ISSN: 3029-0724

Research Article

Journal of Environmental Science and Agricultural Research

SWAT+ Single and Multi-Site Calibration in a Semi-Arid Watershed

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Received: November 20, 2025; **Accepted:** December 01, 2025; **Published:** December 08, 2025

ABSTRACT
Calibration is a critical step in watershed modeling. The availability of more data generally leads to more accurate calibration, making multisite calibration valuable when multiple hydrologic gauging stations are present. In this study, we compare the performance of the SWAT+ model, applied to a watershed in southern Morocco equipped with three gauging stations, by evaluating different calibration strategies provided by the latest version of the SWAT+ Toolbox (v3.0.6). These strategies include single-site calibration (individual calibration at the outlet station), multisite one-step calibration (calibrating all sub-basins simultaneously), and multisite multi-step calibration (calibrating sub-basins sequentially). The analysis aims to improve calibration strategies for watershed modeling under semi-arid climates, where water resource management is particularly sensitive to calibration uncertainties due to data scarcity. It demonstrates that multi-site multi-step calibration significantly improves the spatial representation of hydrological processes compared to single-site calibration, although predictive uncertainty remains high during validation for some sub-basins.

Keywords: Model, SWAT+, Calibration, Multi-Site, Semi-Arid

Introduction

In semi-arid regions, effective water resource management is critically constrained by two interdependent challenges: profound hydrological scarcity and limited observational data. Mathematical simulation models are essential for understanding hydrological dynamics and evaluating management scenarios under these constraints. However, the reliability of such models hinges on robust calibration procedures, which are often hampered by data insufficiency. This creates a pressing need for calibration strategies that maximize the informational value from available monitoring networks.

Hydrological modeling practices have evolved significantly from traditional single-site, single-variable calibration. The conventional approach calibrates a model, typically against streamflow, at a single outlet station. While practical, this method may inadequately represent the spatial heterogeneity of hydrological processes within a basin. Advances in calibration methodology now promote more holistic approaches. Multi-site calibration utilizes data from multiple gauging stations, thereby imposing distributed constraints on the model's internal state. When combined with multi-variable calibration—integrating data such as evapotranspiration and soil moisture—these approaches can significantly enhance the model's physical realism and predictive capability.

This study focuses on the Massa catchment in southern Morocco, a representative semi-arid basin governed by a water-limited, Mediterranean hydro-climate intensified by sub-Saharan influences. The region is characterized by high inter-annual variability and a distinctly bimodal regime: a short, unpredictable wet season (October-April) followed by a protracted dry period, establishing a dominant moisture deficit. The studied sub-basin (3,847 km²) exhibits an average annual rainfall of 215 mm,

Citation: Mohamed Yacoubi. SWAT+ Single and Multi-Site Calibration in a Semi-Arid Watershed. J Envi Sci Agri Res. 2025. 3(6): 1-6.
DOI: doi.org/10.61440/JESAR.2025.v3.114

with high temperatures (mean max: 26.4°C) and significant atmospheric demand, as evidenced by an average annual evapotranspiration of 198.3 mm, accounting for approximately 92% of the precipitation. The average annual flow at the outlet is a modest 3 m^3/s, underscoring the system's aridity.

The Massa basin provides a pertinent case study, being equipped with a network of three hydrometric stations. This research employs the SWAT+ model to investigate the impact of calibration strategy on model performance in this semi-arid context. We applied and compared two distinct calibration schemes: a single-site calibration at the watershed outlet and a multi-site calibration utilizing data from all three available stations. The primary objective is to critically evaluate the contribution of multi-site calibration over the single-site approach, specifically assessing its capacity to improve the spatial representation of hydrological processes and the overall reliability of the model for water resources assessment in a data-scarce, semi-arid environment.

Materials and Methods

The Massa catchment area was modeled using the SWAT+ (Soil and Water Assessment Tool) model. This semi-distributed hydrological model simulates water and pollutant transport in complex watersheds. A core concept is the Hydrologic Response Unit (HRU), which represents unique spatial entities within a sub-basin defined by a specific combination of land use, soil type, and slope. This approach allows for efficient simulation of hydrological processes for each homogeneous land category. The model requires extensive input data, including a Digital Elevation Model (DEM) for watershed delineation, land use/cover and soil type maps for HRU definition, and long-term time-series of weather data (precipitation, temperature, solar radiation, wind, and humidity) to drive the simulations. The model has been widely and successfully applied in Morocco over the last two decades [1].

