with a continuous daily forcing record.

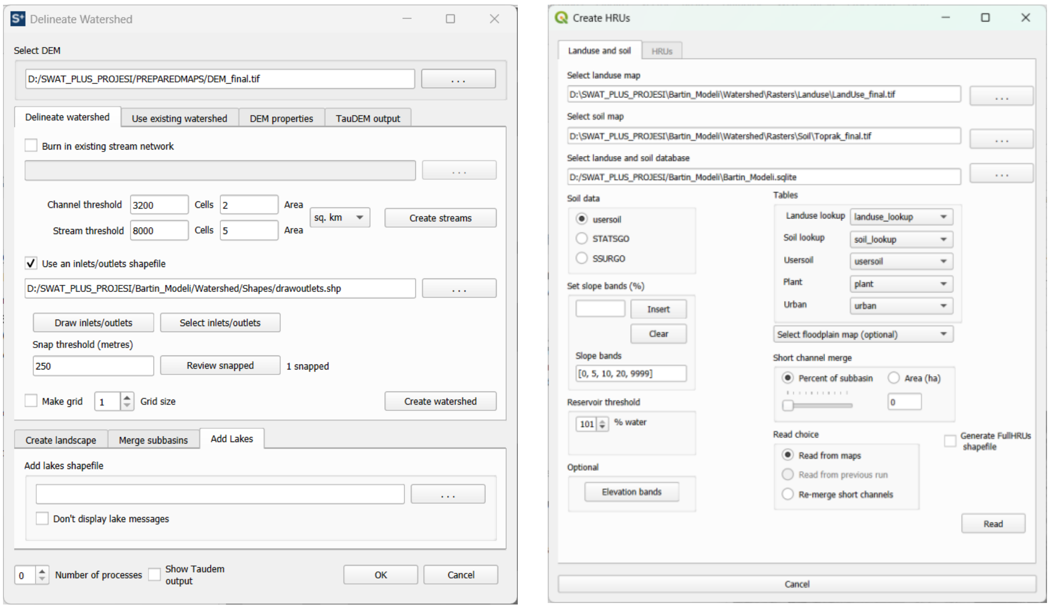
2. Methodology

2.1 SWAT Model Configuration

Hydrological processes in the Arıt Stream sub-basin were simulated using SWAT2012 (Soil and Water Assessment Tool), a physically based, semi-distributed watershed model developed for continuous, long-term simulations of streamflow and other water-balance components. In SWAT2012, a watershed is discretized into subbasins connected by a stream network, and each subbasin is further divided into Hydrologic Response Units (HRUs). HRUs represent unique combinations of land use, soil type, and slope class. Within each subbasin, HRUs are simulated independently and their simulated fluxes are aggregated (area-weighted) and delivered to the subbasin reach for routing through the channel network.

The SWAT2012 model was prepared using the QSWAT3 interface in QGIS (v1.7.2). The stream network and subbasins were derived from the 25 m DEM using a stream definition threshold of approximately 20 km², which produced 13 subbasins and 13 stream reaches. HRUs were created using 5%–5%–10% thresholds for land use, soil, and slope, respectively, and four slope classes (0–5%, 5–10%, 10–20%, and >20%). The final model configuration consisted of 68 HRUs. All spatial layers were processed in the WGS84 / UTM Zone 36N coordinate reference system (EPSG:32636) before model setup.

SWAT2012 computes the water balance at the HRU scale on a daily basis, including precipitation, surface runoff, soil-water storage, evapotranspiration, percolation, lateral flow, and groundwater return flow (baseflow). Surface runoff was estimated using the SCS Curve Number method. Snow accumulation and melt were simulated using a temperature-index (degree-day) approach; key parameters governing snow processes include SFTMP, SMTMP, SMFMX, SMFMN, and TIMP. Channel flow and routing are represented using reach geometry and hydraulic parameters such as Manning's roughness coefficient and channel hydraulic conductivity (CH_K2), which influence travel times and losses along the channel network.



