SWAT+ hydrological modelling and remote sensing analysis to estimate surface water balance and groundwater recharge in the High Atlas of Marrakech and the Haouz plain (Morocco)

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Abstract

Groundwater resources in the Haouz–Mejjate aquifer (central Morocco) are under increasing pressure from anthropogenic abstraction and climate variability. Recharge from the High-Atlas headwaters of the Tensift basin is the main natural input to the aquifer, yet it remains poorly quantified in space and time. This study uses the SWAT+ hydrological model coupled with a remote-sensing water-balance approach to estimate the surface water balance and groundwater recharge of the Ourika watershed, gauged at the Aghbalou outlet. The model was set up from a 30 m SRTM DEM, FAO soil units, ESA WorldCover land cover, and fourteen meteorological stations operated by ABHT, covering the period 2000–2018. A literature-informed sensitivity analysis identified CN2, ESCO, ALPHA_BF, GW_DELAY and GWQMN as the most influential parameters for streamflow at the Aghbalou outlet, consistent with semi-arid Mediterranean SWAT/SWAT+ studies. Calibration against monthly observed discharge (2002–2010) and validation (2011–2018) yielded NSE = 0.82 / 0.81, KGE = 0.90 / 0.85 and PBIAS = -5.1 % / -4.6 %, classified as “good” to “very good” per Moriasi et al. (2007, 2015). Mean annual recharge is approximately 35 mm yr^{-1} (≈ 10 % of rainfall) and is concentrated between November and March. SWAT+ and remote-sensing recharge estimates agree on the wet-season peak once the ETa-product bias is removed. Limitations of the present soft calibration and a stepwise constraint-based hard-calibration roadmap are discussed.

1. Introduction

The Haouz–Mejjate aquifer is the principal groundwater body supporting drinking water, irrigated agriculture and economic activity in the Marrakech region. Long-term piezometric records show a progressive decline in groundwater levels driven by intensive pumping and reduced natural recharge under semi-arid Mediterranean climate. Quantifying the surface water balance of the upstream Atlas catchments and the associated recharge fluxes is therefore essential for sustainable groundwater management.

Specific objectives of this work are:

- Quantify the surface water balance components of the Ourika watershed (precipitation, ET, runoff, soil moisture change).
- Estimate spatially distributed groundwater recharge through three complementary approaches: SWAT+ output, a P − Q − ETa remote-sensing balance, and water table fluctuation when piezometric data become available.
- Evaluate the consistency between SWAT+ and remote-sensing recharge estimates at monthly and annual scales.
- Identify the priority observational constraints required for a future hard calibration of the model.

2. Study area

The Ourika watershed lies on the northern slopes of the High Atlas, approximately 70 km south-east of Marrakech, and drains into the Haouz plain through the Tensift river system. Elevation ranges from approximately 700 m at the Aghbalou gauging station to more than 4 100 m on the Toubkal massif. Mean annual rainfall over the period 2002–2018 ranges from about 200 mm yr^{-1} in the lowlands to more than 700 mm yr^{-1} on the upper slopes, with a marked snow contribution above 2 500 m between December and April. The Aghbalou hydrometric station (channel gis_id 531 in the SWAT+ delineation) provides the daily discharge record used for model calibration and validation.

3. Data and methodology

3.1 Input data

Climate: daily precipitation, minimum and maximum temperature, relative humidity, wind speed and solar radiation from fourteen meteorological stations operated by the Tensift Hydraulic Basin Agency (ABHT) over 2000–2018. Missing values were filled with the SWAT+ weather generator.

Topography: 30 m SRTM digital elevation model (USGS, 2014).

Soil: FAO Digital Soil Map of the World, harmonised to SWAT+ input format.

Land use / land cover: ESA WorldCover 10 m product (2020), reclassified to SWAT+ landuse codes; the cross-walk used in this study replaces BARR/SNOI (which are not valid SWAT+ classes) with BSVG.

Streamflow observations: daily discharge at the Aghbalou outlet (2000–2018), aggregated to monthly mean for calibration and validation.

Remote-sensing water balance: monthly P, Q and ETa products extracted for the catchment from the GR (Groundwater Recharge) workflow, used to compute the residual recharge term P − Q − ETa.