The water cycle is modelled using the following equation [2]:

$$SW_t = SW_o + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{wg})$$

SW_t : Final soil water content at day t (all terms are in mm)
SW_o : Initial soil water content
R_{day} : Amount of precipitation
Q_{surf} : Amount of surface runoff
E_a : Amont of evapotranspiration
W_{seep} : Amount of water entering vadose zone
Q_{wg} : Amount of return flow

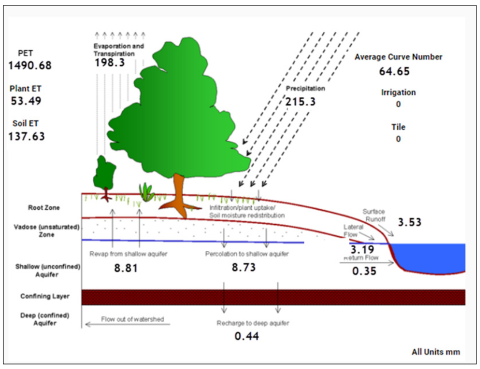

Figure 1: Water cycle of Massa watershed simultated by SWAT+

Study Area

This study focuses on a sub-basin within the larger Massa watershed, situated upstream of the Youssef Ibn Tachfine dam in southern Morocco. The terrain in this studied area is highly varied, with altitudes ranging from 98 to 2360 meters above sea level as it drains the Anti-Atlas mountains. Characterized by a harsh, semi-arid climate, the river is typically an ephemeral watercourse. However, its flow is crucial as it feeds the reservoir and ultimately supports the vital oasis of the Souss-Massa National Park downstream, which is a lifeline for biodiversity and agriculture in this arid region.

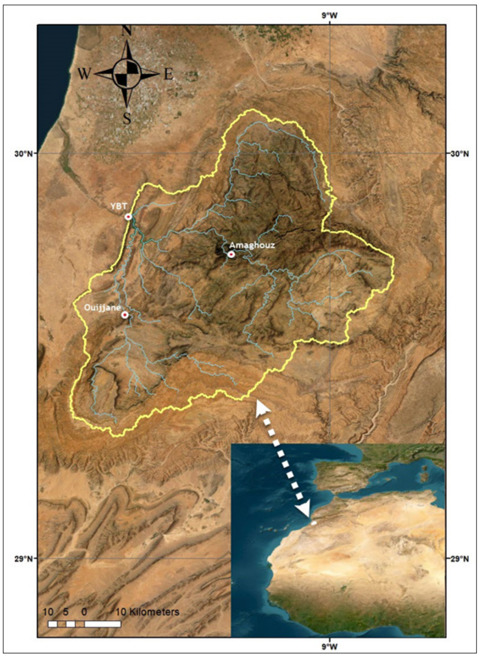

Figure 2: Situation and Hydrologic equipment of the studied watershed: YBT, Amaghouz and Ouijjane

Data Used

The acquisition and preparation of reliable hydrometeorological and geospatial data constituted the foundational step of this historical hydrological investigation. To ensure a comprehensive analysis, these critical datasets were systematically sourced from official regional hydraulic authorities and, where applicable, contemporary open-source geospatial repositories. The core observational data spanned a 24-year period, from 1977 to 2000. This extended timeframe is particularly valuable for hydrological modeling as it likely encapsulates a wide range of climatic conditions and extreme events, thereby providing a robust basis for calibrating and validating the model under diverse scenarios. The core of the model validation relied on observed daily streamflow records, meticulously obtained from the YBT gauging station (Figure 2). This station was strategically selected as the primary basin outlet, serving as the key benchmark for comparing and calibrating all subsequent model outputs. Its long-term records provided the essential "ground truth" against which simulated flows were rigorously assessed.

To accurately capture the spatial heterogeneity of historical rainfall across the catchment, precipitation inputs were derived from a distributed network of three rain gauge stations: YBT, Amaghouz, and Ouijjane (Figure 2). This tri-station approach was crucial for accounting for orographic effects and localized storm events, thereby providing a more robust and spatially representative precipitation input for the period than any single station could. Furthermore, the meteorological variables necessary for calculating potential evapotranspiration (PET)—a key process governing water loss from the basin—were sourced from the Amaghouz station. Specifically, this included historical daily records of temperature and wind speed, which are fundamental drivers in established PET estimation formulas like the Penman-Monteith equation.

