Remote Sensing Supported SWAT Water Budget Analysis for Çınar (Diyarbakır, Türkiye): Flood Risk and Sustainable Watershed Management

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Abstract. This contribution synthesizes a SWAT (Soil and Water Assessment Tool) application for the semi-arid Çınar district (Diyarbakır, Türkiye), where remote-sensing-supported inputs are used to interpret water-balance components in relation to flood risk and sustainable watershed management. The model integrates SRTM-based DEM, supervised land-use/land-cover classification, FAO soil maps, and daily NASA POWER meteorological data, and is calibrated and validated for streamflow and basin water budget using PBIAS, NSE, and RSR within satisfactory–good ranges. The simulated water balance indicates mean annual precipitation of ~601.2 mm, with ~301.4 mm returning to the atmosphere as actual evapotranspiration versus PET of ~985.3 mm, confirming a water-limited regime. Surface runoff (~117.4 mm; 19.5% of rainfall), lateral flow (~18.1 mm; 3.0%), and baseflow (~102.6 mm; 17.1%) together account for ~39.6% of precipitation, while percolation to the shallow aquifer (~114.28 mm; 19.0%) dominates groundwater processes. An average CN of ~78.85, combined with nearly 20% of rainfall becoming quick runoff, signals rapid hydrograph response to intense storms and associated flash-flood potential. These outcomes support conservation agriculture and nature-based solutions—such as infiltration-enhancing practices on croplands, hillslope measures, riparian-buffer rehabilitation, and low-impact development—to reduce CN, enhance infiltration, sustain baseflow, and mitigate flood peaks within an integrated watershed-management framework for Çınar.

Keywords: Remote Sensing, Remote SWAT, Sustainable Water Budget.

1 Introduction

Semi-arid river basins face growing structural water scarcity due to climatic variability, high evaporative demand and intensifying human pressures, especially irrigation. In many Mediterranean and Near Eastern basins, irrigation dominates water withdrawals, while irregular rainfall and long dry seasons reduce the reliability of surface and groundwater resources [1]. These conditions require sustainable management approaches that both quantify current water budgets and clarify how land use, infrastructure and climate jointly modify runoff generation, aquifer recharge and low-flow regimes at the watershed scale.

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Physically based, distributed hydrological models such as the Soil and Water Assessment Tool (SWAT) provide a powerful framework for representing these interactions across heterogeneous topography, soils and land-use mosaics. SWAT has been widely applied to assess water availability, sediment transport and management impacts in a broad range of climatic and physiographic settings [2]. Recent reviews focusing on arid and semi-arid environments highlight its particular value in data-scarce regions, where the integration of remotely sensed inputs (e.g. land use/land cover, surface water extent, vegetation indices) can partly compensate for sparse ground observations and still yield robust simulations of streamflow and water balance components [3,4].

The evolution toward the SWAT+ framework reflects a move to models that better represent complex land and water management systems under changing climate and land-use conditions. In Mediterranean-type watersheds, SWAT and SWAT+ have been used to assess how projected temperature and precipitation changes modify water balance partitioning - typically indicating reduced water yield and shifts between runoff and evapotranspiration under future scenarios [5,6] - while high-resolution optical satellite data enable supervised land-cover classification (agriculture, rangeland, urban areas, water bodies) and enhance the spatial representation of interception, infiltration and actual evapotranspiration in these models.

A further prerequisite for reliable simulations in data-limited regions is the use of consistent meteorological forcing. Satellite and reanalysis products such as NASA POWER provide spatially continuous time series of precipitation, temperature, radiation, wind speed and humidity that can directly force SWAT-type models, and have been shown to reproduce key climatic variables with sufficient accuracy for agro-hydrological applications [7], with recent studies in Türkiye also reporting good agreement with ground observations across diverse climate zones [8]. At the same time, SWAT applications demonstrate that uncertainties in climate forcing, land-cover data and parameterization can substantially affect simulated runoff, evapotranspiration and groundwater, underscoring the need for careful calibration and validation [9].

Within this broader context, semi-arid basins of southeastern Türkiye draining to the Upper Tigris are hydrologically vulnerable systems where agricultural intensification, climatic pressures and limited monitoring infrastructure coincide. The Çınar district of Diyarbakır is a representative case, with seasonally concentrated rainfall and intense convective storms that can trigger damaging floods. Following established modelling practice and evaluation guidelines [10], and using NASA POWER-based meteorological data together with satellite-derived land use/land cover and globally consistent soil and topographic datasets, this study develops a remote sensing-supported SWAT model for the Çınar sub-basin. The specific objectives are to (i) characterize the seasonal precipitation–runoff behaviour of the basin, (ii) quantify the relative contributions of surface and subsurface processes to water yield under semi-arid conditions, and (iii) interpret these dynamics in relation to flood risk and sustainable watershed management in the Upper Tigris context.

