SEASONAL BASED-GLOBAL SENSITIVITY ANALYSIS OF SAC-SMA MODEL PARAMETERS

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Received: 3/9/2025; Accepted: 15/9/2025

Abstract: *This study implemented Sobol-based global sensitivity analysis to assess parameter importance in the Sacramento Soil Moisture Accounting (SAC-SMA) model under contrasting regimes: Flood and dry seasons. The Mu Cang Chai watershed in Nam Mu basin is used as a case study. Results show clear seasonal contrasts in dominant processes and parameter interactions. In the flood season, runoff is strongly governed by lower-zone storages, with LZFSM, LZFPM, and LZTWM presenting the greatest influence. Interactions involving UZFWM further highlight the importance of upper-to-lower zone linkages in shaping flood flows. Calibration for wet conditions should therefore prioritize these storages, while handling percolation and drainage parameters as interaction-driven controls. In the dry season, UZFWM, LZTWM, and UZTWM are dominant parameters, while interaction effects involving impervious areas (PCTIM) also indicate that small surface conditions can modulate drought runoff. These seasonal insights support more efficient calibration to improve SAC-SMA model interpretability.*

Keywords: *SAC-SMA, seasonal sensitivity analysis, Sobol.*

1. Introduction

The Sacramento Soil Moisture Accounting (SAC-SMA) model is one of the most widely used conceptual hydrological models in operational hydrological forecasting by the National Weather Service (NWS) since the 1970s. SAC-SMA simulates the water balance in a watershed through a two-layer structure: An upper and lower layer, each containing both tensed and free water storages, thereby reproducing the processes of infiltration, evapotranspiration, surface runoff, lateral flow, and ground flow [1]. Since model parameters cannot be measured directly from the field, parameter calibration based on measured rainfall-runoff data is a necessary step to apply SAC-SMA in practice [2].

In the past few decades, sensitivity analysis (SA) has become an indispensable tool in the research and application of hydrological models. SA helps to identify parameters that have a large influence on the simulated flow, thereby reducing the number of dimensions in the calibration process, increasing computational efficiency and clarifying the relationship between parameters and the physical processes of the basin [3]. Many conceptual models have demonstrated the importance of SA. For the GR4J model, only a few parameters related to storage capacity and groundwater flow coefficient account for most of the streamflow variability [4]. In the VIC model, Liang et al. [5] and subsequent studies highlighted the high sensitivity of parameters related to snow and evapotranspiration in cold climate regions. Global analyses based on Sobol or Morris have become popular, allowing for the assessment of both the magnitude and interactions of parameter influences; for example, the study by van Werkhoven et al. [6] showed that sensitivity varies significantly with basin scale and climatic conditions. Similarly, Herman et al. [7] emphasized the necessity of global SA for understanding and managing parameter uncertainty in hydrological models. Regarding SAC-SMA, many studies have shown that parameters such as upper tension water

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capacity (UZTWM), upper free water capacity (UZFWM), lower layer capacity (LZFPM, LZFSM) and flow reduction coefficient (LZPK, LZSK) and percolation rate (ZPERC) are the most sensitive, determining the ability to simulate flow [8], [9]. Studies within the NWS hydrologic forecasting system have also noted that selecting and constraining the value ranges of these sensitive parameters can significantly improve model performance [2].

A prominent new research direction is seasonal sensitivity analysis. Hydrological processes are nonlinear and have strong seasonal variations: During the wet season, parameters related to the upper water storage and transmission capacity (UZTWM, UZFWM) are usually more sensitive, while during the dry season, parameters related to evapotranspiration and ground flow (LZPK, LZSK, PFREE) play a dominant role [2]. Recent studies have also shown that assessing sensitivity only over the entire time series may miss important seasonal characteristics, leading to parameter calibration results that lack stability when transferred to other basins or in the context of climate change [11].

Under this context, the implementation of global seasonal sensitivity analysis for the SAC-SMA model is of great significance that is not only to identify key parameter sets for each hydrological period, but also to improve simulation reliability under various climate and land use conditions. This is also the scientific basis for developing sustainable parameter calibration strategies, minimizing uncertainties and increasing the applicability of the SAC-SMA model in flood forecasting and water resources management.