Complementing the time-series data, a thorough watershed characterization was conducted to parameterize the physical attributes of the basin. Land cover and land use, critical determinants of infiltration rates and surface runoff generation, were classified using the Copernicus Land Cover map for 2019 at a high 100-meter resolution (Figure 3). While this represents a more recent land cover state, it was used as the best available proxy to represent the dominant, relatively stable land cover classes during the later part of the study era. Concurrently, soil properties, which are largely static over time and directly influence water storage and transmission, were derived from the OpenLandMap Digital Soil Map at a 250-meter spatial resolution (Figure 4) [3]. This global soil database offered essential information on texture and hydraulic properties. The integration of these diverse datasets—from dynamic historical hydrometeorological forces to the more static watershed characteristics—created a solid, multi-faceted empirical foundation for the ensuing historical hydrological modeling and analysis. Table 1 summarizes all input data used for SWAT+.

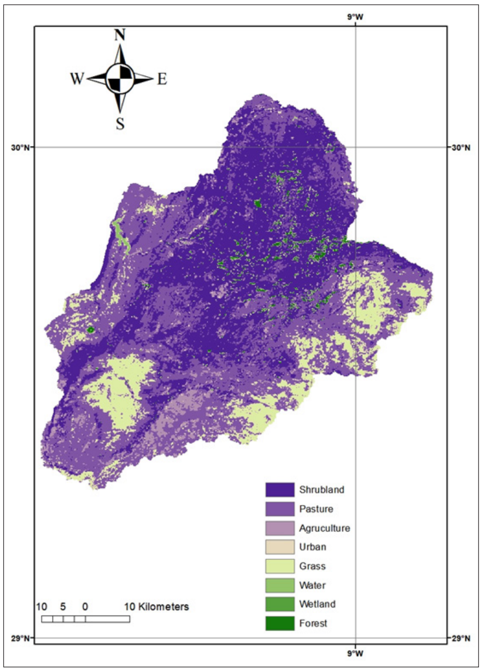

Figure 3: Copernicus global land cover (resolution 100m)

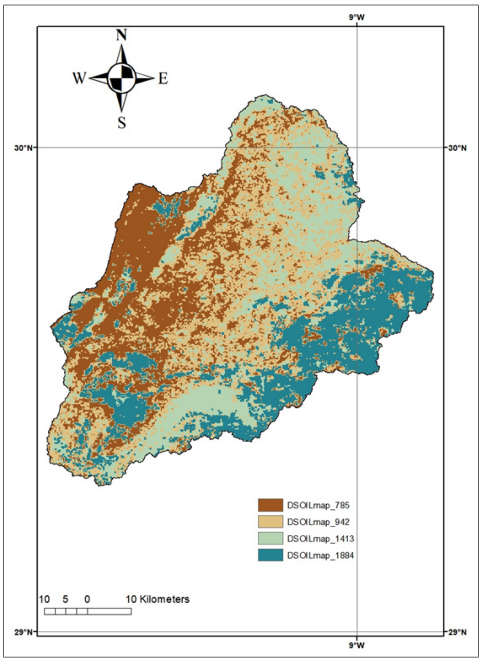

Figure 4: Dsol map:Digital soil open land map (resolution: 250 m)

Table 1: SWAT+ Input Data

Data	Resolution	Source
Topography	30 m	Shuttle Radar Topography mission (SRTM)
Soil	250 m	OpenLand Digital Soil Map
Land use	100 m	Copernicus Land Cover map 2019
Hydro-climatic data	-	Hydraulic Basin Agency of Souss-Massa

Results and Discussion

The hydrological model was driven using daily discharge data spanning the period from 1977 to 2000. To ensure robust model performance, the 24-year record was partitioned into distinct calibration and validation phases. The calibration period, from 1977 to 1990, was selected because it encapsulates a hydrologically representative mix of both dry and wet years, thereby preventing model bias towards a single climatic condition. The subsequent decade, from 1991 to 2000, was reserved for independent model validation (Figure 5).

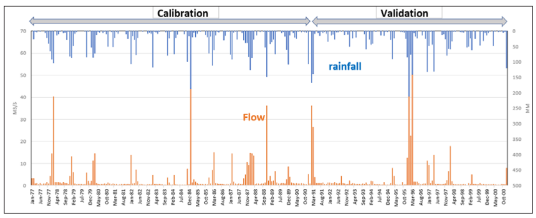

Figure 5: Calibration and validation periods

Model parameter optimization was conducted using the SWAT+ Toolbox (v 3.0.6). An initial global sensitivity analysis, employing the variance-based Sobol method, was performed to identify and quantitatively rank the most influential parameters based on their impact on simulated streamflow [4]. This informed the subsequent automatic calibration process, which focused on adjusting these key parameters to minimize the discrepancy between observed and simulated discharge during the calibration period. Model calibration was conducted using the Dynamically Dimensioned Search (DDS) optimization algorithm, an efficient stochastic method designed for high-dimensional parameter spaces [5].