3.2 SWAT+ model setup

Watershed delineation, HRU generation and database compilation were carried out in QSWAT+ (QGIS 3.22) and SWAT+ Editor v3.0.8. Channel and stream thresholds of 0.3 km² were used during sub-basin delineation. HRUs were defined with multiple-option thresholds of 10 % / 15 % / 15 % for land use, soil and slope respectively, with three slope classes (0–8 %, 8–25 %, > 25 %). The Penman–Monteith method was selected for potential evapotranspiration, the variable storage method for channel routing, and the soil moisture method for the daily curve number. The simulation period is January 2000 – December 2018, with the first two years used as warm-up.

3.3 Parameter sensitivity analysis

A literature-informed sensitivity ranking was applied prior to calibration, following the Morris elementary-effects framework (Morris 1991; van Griensven et al. 2006). Twelve parameters covering surface runoff, soil, groundwater and channel routing processes were screened. The ranking adopted in this study reflects the consensus from semi-arid Mediterranean SWAT/SWAT+ applications (Cibin et al. 2010; Arnold et al. 2012; Brouziyne et al. 2018; Kaboré et al. 2022). Table 1 lists the parameters retained for further calibration.

Rank	Parameter	Process	Calibration range
1	CN2	Surface runoff (SCS curve number)	± 15 %
2	ESCO	Soil evaporation compensation	0.05–0.95
3	ALPHA_BF	Baseflow recession constant	0.01–0.50
4	GW_DELAY	Groundwater delay time (days)	10–500
5	GWQMN	Threshold for return flow (mm)	0–5 000
6	SOL_AWC	Soil available water capacity	± 20 %
7	SURLAG	Surface runoff lag coefficient	0.01–8
8	EPCO	Plant uptake compensation	0.01–1.00
9	REVAPMN	Threshold for revap (mm)	0–500
10	CH_N2	Manning n, main channel	0.014–0.150
11	GW_REVAP	Groundwater revap	0.02–0.20

		coefficient	
12	CH_K2	Effective hydraulic conductivity (mm/h)	0–500

Table 1. Parameters retained after literature-informed sensitivity screening.

3.4 Calibration and validation strategy

The model was calibrated against monthly mean observed discharge at the Aghbalou outlet over 2002–2010 and validated over 2011–2018. The current (V01 baseline) calibration is a soft calibration: parameter ranges were informed by the sensitivity ranking above and the values were adjusted manually within physically plausible ranges (Arnold et al. 2012, 2015) until model performance reached the satisfactory thresholds defined by Moriasi et al. (2007, 2015). Performance was evaluated with the Nash–Sutcliffe efficiency (NSE), Kling–Gupta efficiency (KGE), coefficient of determination (R^2) and percent bias (PBIAS).

4. Results

4.1 Streamflow calibration and validation

Period	NSE	KGE	R^2	PBIAS (%)
Calibration (2002–2010)	0.82	0.90	0.83	-5.1
Validation (2011–2018)	0.81	0.85	0.81	-4.6

Table 2. Goodness-of-fit metrics for monthly streamflow at the Aghbalou outlet. All metrics fall within the "very good" range of Moriasi et al. (2015).

The SWAT+ model captures the timing of seasonal peaks and the inter-annual variability of discharge across both calibration and validation periods. The slightly negative PBIAS indicates a small overall under-prediction (< 6 %) consistent with snowmelt-related uncertainty in the upper headwaters.

4.2 Monthly water-balance components

At basin scale, simulated actual evapotranspiration accounts for approximately 85 % of precipitation, with surface runoff and groundwater recharge concentrated between November and March. Summer months (June–September) contribute negligibly to either runoff or recharge.

4.3 Annual groundwater recharge

Mean annual recharge over 2002–2018 is approximately 35 mm yr^{-1}, equivalent to 7–17 % of annual rainfall depending on the year. Wet-year peaks occur in 2009, 2014 and 2018; dry-year minima in 2005 and 2017.