Select DEM: D:/SWAT_PLUS_PROJESI/PREPAREDMAPS/DEM_final.tif
☐ Burn in existing stream network
Channel threshold 3200 Cells 2 Area
Stream threshold 8000 Cells 5 Area
sq. km
☑ Use an inlets/outlets shapefile
D:/SWAT_PLUS_PROJESI/Bartin_Modeli/Watershed/Shapes/drawoutlets.shp
Snap threshold (metres) 250
1 snapped
☐ Make grid 1 Grid size
Add lakes shapefile
☐ Don't display lake messages
0 Number of processes ☐ Show Taudem output

Select landuse map: D:\SWAT_PLUS_PROJESI\Bartin_Modeli\Watershed\Rasters\Landuse\LandUse_final.tif
Select soil map: D:\SWAT_PLUS_PROJESI\Bartin_Modeli\Watershed\Rasters\Soil\Toprak_final.tif
Select landuse and soil database: D:/SWAT_PLUS_PROJESI/Bartin_Modeli\Bartin_Modeli.sqlite
Soil data: ● usersoil ○ STATSGO ○ SSURGO
Set slope bands (%)
Slope bands [0, 5, 10, 20, 9999]
Reservoir threshold 101 % water
Optional
Tables
Landuse lookup landuse_lookup
Soil lookup soil_lookup
Usersoil usersoil
Plant plant
Urban urban
Select floodplain map (optional)
Short channel merge: ● Percent of subbasin ○ Area (ha) 0
Read choice: ● Read from maps ○ Read from previous run ○ Re-merge short channels
☐ Generate FullHRUs shapefile

(a) (b)

Figure 4. QSWAT model setup: (a) watershed delineation options used for the Arıt Basin; (b) Hydrologic Response Units (HRUs) definition with land use/soil lookups and slope bands.

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) \;+\; \gamma\left(\frac{900}{T+273}\right) u_2\,(e_s - e_a)}{\Delta \;+\; \gamma\,(1 + 0.34\,u_2)}$$

PET data rationale. Potential evapotranspiration (PET) was computed in SWAT2012 using the Penman–Monteith method. Because station observations of solar radiation, relative humidity, and wind speed were not available for the forcing station, these variables were generated using the SWAT weather generator (WGEN) based on long-term climatological statistics. This enabled a physically based PET estimate consistent with the available precipitation and temperature records.

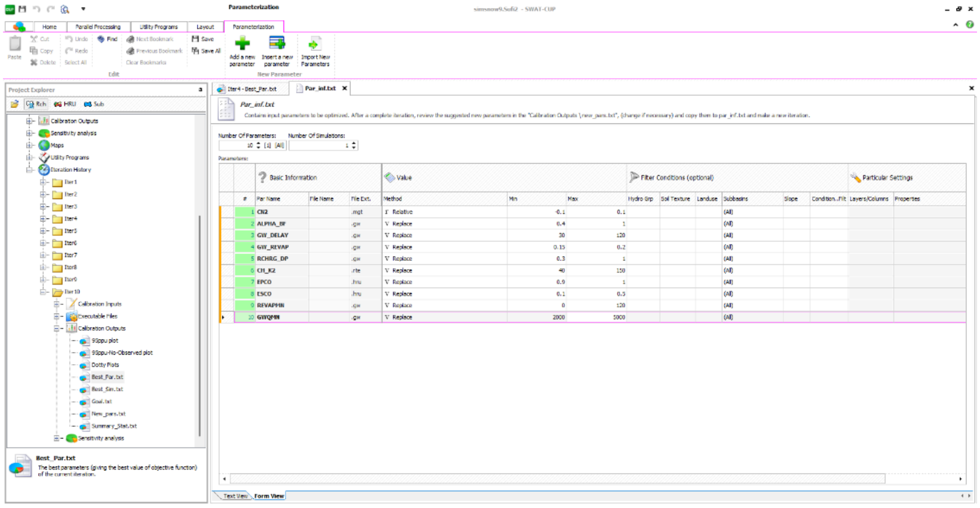
Model simulations were executed with SWAT2012 Editor (v2012.10_7), and sensitivity analysis and calibration/validation were performed in SWAT-CUP (v5.2.1) using the SUFI-2 algorithm. The model was run at a daily time step for 1 January 2010–31 December 2023. A two-year warm-up period (2010–2011; NYSKIP = 2) was applied to reduce sensitivity to initial conditions in soil moisture and groundwater storage. Model evaluation was conducted for 2012–2023 by aggregating simulated daily streamflow at the Darıören outlet (Reach 1) to monthly values, consistent with the temporal resolution used for calibration and validation.