2 Materials and Methods

The study area is the semi-arid Çınar sub-basin in Diyarbakır (southeastern Türkiye), where rainfed and irrigated cropland, rangeland and small urban settlements dominate a gently sloping plain–foothill system. Hydrological processes were simulated with the semi-distributed, continuous-time Soil and Water Assessment Tool (SWAT), which is designed for basin-scale assessment of water balance and management impacts [11].

Topography was represented with the 30 m Shuttle Radar Topography Mission (SRTM) digital elevation model, projected to WGS84/UTM Zone 37N and processed in SWAT for watershed delineation, stream-network extraction and slope classes [12]. The suitability of 30 m SRTM data for basin morphometry and drainage-network derivation in hydrological studies is well documented, especially when combined with basic quality control and hydrologic conditioning [13]. Soil physical properties (texture, available water capacity, bulk density, hydraulic conductivity) were taken from the FAO Digital Soil Map of the World and translated to SWAT soil parameters using standard large-scale model setup procedures.

Land use/land cover (LULC) information was derived from Landsat 8 OLI/TIRS imagery (30 m) using supervised maximum likelihood classification. Training samples were defined to separate major classes (cropland, rangeland/grassland, urban/peri-urban and open water), and classification accuracy was checked against high-resolution visual interpretation. Maximum likelihood and related supervised schemes are widely used for agricultural and semi-arid land-cover mapping with Landsat-type data and have shown robust performance when classes are spectrally separable and training data are representative [14,15].

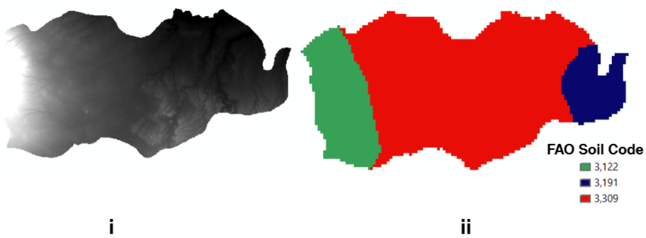

Fig. 1. (i) Digital Elevation Model (DEM) and (ii) soil map of study area .

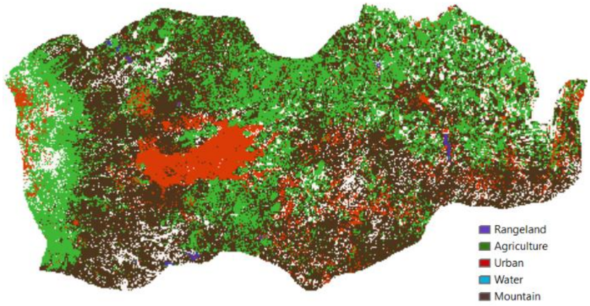

Fig. 2. Land use map of study area .

Daily meteorological forcing (precipitation, maximum and minimum air temperature, relative humidity, wind speed and shortwave radiation) was obtained from the NASA POWER database for a representative point over the basin and converted to SWAT input files using the nasapower workflow [16]. NASA POWER reanalysis products are generally suitable for agro-hydrological applications under sparse ground observations, with good agreement for temperature and radiation and acceptable performance for humidity and wind in many climates [17,18]. The resulting time series were checked for missing or inconsistent values and used as spatially uniform inputs that SWAT internally distributes to the hydrologic response units (HRUs).

SWAT was set up to simulate surface runoff, infiltration and percolation, soil-moisture dynamics, shallow and deep groundwater flow, and evapotranspiration under semi-arid agricultural conditions. HRUs were defined as unique combina-tions of LULC, soil and slope using thresholds selected to preserve dominant cropland patterns while limiting complexity, in line with large-basin SWAT practice [19]. Streamflow at the basin outlet was used for calibration and validation after a warm-up period to stabilize soil and groundwater storages. The model was run for 2000–2024, with 2000–2010 used for calibration and 2011–2024 for validation. Parameter optimization and uncertainty analysis were performed with the SUFI-2 algorithm in SWAT-CUP, targeting sensitive parameters governing runoff generation, soil water storage and baseflow. Model performance was assessed using NSE, R^2, PBIAS and RSR, following recommended SWAT calibration and uncertainty-analysis protocols [20].

3 Results

The calibrated SWAT model reproduced daily streamflow at the Çınar basin outlet with performance statistics in the "satisfactory–good" range, yielding NSE = 0.516, R^2 = 0.501 and PBIAS = −9.21% for the validation. PBIAS thus remains within accepted limits for monthly flows, and these results are comparable to SWAT applications in other semi-arid and mountainous basins, where NSE typically > 0.5 and PBIAS is within ±15–20% [21], supporting the use of the model for diagnostic basin water-balance analysis.