Year	Precipitation (mm)	Recharge (mm)	Recharge / P (%)
2002	327.2	25.3	7.7
2003	364.9	28.7	7.9
2004	304.7	31.9	10.5
2005	219.9	25.0	11.3
2006	412.1	41.8	10.1
2007	302.3	37.0	12.2
2008	343.7	23.5	6.8

2009	429.8	71.0	16.5
2010	420.1	55.4	13.2
2011	433.7	36.4	8.4
2012	361.9	26.1	7.2
2013	226.0	32.3	14.3
2014	481.4	62.5	13.0
2015	328.4	55.2	16.8
2016	321.9	27.3	8.5
2017	199.0	16.7	8.4
2018	485.4	54.5	11.2

Table 3. Annual basin-averaged precipitation, simulated recharge and the recharge-to-rainfall ratio over 2002–2018.

4.4 SWAT+ versus remote-sensing recharge

SWAT+ and the remote-sensing residual P − Q − ETa agree on the November–March wet-season peak. The raw remote-sensing residual overestimates recharge by approximately a factor of 5 because of the low bias of the ETa product in semi-arid mountain catchments; once rescaled to the same annual total as the SWAT+ simulation, the seasonal shapes of the two estimates align, with SWAT+ exhibiting the expected one-month delay associated with soil-moisture filling.

5. Conclusions and perspectives

5.1 Key findings

- SWAT+ reproduces monthly discharge at the Aghbalou outlet with NSE of 0.81–0.82 and KGE of 0.85–0.90 over an 17-year record.
- Mean annual recharge is approximately 35 mm yr^{-1} (≈ 10 % of rainfall) with strong inter-annual variability driven by the wet years 2009, 2014 and 2018.
- Recharge is concentrated between November and March and is near-zero between June and September.
- SWAT+ and remote-sensing recharge agree on the seasonal timing once the ETa-product bias of the remote-sensing residual is accounted for.

5.2 Limitations of the current soft calibration

- Manual tuning fits monthly discharge at the outlet but does not constrain the internal partitioning of precipitation into surface runoff, groundwater recharge and evapotranspiration (Pfannerstill et al. 2017; Arnold et al. 2015).
- Equifinality is not quantified: many parameter combinations can reproduce a similar discharge time series while simulating substantially different subsurface fluxes (Beven 2006; Clark et al. 2021).
- Snowmelt parameters in the High-Atlas headwaters and the transmission losses along the channel network rely on default SWAT+ values and have not been calibrated against independent observations.
- The remote-sensing residual is sensitive to the choice of ETa product. A multi-product ensemble would replace the current single-product rescaling.

5.3 Next steps: constraint-based hard calibration

The next iteration of the model (V02) will adopt the stepwise constraint-based calibration framework recently formalised by Shafiei et al. (2026). The framework comprises (i) model setup verification using SWATdoctR (Plunge et al. 2024), (ii) a water-balance soft calibration using the SWATtunR R package (Plunge et al. 2025) and the runoff coefficient as the primary soft target, and (iii) a constraint-based hard calibration in which Latin-Hypercube samples are screened against process-based constraints prior to evaluation against the discharge time series.

The following observational constraints will be incorporated:

- Piezometric heads in the Haouz–Mejjate aquifer, used to constrain the timing and magnitude of simulated groundwater recharge (Le Page et al. 2012; Bouchaou et al. 2018).
- Remote-sensing actual evapotranspiration from a multi-product ensemble (MOD16, GLEAM, SSEBop) used as a soft constraint on the simulated ETa per HRU (Herman et al. 2018; Rajib et al. 2018).
- MODIS daily snow-cover area in the High-Atlas headwaters, used to constrain snowmelt parameters (Boudhar et al. 2009; Marchane et al. 2015).
- Baseflow index derived from the Lyne–Hollick digital filter applied to the observed discharge record, used to constrain the groundwater contribution to streamflow (Lyne & Hollick 1979; Ladson et al. 2013).

This combination is expected to reduce equifinality, quantify the uncertainty of the simulated water balance, and build a model that performs well for the right reasons in the sense of Kirchner (2006). The ultimate objective is the coupling of the calibrated SWAT+ model with a MODFLOW representation of the Haouz–Mejjate aquifer to support operational decisions on groundwater allocation under climate stress.

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