2.2 Calibration and Validation Procedure

Calibration and validation were conducted against observed streamflow at the Darıören gauging station (DSİ, D13A049) located at the outlet of the Arıt Basin. Although the station provides a long daily discharge record (1984–2024), only the period overlapping the meteorological forcing and the model simulation window was considered. Daily discharge ($m^3\ s^{-1}$) was aggregated to monthly mean values to match the monthly evaluation scale adopted in this study. Because the SWAT2012 watershed delineation (≈130 km^2) differs slightly from the official station drainage area (137 km^2), the observed discharge series was scaled by the drainage-area ratio (Qobs × 130/137 ≈ 0.95) prior to calibration.

The model was run at a daily time step for January 2010–December 2023. The first two years (2010–2011) were treated as a warm-up period and excluded from performance assessment. The remaining record was split into an independent calibration period (2012–2018) and a validation period (2019–2023). This split-sample design allowed the parameter set obtained in calibration to be tested under an independent set of hydroclimatic conditions and reduced the risk of overfitting.

Automatic calibration was performed using SWAT-CUP with the SUFI-2 algorithm. SWAT-CUP was linked to the SWAT2012 TxtInOut directory and executed multiple model runs by sampling predefined parameter ranges using Latin hypercube sampling. The calibration variable was monthly streamflow at the outlet section representing Darıören (FLOW_OUT at Reach 1; FLOW_OUT_1 in SWAT-CUP), extracted from the SWAT2012 output.rch file. After each iteration, model performance and prediction uncertainty were evaluated, and parameter ranges were updated toward improved agreement between simulated and observed monthly flows. Monthly Nash–Sutcliffe Efficiency (NSE) was used as the primary objective function, while additional statistics (R^2, Kling–Gupta Efficiency (KGE), percent bias (PBIAS), and RMSE-based indices such as RSR) were used to support interpretation. Uncertainty was summarized using the 95% prediction uncertainty (95PPU) envelope and its p-factor (coverage) and r-factor (bandwidth) indicators. Following calibration, the final best parameter set was kept fixed and applied to the validation period without further optimization so that model robustness could be assessed under independent conditions. Figure 5 presents a representative view of the SWAT-CUP (SUFI-2) setup used for monthly streamflow calibration and validation.



Best_Par.txt
The best parameters (giving the best value of objective function) of the current iteration.

Par_inf.txt
Contains input parameters to be optimized. After a complete iteration, review the suggested new parameters in the "Calibration Outputs \new_pars.txt", (change if necessary) and copy them to par_inf.txt and make a new iteration.

Number Of Parameters: 10 [1] [All]
Number Of Simulations: 1

Parameters:

Basic Information				Value			Filter Conditions (optional)						Particular Settings	
#	Par Name	File Name	File Ext.	Method	Min	Max	Hydro Grp	Soil Texture	Landuse	Subbasins	Slope	Condition..Filt	Layers/Columns	Properties
1	CN2		.mgt	r Relative	-0.1	0.1				(All)				
2	ALPHA_BF		.gw	V Replace	0.4	1				(All)				
3	GW_DELAY		.gw	V Replace	30	120				(All)				
4	GW_REVAP		.gw	V Replace	0.15	0.2				(All)				
5	RCHRG_DP		.gw	V Replace	0.3	1				(All)				
6	CH_K2		.rte	V Replace	40	150				(All)				
7	EPCO		.hru	V Replace	0.9	1				(All)				
8	ESCO		.hru	V Replace	0.1	0.5				(All)				
9	REVAPMN		.gw	V Replace	0	120				(All)				
10	GWQMN		.gw	V Replace	2000	5000				(All)				

Figure 5. SWAT-CUP (SUFI-2) interface illustrating the calibration–validation setup for monthly streamflow at Darıören (warm-up: 2010–2011; calibration: 2012–2018; validation: 2019–2023) and the tested parameter ranges.