We conducted a sensitivity analysis for the entire watershed, identifying eight sensitive parameters. Among these, we retained the four most sensitive: the soil evaporation compensation factor (ESCO), the initial SCS runoff curve number for moisture condition II (CN2), the maximum canopy storage (CANMX), and the available water capacity of the soil layer (SOIL_AWC).

To evaluate the model's spatial robustness, three distinct calibration strategies were implemented: single-site, multisite-one-step, and multisite-multistep calibration. The first strategy involved a single calibration targeting the YBT station at the watershed outlet. The second strategy, a multisite-one-step approach, involved independently introducing the four sensitive parameters for the three sub-watersheds (Amaghouz, Ouijjane, and the intermediate basin) and then calibrating them simultaneously for the entire system (Figure 6). The third and most complex strategy was a multisite-multistep calibration. This sequential process began by introducing the four sensitive parameters to calibrate the Amaghouz sub-watershed. Upon achieving satisfactory performance, the same operation was repeated sequentially for the Ouijjane sub-watershed and finally for the intermediate basin, ensuring a step-wise optimization of the internal watershed processes (Figure 7).

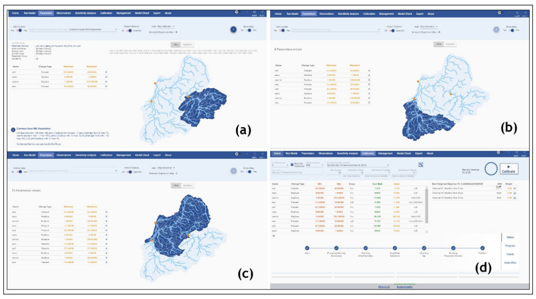

Figure 6: Multisite- one- step calibration: parameters introduction for Amaghouz station (a), parameter's introduction for Ouijjane station (b), parameter's introduction for the Intermediate basin (c) and (d) one step calibrated parameters for the whole basin

The calibration results demonstrate a clear improvement in model performance when transitioning from a single-site to a multi-site approach, particularly for the interior stations. For the outlet station (YBT), the Nash-Sutcliffe Efficiency NSE (Table 3) consistently shows a strong model fit (0.69 across all methods, as detailed in Table 4). Furthermore, the Percent Bias (PBIAS) at YBT significantly improves from 19.96% to 2.16% with multi-site multi-step calibration, elevating the water balance error rating from "unsatisfactory" to "very good."

The benefits are even more pronounced for the interior stations. Amaghouz exhibits a steady increase in NSE (from 0.58 to 0.66) and a dramatic shift in PBIAS from a substantial underestimation (19.96%) to a slight overestimation (-2.02%), which is considered excellent. Similarly, Ouijjane's NSE improves from a poor 0.29 to a more reasonable 0.40, while its PBIAS is reduced from 19.96% to 15.80%. These findings underscore that multi-site strategies, especially the multi-step method, are crucial for constraining the model to more accurately represent internal watershed processes, thereby achieving a better overall spatial water balance across all three gauges rather than optimizing for a single location.

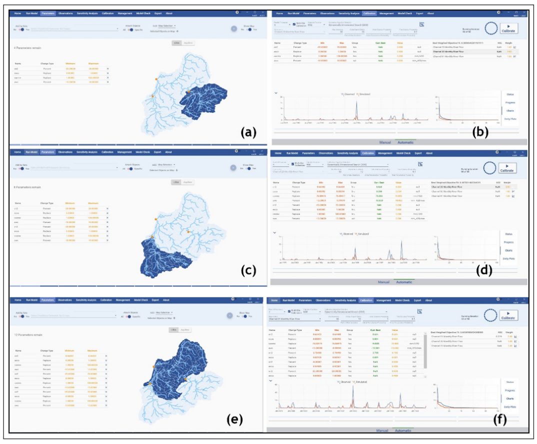

Figure 7: Multisite- multi- step calibration: parameters introduction for Amaghouz sub-basin (a) and Calibration (b), parameter's introduction for Ouijjane sub-watershed (c) and Calibration (d) and parameter's introduction for the intermidiate basin (e) and Calibration (f)

Table 2: Used Performance Metrics [6]

Performance Metric	Expression	Value Range	Optimal Value
NSE	$1-\frac{\sum_{i=1}^{n}(x_i-y_i)^2}{\sum_{i=1}^{n}(x_i-\bar{x})^2}$	(-∞,1]	1
PBIAS	$100\frac{\sum_{i=1}^{n}(x_i-y_i)}{\sum_{i=1}^{n}x_i}$	(-∞, +∞)	0

n : number of observations $\bar{x}$: mean value of observed
x_i : observed data y_i : simulated data