2. Methodology

2.1. Study area and Data

The Mu Cang Chai basin, located in the Nam Mu River in Northwest Vietnam, covers an area of 230 km^2 with a river length of 71.6 km (Figure 1). The Nam Mu is a major tributary of the Da River which is vital for hydropower, domestic use, and agriculture. The flow rate in the basin is monitored by the Mu Cang Chai hydrological station on the Nam Kim River. Its topography consists mainly of medium mountains (700-1500 m) interspersed with lowland plains, while higher elevations above 1500 m are concentrated in the north and east. The basin has a tropical monsoon climate with annual rainfall of 2000-2500 mm, concentrated from May to August, often causing floods due to steep terrain. Temperatures range from 5-20°C (minimum) to 25-35°C (maximum).

This study uses hydro-meteorological data collected at the Mu Cang Chai station from January 1, 1984, to December 31, 2024 to feed the SAC-SMA model (Figure 2). The meteorological variables include daily precipitation and observed daily maximum and minimum temperatures. The hydrological data consist of daily streamflow at the Mu Cang Chai station.

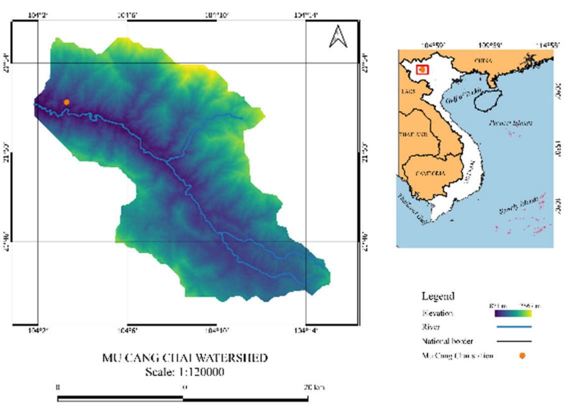

Figure 1. The Mu Cang Chai basin

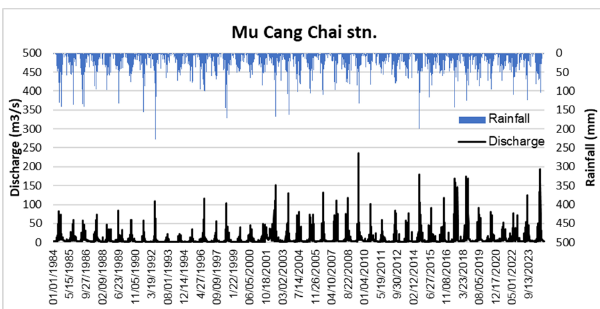

Figure 2. Rainfall and flow data at the Mu Cang Chai station

2.2. SAC-SMA model

The Sacramento Soil Moisture Accounting (SAC-SMA) model is a lumped conceptual rainfall-runoff model that represents the catchment as a two-layer soil system (Figure 3). Each layer is divided into tension water storage, which holds water tightly bound to soil particles, and free water storage, which drains more readily. The upper zone consists of the Upper Zone Tension Water (UZTWM) and Upper Zone Free Water (UZFWM), which control interception, infiltration, and quick interflow. The lower zone is represented by the Lower Zone Tension Water (LZTWM) and two free water storages: A primary (LZFPM) and supplemental (LZFSM) reservoir, which control slow and fast baseflow recession, respectively. Percolation between layers is regulated by nonlinear functions defined by parameters such as ZPERC and REXP. Additional parameters account for impervious area runoff (PCTIM), direct runoff, and preferential flow (PFREE). In total, the model uses 13 major and several minor parameters to simulate processes of precipitation partitioning, evapotranspiration, infiltration, interflow, and groundwater flow, providing a comprehensive framework for streamflow forecasting and water balance studies (see Appendix 1).