2.3 Calibration Strategy

Calibration was conducted with a focused set of hydrological parameters rather than adjusting a large number of variables simultaneously. The selected parameters were chosen to represent the dominant processes controlling monthly discharge at the basin outlet: (i) surface runoff generation (CN2), (ii) shallow aquifer storage and baseflow response (ALPHA_BF, GW_DELAY, GWQMN, GW_REVAP, REVAPMN, and RCHRG_DP), (iii) evapotranspiration partitioning via soil evaporation and plant uptake (ESCO and EPCO), and (iv) channel transmission losses and seepage (CH_K2). Preliminary trials also considered additional parameters (e.g., SOL_AWC and SURLAG); however, sensitivity checks indicated a relatively limited influence on the objective function, so later iterations placed more emphasis on groundwater and channel parameters.

In SWAT-CUP, parameter updates follow a prefix notation that specifies how the change is applied. The r__ prefix indicates a relative (proportional) adjustment to existing parameter values, while the v__ prefix replaces the parameter with an absolute value for the corresponding file group (mgt, gw, hru, or rte).

For example, r__CN2.mgt = −0.05475 corresponds to an approximately 5.5% reduction applied to the baseline CN2 values. Initial parameter ranges were selected to remain physically plausible and were kept broad in the first SUFI-2 runs; ranges were then progressively refined as performance improved. Range updates were guided by the monthly NSE objective function together with the SUFI-2 uncertainty diagnostics (95PPU coverage and band width). Before accepting a calibration run, the parameter type (r or v), enable status, and file–parameter mapping were checked to ensure that updates were actually applied. The final best parameter set (Best_Par) was then fixed and used without further adjustment in the validation period.

Table 2. Calibration parameters, update type, search ranges, and best values (Best_Par) used in SWAT-CUP (SUFI-2).

Parameter (SWAT-CUP code)	**Update type**	**Unit**	**Calibration range**	**Best value (Best_Par)**	**Hydrological role / expected effect on flow**
r__CN2.mgt	r__ (relative)	—	−0.20 … +0.20	−0.05475	Surface runoff potential
v__ALPHA_BF.gw	v__ (replace)	1/day	0.00 … 1.00	0.22680	Baseflow recession
v__GW_DELAY.gw	v__ (replace)	day	0 … 100	30.90	Groundwater delay
v__GW_REVAP.gw	v__ (replace)	—	0.02 … 0.20	0.13720	Shallow aquifer revap
v__RCHRG_DP.gw	v__ (replace)	—	0.00 … 1.00	0.15690	Deep percolation fraction
v__GWQMN.gw	v__ (replace)	mm	0 … 5000	1764.50	Threshold for return flow
v__REVAPMN.gw	v__ (replace)	mm	0 … 500	159.80	Threshold for revap
v__EPCO.hru	v__ (replace)	—	0.50 … 1.00	0.92060	Plant uptake compensation
v__ESCO.hru	v__ (replace)	—	0.50 … 1.00	0.65430	Soil evaporation compensation
v__CH_K2.rte	v__ (replace)	mm/hr	0 … 200	172.07	Channel seepage / transmission loss

3. Results and Discussion

3.1 Model Performance Evaluation

Model performance was evaluated by comparing simulated and observed monthly discharge at the Darıören outlet. The SWAT-CUP statistics for the calibration (2012–2018) and validation (2019–2023) periods are summarized in Table 3.

For the calibration period, the model achieved NSE = 0.79 and R^2 = 0.84, indicating that the seasonal and interannual variability of monthly flows is reproduced well. The Kling–Gupta Efficiency (KGE) of 0.71 and RSR of 0.46 further support good overall agreement on a monthly basis.

In the validation period, performance remained similar (NSE = 0.78; R^2 = 0.83; KGE = 0.70; RSR = 0.47). The close agreement between calibration and validation suggests that the parameter set is transferable and the model is not overly tuned to a single period.

PBIAS values were −16.9% (calibration) and −20.9% (validation), indicating a systematic tendency to overestimate total monthly discharge volume. This bias should be kept in mind when the model is used for applications that depend on absolute water volumes, even though the timing and relative variability are captured satisfactorily.