The long-term water-balance analysis indicates a mean annual precipitation of ~601.2 mm in the Çınar basin. About half returns to the atmosphere as actual evapotranspiration (ET ≈ 301.4 mm), while potential evapotranspiration is much higher (PET ≈ 985.3 mm), confirming a structurally water-limited regime. Surface runoff (SURQ ≈ 117.4 mm; ~19.5% of P), hillslope lateral flow (LATQ ≈ 18.1 mm; ~3.0%) and baseflow (GW_Q ≈ 102.6 mm; ~17.1%) together sum to ~39.6% of annual precipitation, indicating that roughly two-fifths of rainfall is routed to streamflow. Percolation to the shallow aquifer is ~114.3 mm (~19.0% of P), whereas deep-aquifer recharge is minor (~6.4 mm; ~1.1%), pointing to predominantly shallow groundwater circulation. The basin-average Curve Number (CN ≈ 78.85) indicates moderate-to-high runoff potential, and revap from the shallow aquifer to the root zone (~16.5 mm) highlights the role of shallow groundwater in supporting vegetation during dry periods.

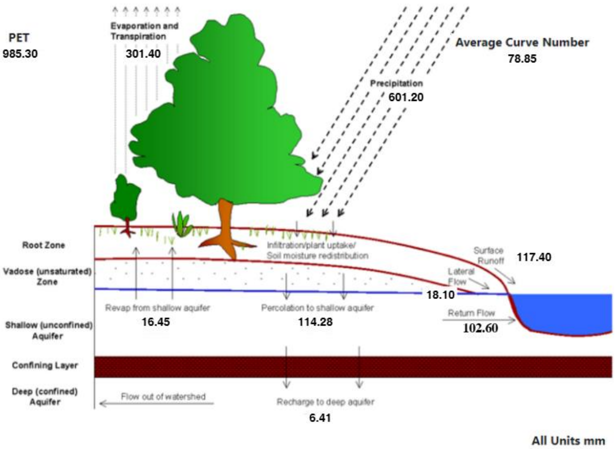

Fig. 3. Hydroclimatic and hydrological setting of the Çınar watershed.

The obtained partitioning between surface runoff, lateral flow, baseflow and evapotranspiration is consistent with SWAT-based water-balance studies at sub-catchment scale in other semi-arid environments, where actual evapotranspiration commonly consumes 40–60% of annual precipitation and combined surface–subsurface flows represent 30–50% of the water budget [22]. Likewise, the magnitude of percolation to shallow aquifers relative to deep recharge is comparable to values reported for semi-arid basins in North Africa and Southwest Asia, where shallow groundwater systems respond sensitively to land-use and climate perturbations [23,24].

From a hydrological response perspective, the combination of CN near 79 and the fact that nearly one-fifth of rainfall is transformed directly into surface runoff suggests a propensity for rapid hydrograph rise during short, high-intensity storm events. Similar behaviour—characterized by flashy runoff, elevated event-scale runoff coefficients and strong sensitivity of peak flow to curve-number parameterization—has been documented in SWAT applications to semi-arid basins with comparable soil and land-use conditions [25]. In Çınar, this structural tendency, together with the limited deep recharge, indicates that flood peaks are primarily controlled by near-surface processes and shallow aquifer dynamics rather than by long-term groundwater storage, a result that is critical for subsequent flood-risk and management-oriented interpretations. Open-water features are strongly aligned with ephemeral and seasonal stream corridors, as well as with engineered water bodies such as irrigation ponds and small reservoirs. This spatial organization is typical of semi-arid basins in which surface-water storage is localized and closely tied to both topography and infrastructure.

4 Conclusion

This study developed a remote sensing–supported SWAT model for the semi-arid Çınar basin in the Upper Tigris region using freely available global datasets (SRTM, FAO soil maps, Landsat-derived LULC and NASA POWER meteorology). The model achieved satisfactory performance in reproducing daily streamflow at the basin outlet, with NSE = 0.516, R^2 = 0.501 and PBIAS = −9.21%, which fall within commonly accepted thresholds for SWAT applications in semi-arid and mountainous catchments [10,21]. Long-term water-balance results indicate a structurally water-limited regime, in which approximately half of the mean annual precipitation is lost as evapotranspiration, while surface runoff, hillslope lateral flow and shallow-aquifer baseflow together convert roughly two-fifths of rainfall into streamflow. Limited deep-aquifer recharge and a relatively high basin-average Curve Number point to hydrological behaviour dominated by near-surface and shallow groundwater processes.

From a flood-risk perspective, the combination of seasonally concentrated rainfall, intense convective storms and moderate-to-high runoff potential implies a sensitivity to rapid runoff generation and flash-flood response, particularly on cultivated slopes and along ephemeral channels. In this context, conservation-oriented land and water management practices—such as conservation tillage, residue management, contour farming, small farm ponds and check dams, and the restoration of riparian buffer strips—can help reduce peak flows, enhance infiltration and support the buffering capacity of shallow aquifers. At the same time, the modelling framework demonstrated here illustrates how SWAT, driven by NASA POWER and satellite-derived land surface information, can provide physically based diagnostics of water-balance components in data-scarce semi-arid basins.

Future work could incorporate time-varying LULC maps, explicit representation of irrigation and small reservoirs, and scenario-based land-use and climate analyses, further enhancing the role of SWAT-type models as decision-support tools for flood risk mitigation and sustainable watershed management in the Upper Tigris and other semi-arid regions.

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