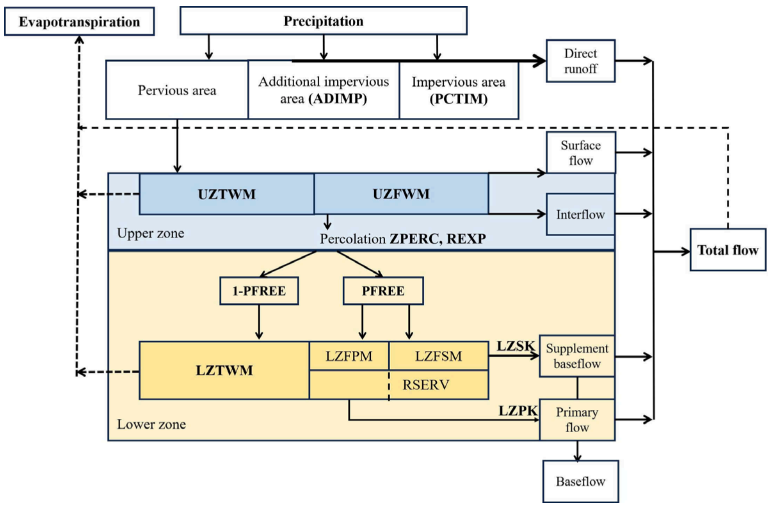

Figure 3. SAC-SMA model structure (adopted from [12])

2.3. Sensitivity Analysis

In this study, the global sensitivity analysis method of Sobol was applied to identify the most important parameters of the SAC-SMA model. This is a widely used technique for exploring the importance of parameters in many hydrological models. The idea behind this method is that the total variance of the model output is decomposed into separate components, including the variances attributed to individual parameters and those arising from parameter interactions, with their contribution ratios measuring the sensitivity indices [13], [14]. The main effects of individual parameters are represented by first-order indices, while higher-order indices capture the combined effects of groups of parameters, and the total-order index reflects the overall impact of each parameter and its interactions with all other parameters. The total variance of the model output F(x) is mathematically described as follows:

$$\boldsymbol{F}(\boldsymbol{x}) = \sum_{i=1}^{N} \boldsymbol{F}_i + \sum_{i \leq j \leq n}^{N} \boldsymbol{F}_{ij} + \cdots + \sum_{i \leq n}^{N} \boldsymbol{F}_{1\ldots N} \quad (1)$$

Where: N is number of model parameters; F_i represents the first-order variance of parameter i; F_{ij} reflects interaction between the parameter i and parameter j. The first-order, the second-order, and total-order sensitivity indices can be accordingly stated as follows:

$$S_i = \frac{F_i}{F(x)} \quad (2)$$

$$S_{ij} = \frac{F_{ij}}{F(x)} \quad (3)$$

$$S_{Ti} = 1 - \frac{F_{\sim i}}{F(x)} \quad (4)$$

The sensitivity of SAC-SMA model's parameters is evaluated by the Nash-Sutcliffe efficiency (NSE) [15] for flood and logNSE [16] for dry seasons.

$$NSE_{flood} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs,f} - Q_{sim,f}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,f} - Q_{fmean}\right)^2} \quad (5)$$

$$logNSE_{dry} = 1 - \frac{\sum_{i=1}^{n}\left(log\left(Q_{obs,d}\right) - \log\left(Q_{sim,\mathrm{d}}\right)\right)^2}{\sum_{i=1}^{n}\left(log\left(Q_{obs,d}\right) - log\left(Q_{obs,d}\right)_{mean}\right)^2} \quad (6)$$

Where, $Q_{obs,f}$ and $Q_{sim,f}$ are observation and simulation in flood season, respectively; $Q_{obs,d}$ and $Q_{sim,d}$ are observation and simulation in dry season, respectively; Q_{fmean} and Q_{dmean} are the average values of observed flood flow and dry flow; *log(Q)* is natural logarithm of dry flow; *n* is the total number of time steps.

To perform seasonal sensitivity analysis (SSA) for the SAC-SMA model, the hydrological simulation during the considered period (1/1/1984-31/12/2024) is decomposed into seasonal periods, e.g., flood and dry seasons based on rainfall distributions and local hydrological characteristics. The global sensitivity analysis method Sobol is applied to decompose the model output variance into components attributable to individual parameters and parameter interactions. First-order, second-order and total-order sensitivity indices were calculated for each season, allowing for a direct comparison of the changing role of parameters between the wet and dry seasons. This analysis helps to identify parameters with dominant seasonal influences. The SSA results thus become the basis for proposing a seasonal parameter calibration strategy that both reduces uncertainty and improves model stability and transferability in the context of climate change.