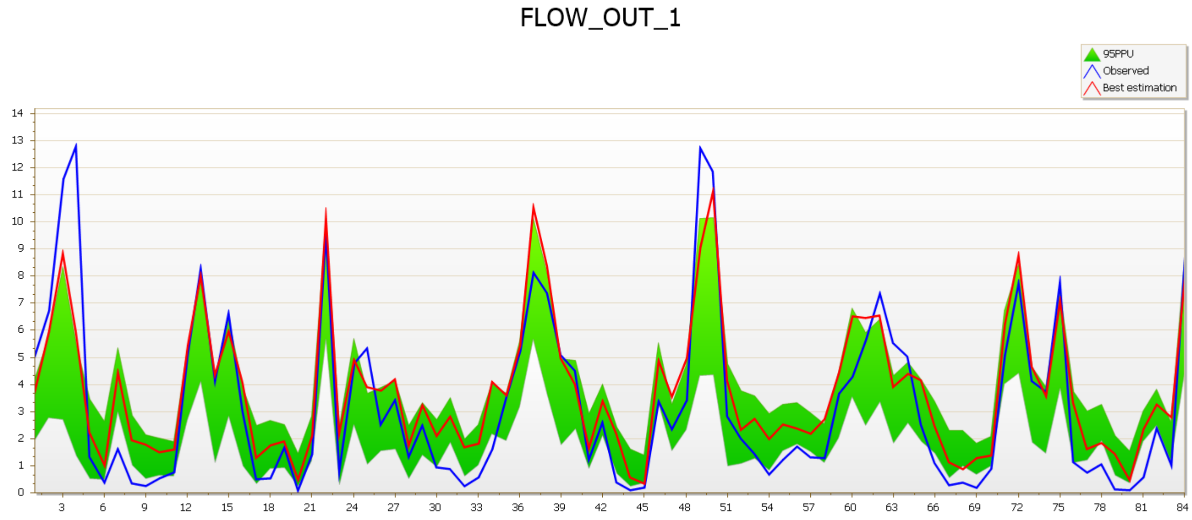
Uncertainty diagnostics for the calibration period yielded p-factor = 0.58 and r-factor = 0.75, meaning that 58% of the observed monthly flows were bracketed by the 95PPU band with a moderate band width. In the validation period, only a single simulation was run with the best parameter set; therefore, the 95PPU band (and p-/r-factors) was not produced.

Figure 6 presents the observed and simulated monthly hydrographs for both periods and illustrates that the model captures the main seasonal pattern, while some high-flow months are overestimated, consistent with the negative PBIAS values.

Table 3. Monthly streamflow performance statistics at Darıören (FLOW_OUT_1).

Period	**NSE**	**R^2**	**KGE**	**RSR**	**PBIAS (%)**	**p-factor**	**r-factor**
Calibration (2012–2018)	0.79	0.84	0.71	0.46	−16.9	0.58	0.75
Validation (2019–2023)	0.78	0.83	0.70	0.47	−20.9	—	—

Note: NSE = Nash–Sutcliffe Efficiency; R^2 = coefficient of determination; KGE = Kling–Gupta Efficiency; RSR = RMSE/standard deviation of observations; PBIAS = percent bias; p-factor and r-factor are SUFI-2 95PPU uncertainty measures (reported for calibration only).



(a) calibration

Iter5 - 95ppu plot

The 95ppu of all variables. Also shown are observations and best simulation of the current iteration.

95ppu plot

The 95ppu of all variables. Also shown are observations and best simulation of the current iteration.

Parallel Processing License Status: Limited | SWAT Version: 2012, Processor Architecture: 64-bit

(b) validation

Figure 6. Observed and simulated monthly discharge at Darıören: (a) calibration (2012–2018); (b) validation (2019–2023).

3.2 Flow Dynamics and Model Behavior

In addition to the summary performance statistics (Table 3), observed–simulated hydrographs and two distribution-based diagnostics were examined to diagnose model behavior across different parts of the flow regime. Specifically, the monthly hydrographs (Figure 6), 1:1 scatter plots (Figure 7), and flow-duration curves (FDC; Figure 8) were used to identify where the calibrated SWAT2012 setup reproduces the observed dynamics well and where systematic discrepancies persist.