The validation period reveals the model's predictive capability and exposes some transferability issues, particularly for the Ouijjane station (Table 4). While the outlet station YBT maintains a satisfactory and stable Nash-Sutcliffe Efficiency (NSE) (around 0.52-0.55) and shows a positive trend with a reduction in Percentage Bias (PBIAS) from 36.07% to 23.71%, the results for the interior stations are more concerning. Amaghouz performs reasonably well, with NSE values between 0.47-0.50 and a PBIAS that, while elevated from calibration, remains under 26%. The major challenge is Ouijjane, where all NSE values are low or negative, and PBIAS is strongly negative (below -13%), indicating a consistent and large overestimation of streamflow. This suggests that the model parameters calibrated for Ouijjane may not be fully robust under different climatic conditions, or that specific, unaccounted local processes (like water abstraction or groundwater interactions) significantly affect this sub-basin. Overall, the model demonstrates acceptable performance at the watershed outlet but requires further investigation and potentially additional data for the internal stations, especially Ouijjane, to improve its reliability for predictive purposes across the entire basin.

Table 3: Results of calibration strategies for the period 1977-1990

Calibration	Amaghouz		Ouijjane		YBT	
	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS
Single site	0.58	19.96	0.29	19.96	0.69	19.96
Multi-site one step	0.65	2.80	0.39	21.91	0.69	18.16
Multi-site multi-step	0.66	-2.02	0.40	15.80	0.69	2.16

Table 4: Results of validation for the period 1991-2000

Validation	Amaghouz		Ouijjane		YBT	
	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS
Single site	0.53	0.89	-1.21	-64.28	0.52	36.07
Multi-site one step	0.47	25.90	-0.10	-13.53	0.53	33.83
Multi-site multi-step	0.50	17.49	0.01	-16.72	0.55	23.71

Conclusion

This study demonstrates the significant impact of calibration strategy on the performance and spatial reliability of the SWAT+ model in a semi-arid watershed. The comparative analysis between single-site and multi-site approaches underscores a critical finding: calibrating solely at the watershed outlet, while yielding good local performance, fails to adequately represent the internal hydrological heterogeneity of the Massa basin. The single-site calibration resulted in a model that was effectively "tuned" for the YBT station but produced substantial errors at the interior stations of Amaghouz and Ouijjane, as evidenced by high Percentage Bias (PBIAS) values. This confirms the limitation of a lumped calibration in capturing the spatial variability of processes like infiltration, runoff generation, and evapotranspiration across a complex, semi-arid landscape.

The transition to multi-site calibration, particularly the multi-site multi-step method, proved to be a substantial improvement. By imposing distributed constraints on the model, this strategy forced a more realistic representation of the water balance across all sub-basins. The results clearly show that the multi-site multi-step calibration not only maintained excellent performance at the outlet but also dramatically improved the Nash-Sutcliffe Efficiency (NSE) and PBIAS for the internal stations during the calibration phase. The ability of this method to refine parameters sequentially for each sub-watershed allowed for a more physically consistent simulation of the flow pathways contributing to the overall basin response. This leads to a model that is not just a black box for the outlet but a more trustworthy tool for understanding internal dynamics, which is essential for targeted water resources management, such as assessing the impact of local interventions or climate change on specific sub-regions.

However, the validation period revealed important limitations and highlighted the challenges of modeling in data-scarce, semi-arid environments. The transferability of the calibrated parameters to an independent time period was not fully successful, especially for the Ouijjane sub-basin, where performance remained poor. The consistently high PBIAS at Ouijjane suggests that certain basin-specific processes, potentially including transmission losses, groundwater abstractions, or the high variability of convective rainfall, are not fully captured by the current model structure or parameterization. This indicates that while multi-site calibration enhances spatial robustness, the model's predictive uncertainty can remain high for specific locations due to unaccounted hydrological complexities or data limitations.

In conclusion, this research strongly advocates for the adoption of multi-site multi-step calibration in semi-arid watershed modeling whenever streamflow data from multiple stations are available. It is a crucial step towards achieving greater spatial realism. Nevertheless, the persistent challenges during validation underscore that improved calibration alone cannot fully overcome the structural and data-related uncertainties inherent in these environments. Future work should focus on integrating additional data types, such as remote sensing-based evapotranspiration or soil moisture, into a multi-variable calibration framework. Furthermore, a more detailed investigation into the hydrological processes dominating the Ouijjane sub-basin is necessary to enhance the model's predictive reliability and its ultimate utility as a decision-support tool for water managers in water-stressed regions like southern Morocco.

Acknowlegement: Hydraulic Basin Agency of Souss Massa

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