3. Results and discussion

3.1. Sobol sensitivity analysis in flood season

As mentioned above, the importance of SAC-SMA's parameters in simulating flood flow in Mu Cang Chai watershed during flood season is reflected by Sobol's indices. The first-order indices (S1) quantify independent contributions to output variance the simulation. The highest values are associated with LZFSM (S1=0.154), LZTWM (S1=0.131), and LZFPM (S1=0.126) (Table 1). These parameters act as the primary independent drivers of runoff generation: The lower-zone tension water capacity establishes the antecedent wetness threshold, while the supplemental and primary free water storages govern the magnitude and persistence of flood response. ADIMP also exhibits a relatively strong independent effect (S1=0.103), presenting the direct role of variable contributing areas in surface runoff production. By contrast, drainage coefficients (LZPK, LZSK), percolation parameters (ZPERC, REXP), and upper-zone coefficients (UZK, UZTWM) have small S1 which indicates their minor contribution in modelling during flood conditions.

The total Sobol indices (ST) capture both direct and interactive effects, and the largest discrepancies between S1 and ST highlight interaction-driven influences (Figure 4). LZFSM rises from 0.154 to 0.376, LZFPM from 0.126 to 0.249, and UZFWM from 0.083 to 0.191, indicating strong amplification through interaction with other processes. Similarly, REXP and ZPERC have negligible first-order values but non-trivial total effects (ST=0.046 and 0.035, respectively). These numbers demonstrate that although they are weak on their own, they become critical when coupled with storage capacities and drainage rates to control flood flow computation. Drainage parameters show the same pattern, with total sensitivities two to three times larger than their first-order values. In contrast, ADIMP almost shows a non-interactive effect due to nearly identical ST and S1.

The pairwise interaction indices (S2) reveal which parameter combinations dominate the interaction structure (Figure 5). The strongest are LZFPM–UZFWM that suggests the joint activation of primary baseflow storage by upper-zone free water recharge. LZFSM–LZTWM (S2=0.07) explains the control of lower-zone tension water state on supplemental runoff generation. Smaller but consistent interactions involve REXP and ZPERC with UZFWM, LZFSM, and the lower-zone drainage coefficients, consistent with the nonlinear percolation law coupling infiltration, storage, and drainage.

Table 1. Results of Sobol sensitivity (S1 and ST) in flood season (NSE)

Parameter	First-order index (S1)	Total-order index (ST)
uztwm	0.006	0.010
uzfwm	0.083	0.191
lztwm	0.131	0.121
lzfpm	0.126	0.249
lzfsm	0.154	0.376
adimp	0.103	0.099
uzk	0.004	0.004
lzpk	0.022	0.059
lzsk	0.024	0.064
zperc	0.016	0.035
rexp	0.006	0.046
pctim	0.014	0.018
pfree	0.000	0.014

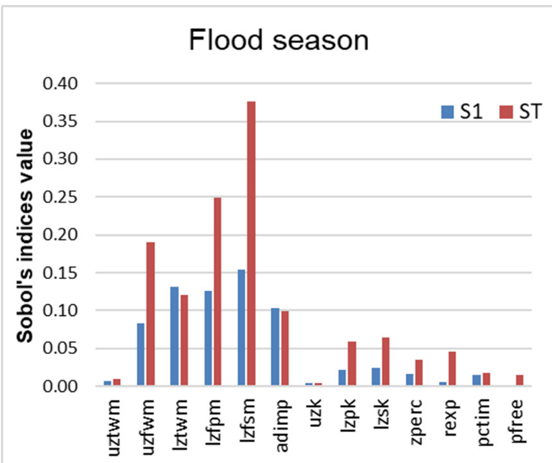

Figure 4. Comparison of independent and total influences of SAC-SMA's parameters in flood season