The monthly hydrographs indicate that the model reproduces the dominant seasonal signal of the Arıt Basin in both calibration (2012–2018) and validation (2019–2023). Wet-season flow increases and dry-season recessions occur in phase with the observations, demonstrating that the timing of the basin-scale response is represented credibly at the monthly time step. The overall similarity of hydrograph behavior between the two periods is consistent with the stable performance metrics across calibration and validation, suggesting that the calibrated parameter set generalizes to independent conditions rather than relying on a narrow set of months.
Low-flow behavior is represented reasonably well at monthly resolution. Extended low-flow periods evident in the observations are reflected in the simulations, indicating that groundwater storage and recession processes sustain discharge during rain-free months rather than producing an unrealistically "flashy" response. At the same time, the negative PBIAS values reported for both periods imply a systematic tendency to simulate higher total discharge volumes than observed. This points to a modest overestimation tendency, which is consistent with slightly elevated simulated baseflow and/or mid-range flows in some months.

High-flow months show mixed agreement, which is common for small, steep, and humid catchments evaluated at monthly resolution. Many wet-season peaks are reproduced in general magnitude and seasonal timing, but some high-flow months are over-simulated, consistent with the negative PBIAS. Several factors can contribute to this pattern. First, the basin is forced by a single meteorological station, so spatially localized intense precipitation may not be represented proportionally in the basin-average forcing. Second, the daily SCS-CN runoff formulation and subsequent monthly aggregation can smooth event variability and shift part of the response into adjacent months. Third, uncertainties in soil hydraulic properties and groundwater parameters can translate into a small but persistent volume bias.

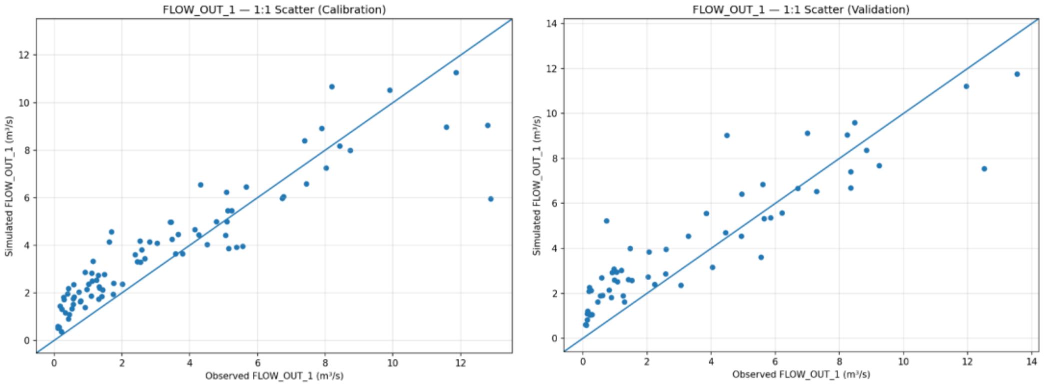


Figure 7. 1:1 scatter of observed vs. simulated monthly discharge (m³ s⁻¹): calibration (2012–2018); validation (2019–2023). Solid line = 1:1; dashed line = least-squares fit

The 1:1 scatter plots (Figure 7) provide an integrated, flow-range-wide check of model–observation agreement. In both calibration and validation, the point cloud generally clusters around the 1:1 line, indicating that the model reproduces low and medium flows without strong distortion and maintains a robust linear association with the observations ($R^2 \approx 0.84$ for calibration and 0.83 for validation). Given the negative PBIAS, a limited tendency for points to fall above the 1:1 line is expected—particularly for the higher-discharge months—indicating modest overestimation during some wet months.

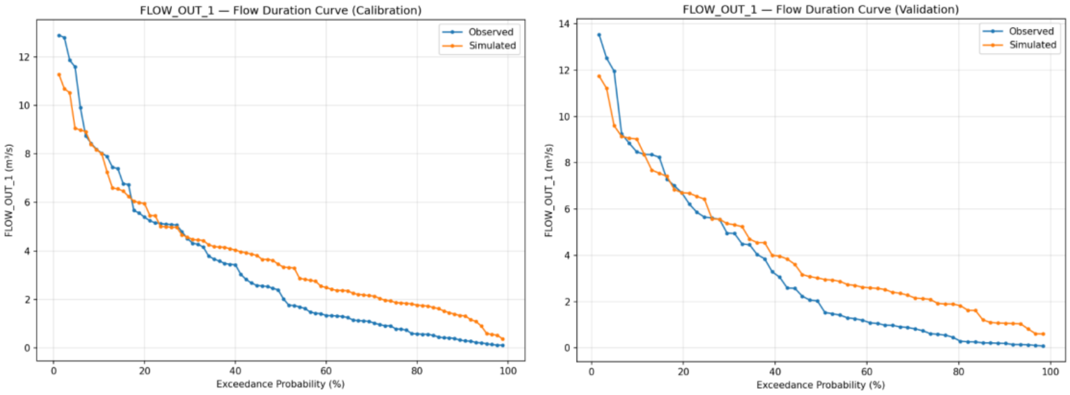


Figure 8. Flow-duration curves (FDC) of observed and simulated monthly discharge for calibration and validation periods, used to assess model behavior across high-flow, mid-flow, and low-flow regimes.

Flow-duration curves (Figure 8) complement the scatter plots by assessing the full discharge distribution via exceedance probability. The simulated and observed curves follow a similar overall shape, indicating that the model captures the structure of the basin's flow regime (high-flow tail, mid-range flows, and low-flow behavior). Where the simulated curve lies above the observed curve, discharge is overestimated; where it lies below, discharge is underestimated. In this study, the FDC was used particularly to check whether there was a distinct divergence in the low-flow end of the distribution and to assess the physical consistency of baseflow-related parameters. Close agreement in the low-flow region supports a realistic recession behavior, while any persistent separation would indicate bias in groundwater contributions.

Taken together, the hydrographs, scatter plots, and flow-duration curves reinforce the conclusions drawn from the numerical metrics: the calibrated SWAT2012 model provides a consistent and transferable representation of monthly streamflow dynamics at the Darıören outlet.

The remaining discrepancy is primarily systematic (a modest overestimation tendency, reflected by negative PBIAS) rather than erratic year-to-year instability. This behavior is suitable for monthly water-budget interpretation and scenario impact assessment; however, applications that require stronger reproduction of extremes (flood peaks or very low flows) would benefit from finer-resolution inputs, additional stations, and/or objective functions that explicitly weight the tails of the flow distribution.

3.3 Comparison with Literature and Implications

The monthly streamflow performance achieved in this study is consistent with ranges commonly reported for SWAT-based watershed simulations. Following widely used evaluation guidelines (e.g., Moriasi et al., 2007), the calibration and validation statistics (NSE = 0.79 and 0.78; RSR = 0.46 and 0.47) indicate good performance at the monthly time step, while the |PBIAS| values (16.9–20.9 %) suggest a systematic bias (overestimation under the sign convention adopted in this study) that remains within a commonly accepted “satisfactory” class for monthly discharge.

In the context of SWAT applications in Türkiye, the Arıt results also fall within typical reported ranges. For instance, the national review by Peker and Cüceloğlu (2022) summarizes that many Turkish SWAT studies obtain monthly NSE values on the order of ~0.5–0.8 under diverse physiographic conditions. Higher NSE values are sometimes achieved in larger or less flashy basins or with denser monitoring networks (e.g., Duru et al., 2018), highlighting the influence of basin scale, hydroclimatic variability, and data availability on achievable skill.

From an application standpoint, the calibrated model is most defensible for monthly to seasonal analyses such as water-yield interpretation, drought-sensitivity screening, and comparative scenario assessments (climate variability and land-management alternatives). However, the persistent bias and the annual water-balance diagnostics (low simulated evapotranspiration and relatively high runoff coefficients in the annual summaries) indicate that further improvements in meteorological forcing representativeness and independent constraints on evapotranspiration (e.g., satellite-based ET products) would strengthen the physical realism of the basin water balance. Accordingly, results should be interpreted cautiously when absolute flow volumes are required, and flood-focused applications would require dedicated evaluation and calibration at daily/event scales.

4. Conclusions and Future Work

This study developed, calibrated, and validated a SWAT2012 hydrological model for the Arıt Stream sub-basin and evaluated its monthly discharge at the Darıören outlet for 2012–2023, with 2010–2011 used as a warm-up period. Calibration and validation were performed in SWAT-CUP using the SUFI-2 algorithm (2012–2018 calibration; 2019–2023 validation). The model achieved NSE ≈ 0.79 in calibration and 0.78 in validation, with R^2 ≈ 0.84–0.83, KGE ≈ 0.71–0.70, and RSR ≈ 0.46–0.47, indicating good monthly skill and consistent transferability between periods.