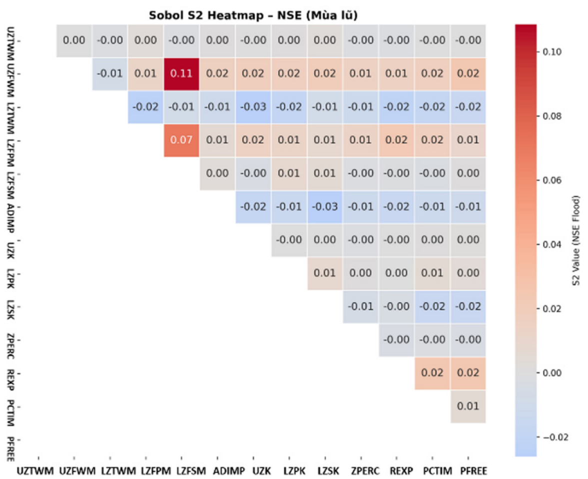

Figure 5. Heatmap of S2 index in flood season

3.2. Sobol sensitivity analysis in dry season

Regarding sensitivity analysis of the logNSE index in dry season, S1 results highlight LZPK as the most dominant contributor (S1=0.501), followed by UZTWM (S1=0.089) and LZFPM (S1=0.103). This pattern indicates that low flow generation is governed primarily by the depletion rate from free primary lower storage and the tension storage in the upper (Table 2). Whereas, the release rate from the lower zone plays the most important role with remarkably greater value than others.

Similarly, ST results illustrate that LZPK retains the largest overall impact (ST=0.613), followed by UZTWM (0.236) and LZFPM (0.176) (Figure 6). The significant gap between S1 and ST for the UZTWM and LZFPM suggest that they interact strongly with other parameters to influence runoff. Even though the direct effect of UZTWM and LZFPM are modest, their combined effects on low flow are considerable. The minor gap of LZPK indicates its strong independent role in logNSE response.

When it comes to S2, Figure 7 underscores strong pairwise couplings, particularly between LZPK with UZTWM and LZTWM (S2=0.08-0.09). These findings confirm the importance of coordinated upper- and lower tension zone soil moisture dynamics in sustaining flow during the dry season. Notably, interactions between these parameters and lower free storage-related parameter (LZPK) are also visible, suggesting that even small changes in depletion rate can significantly affect the flow in dry season.

Table 2. Results of Sobol sensitivity (S1 and ST) in dry season (logNSE)

Parameter	First-order index (S1)	Total-order index (ST)
uztwm	0.089	0.236
uzfwm	0.010	0.004
lztwm	-0.002	0.005
lzfpm	0.103	0.176
lzfsm	-0.006	0.016
adimp	0.006	0.006
uzk	-0.001	0.001
lzpk	0.501	0.613
lzsk	0.014	0.067
zperc	0.001	0.001
rexp	0.000	0.001
pctim	0.003	0.002
pfree	0.011	0.017

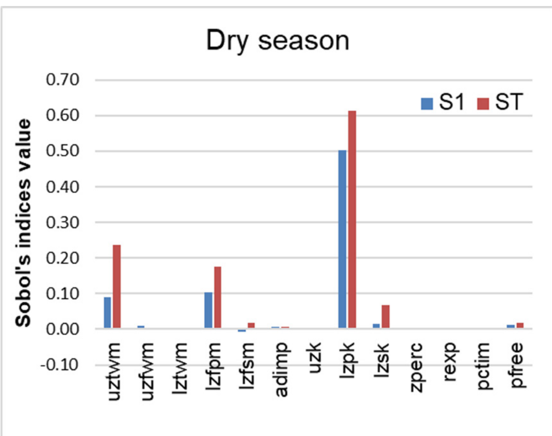

Figure 6. Comparison of independent and total influences of SAC-SMA's parameters in dry season