- The SWAT2012 model reproduces the seasonal pattern of monthly streamflow at the basin outlet and demonstrates stable performance in an independent validation period, supporting its use as a baseline for scenario comparisons and planning studies.

- PBIAS values (−16.9 % calibration; −20.9 % validation) indicate a persistent discharge overestimation under the adopted sign convention; this bias should be considered when interpreting absolute volumes and water-balance components.

- Annual water-balance diagnostics point to low simulated evapotranspiration and relatively high runoff coefficients, implying that additional forcing data and evapotranspiration constraints would improve the physical consistency of the simulated water balance.

4.1 Climate Change Impact Analysis

The calibrated SWAT2012 setup provides a baseline for climate-impact studies in the basin. Future work can force the model with bias-corrected climate projections to quantify potential changes in seasonal water availability, drought severity, and the frequency of high-flow months. Scenario design can follow established SWAT climate-impact workflows in Türkiye (e.g., Özdemir et al., 2024), with emphasis on ensemble projections and uncertainty reporting.

4.2 Land Use Change Scenarios

Land-use and land-management scenarios (e.g., forest management changes, conversion between forest and agriculture, or localized urban expansion) can be explored by modifying land-cover inputs to assess impacts on runoff generation, baseflow contribution, and total water yield. Such scenario runs can support basin-scale planning by quantifying hydrologic trade-offs and identifying changes that increase flood sensitivity or reduce dry-season flows.

4.3 Water Quality and Erosion Modeling

Although the present study focused on streamflow, the same SWAT2012 framework can be extended to sediment and nutrient simulations when suitable monitoring data become available for calibration. This would allow identification of erosion-prone areas and evaluation of best management practices (e.g., riparian buffers, slope stabilization, reduced soil disturbance) to reduce sediment and nutrient delivery to the stream network.

4.4 Water–Energy Nexus Analysis

The Arıt Stream is a headwater tributary within the Bartın River system, and its flow regime can influence downstream water uses and potential small-scale hydropower opportunities. The calibrated SWAT2012 model produces continuous daily discharge time series at the basin outlet, which can be post-processed to (i) build flow-duration curves, (ii) estimate firm and mean energy production for candidate run-of-river schemes, and (iii) test the reliability of environmental-flow constraints under alternative scenarios. A practical next step is to couple SWAT-derived discharge series with a dedicated hydropower screening workflow; for example, Garcia et al. (2024) demonstrate a SWAT+-based framework (S+HydPower) that evaluates climate- and management-driven changes in hydropower generation while accounting for environmental flows. A comparable post-processing approach can be applied using the Arıt SWAT2012 outputs to explore trade-offs between energy production, low-flow reliability, and ecological flow requirements under combined climate and land-use scenarios.

Because hydropower feasibility is sensitive to low-flow conditions and short-term variability, the water–energy analysis should rely on daily simulations and should include additional verification of the model’s low-flow behavior (and any systematic volume bias) before translating discharge series into power estimates. Where possible, incorporating additional meteorological stations or gridded climate products, and improving local soil and groundwater characterization, would help reduce uncertainty in dry-season flows—typically the limiting factor for run-of-river schemes.

Overall, this study demonstrates that a SWAT2012 model can be implemented for the Arıt Stream Basin using a single-station meteorological forcing and the available DSİ discharge record, and can reproduce monthly discharge dynamics at a satisfactory level for planning applications. Monthly calibration and validation yielded NSE = 0.79 and 0.78, respectively, with RSR ≈ 0.46–0.47, while PBIAS indicates a systematic overestimation of streamflow (−16.9 % to −20.9 %). These results support the use of the model for relative, scenario-based assessments (e.g., direction and magnitude of change in seasonal water yield) but also suggest that absolute volumetric estimates should be interpreted with care, particularly during low-flow periods. Future work that adds multi-station climate forcing, improves representation of soils and groundwater processes, and evaluates daily flow extremes would strengthen the model’s applicability for flood- and drought-focused analyses and for water–energy nexus studies.

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