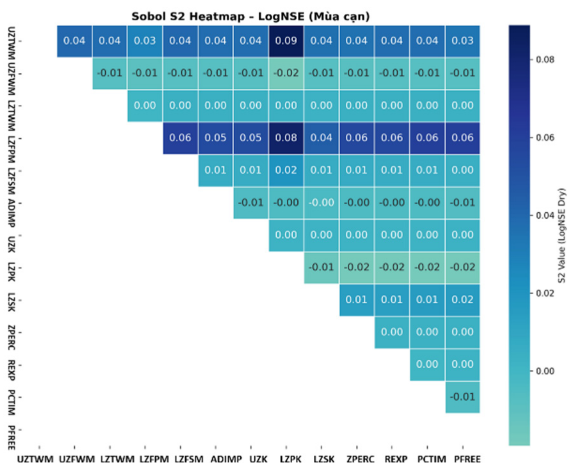

Figure 7. Heatmap of S2 index in dry season

3.3. Discussion

The Sobol analysis indicates prioritizing LZFSM, LZFPM, LZTWM, UZFWM, and ADIMP to achieve the greatest improvement in flood-season simulations in Mu Cang Chai watershed. Conversely, less sensitive parameters such as UZTWM, UZK, PCTIM, and PFREE can be fixed at reasonable a priori values to reduce search space in calibration step. For interaction-dominated parameters (ZPERC, REXP, LZPK, LZSK), joint calibration with the dominant group is advisable to maintain stability and minimize multiple solutions.

The sensitivity results for the dry season show a different structure of parameter influence compared to the flood period. Overall, the dry-season sensitivity analysis emphasizes that depletion rate in the lower free storage (LZPK) are the key independent drivers of low flow, while soil moisture storage capacities in the tension zones (UZTWM, LZTWM) primarily contribute through interactions. This implies that calibration for dry-season performance should prioritize depletion rate from free-low storage, while ensuring that interaction-driven parameters such as UZTWM and LZTWM are constrained to realistic values.

4. Conclusions

This study applied Sobol-based global sensitivity analysis to investigate the parameter importance of the Sacramento Soil Moisture Accounting (SAC-SMA) model under contrasting hydrological regimes, namely the flood and dry seasons. These findings highlight that SAC-SMA parameter sensitivity is highly season-dependent: Flood flows are governed by deep storage and release, while dry-season dynamics are driven by soil moisture availability in upper and tension storages. The clear interaction structures revealed by second-order Sobol’s indices underscore the need for targeted calibration strategies that account for both independent and interaction-driven parameters rather than treating them uniformly. Thus, by applying the Sobol’s framework, we can identify the key parameters under different temporal conditions to implement a rational calibration that enhances the simulation capability of the SAC-SMA model.

Author contribution statement: *Luong Tuan Trung: Generating and outlining the research; Luong Huu Dung: Outlining the research and developing the methodology; Ngo Thi Thuy: Developing the methodology and commanding modelling.*

Acknowledgement: *This research was supported by the Ministry of Agriculture and Environment Minitrial Project “Research on developing open-source hydrology model of SAC-SMA integrating artificial intelligent model in real-time flood forecasting, a case study in Nam Mu basin” (code: TNMT.DL.2023.06).*

Competing interest statement: *The authors declare that this article was the work of the authors, has not been published elsewhere, has not been copied from previous research; there was no conflict of interest within the author group.*

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Appendix 1. Description of parameters in SAC-SMA model (adopted from [14])

Parameter Category	Parameter	Description	Reference range
Storage capacity	UZTWM	Upper zone tension water maximum storage (mm)	1 - 150
	UZFWM	Upper zone free water maximum storage (mm)	1 - 150
	LZTWM	Lower zone tension water maximum storage (mm)	1-1000
	LZFSM	Lower zone free water supplement maximum storage (mm)	1-1000
	LZFPM	Lower zone free water primary maximum storage (mm)	1-1000
Runoff depletion rates	UZK	Upper zone free water lateral depletion rate (1/day)	0.1-0.5
	LZPK	Lower zone primary free water depletion rate (1/day)	0.0001-0.25
	LZSK	Lower zone supplement free water depletion rate (1/day)	0.01-0.25
Percolation rate	ZPERC	Maximum percolation rate	1-250
	REXP	Exponent of the percolation equation	0-5
Impervious area	ADIMP	Additional impervious area	0-0.4
	PCTIM	Impervious fraction of the watershed	0.000001 - 0.1
	PFREE	Percentage of water percolation directly to lower zone free water storage	0-0.6
Minor parameter	RIVA	Riparian vegetation fraction	0
	SIDE	Ratio of deep recharge to channel baseflow	0
	RESERV	Percentage of lower zone free water not transferable to lower zone tension water	0.3