

The impact of calibration strategies on future evapotranspiration projections: a SWAT-T comparison of three hydrological modeling approaches in West Africa

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Abstract.

Actual evapotranspiration (AET) is a key component of the water cycle and a crucial source of uncertainty in hydrological modeling, particularly for sub-humid and AET-dominant regions such as West Africa. In this region, climate change is projected to be substantial, which will catalyze hydrological changes. In the climate-hydrological modeling chain for impact assessment, multiple sources of uncertainty are embedded. ~~While the uncertainties inherent in general circulation models (GCM) are difficult to reduce, minimizing uncertainties from hydrological modeling remains a critical focus for researchers and practitioners.~~ Hence, the present study investigates how different calibration strategies influence simulated future hydrological projections in West Africa. Given the key role of AET in West Africa, the study particularly evaluates how calibration shapes simulated future AET dynamics. In addition, we test whether a specific plant growth modeling, attributed as leaf area index (LAI), can be used as a proxy to predict AET. The Bététou Catchment in Benin is selected as a demonstration case along hydrological modeling with the eco-hydrological SWAT-T model. To investigate calibration impacts, we apply three strategies, which range from simple (discharge (Q) only) to more comprehensive (Q and LAI; Q, LAI, and AET) approaches. We ~~use~~ apply the Robust Parameter Estimation algorithm in each calibration strategy to address parameter ~~equifinality~~equifinality. We use the standardized future climate data from ISIMIP3b (CMIP6) with five GCMs and three emission scenarios and evaluate changes for the near (2031–2050) and far (2070–2099) future periods. The ~~findings show that the amount of future annual AET depends~~ calibration results demonstrate that the combined "Q + LAI" improves representation of the AET seasonal pattern compared with "Q only". From "Q only" to "Q + LAI", the minimum (median) performance increases from $E_{KGE,AET} = 0.59$ ($E_{KGE,AET} = 0.84$) to $E_{KGE,AET} = 0.81$ ($E_{KGE,AET} = 0.86$), respectively. The findings moreover show that projected changes in annual AET depend on the calibration strategy, where ~~the change signal for all strategies indicates AET increases.~~ The approach including AET calibration (Q, LAI, AET) shows high future changes, with e.g., multi-model mean changes for SSP5–8.5 of $\Delta E_{near} = 5.8\%$ and $\Delta E_{far} = 8.4\%$. The results moreover demonstrate that the combined all strategies indicate increasing future AET. More precisely, the "Q + LAI" (886 to 918 mm yr⁻¹) and "Q + LAI + AET" can be used as a proxy to predict AET rates at the catchment scale. For discharge, the change signal mostly indicates future decreases across all calibration strategies with multi-model mean changes for SSP5–8.5 of $\Delta Q_{far} = -7.0\%$ (Q, LAI, AET) to $\Delta Q_{far} = -1.6\%$

25 ~~(Q only). Yet~~ (904 to 932 mm yr⁻¹) approaches show similar climate sensitivities and project higher future annual AET rates than the "Q only" approach (846 to 889 mm yr⁻¹). For discharge, contrasting predictions of future changes depending on single GCMs are simulated, mostly indicating decreases across all calibration strategies. The present study ~~underseores the relevance of uncertainty integration in climate-hydrological modeling and~~ provides insights into how calibration choices affect AET simulations for hydrological projections in West Africa. While this study demonstrates that detailed LAI modeling can improve the simulation of seasonal AET dynamics, further research is required to evaluate whether LAI can be used as a reliable proxy for AET in hydrological watershed models.

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1 Introduction

Actual evapotranspiration (AET) is a key hydrological attribute commonly used as an indicator related to water availability (Chawanda et al., 2024), and to estimate agricultural, vegetation, and drought stressors (Rind et al., 1990; Fisher et al., 2017; Miralles et al., 2025). In the regional hydrology in the sub-humid parts of West Africa, AET, vegetation phenology, and soil moisture are paramount to the land-atmosphere feedbacks (Hingerl et al., 2025). In these mechanisms, AET plays an essential role where its rate to precipitation can be up to 80 % (Rodell et al., 2015). In tropical and perennial vegetated regions, the contribution of plant transpiration to AET is particular high (Wei et al., 2017) given the direct linking of plant growth and leaf area index (LAI) to the canopy conductance (Good et al., 2014; Wang et al., 2014).

40 Climate change impacts on the future hydrology in West Africa are projected to be substantial. It is reasonably certain that precipitation and temperature intensities increase for the entire West African region, specifically leading to higher mean air temperatures, more frequent extreme heat days, and recurring sub-daily heavy precipitation events (IPCC, 2022). The change of mean annual precipitation in West Africa is spatially contrasting, where drying in the western and wettening in the eastern parts are projected (IPCC, 2022). The hydrological response to future climate changes is typically assessed in a climate-hydrological modeling chain. In this, hydrological (impact) models are forced with downscaled climate projections of general circulation models (GCMs) under various greenhouse gas emission scenarios. Since hydrological responses to future climate conditions are assessed using models calibrated under current climate, robust calibration strategies and model parametrisation are essential (Krysanova et al., 2017; Hattermann et al., 2018).

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The sensitivity of the calibration strategy on the regional-scaled climate impact assessment is well-documented (Huang et al., 2020; Ismail et al., 2020; Koch et al., 2020; Mishra et al., 2020; Wen et al., 2020). These studies report impacts of simple (discharge only) compared to comprehensive (multi-gauge or multi-objective) calibration strategies, particularly with respect to future discharge changes. For instance, future projected discharge can be up to 10 % higher for models from multi-objective calibration compared to discharge only approaches (Huang et al., 2020).

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These studies however relied on single-best model parametrisations for the climate impact assessment. Model equifinality impairs robust hydrological modeling for current (Beven, 2006) and future climate (Her et al., 2019), because multiple model parameter sets can accurately represent the hydrological cycle. Different approaches to address parameter equifinality exist, such as Generalized Likelihood Uncertainty Estimation (Beven and Binley, 2014), Robust Parameter Estimation (ROPE) (Bár-

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dossy and Singh, 2008), or Markov Chain Monte Carlo methods (Roberts and Rosenthal, 2004), among others, with which multiple equally-well performing parameter sets can be derived. The uncertainty contributions from GCMs typically exceed those stemming from parameter equifinality, as shown by studies such as Her et al. (2019) or Brigode et al. (2013). Yet, the direction and magnitude of future hydrological changes can still vary considerably depending on the calibration strategy and parameter sets (Mendoza et al., 2016).

Among other hydrological impact models, the Soil and Water Assessment Tool (SWAT) model and its open-source successor SWAT+ have been widely applied for climate impact assessment in West Africa (Akoko et al., 2021). It is a process-describing model specified to represent catchment hydrology, crop management and vegetation growth (Arnold et al., 1998). Climate impact studies have covered the Niger Basin (Angelina et al., 2015; Eisner et al., 2017; Krysanova et al., 2017; Animashaun et al., 2023; Chawanda et al., 2024); the Mono River (Houngue et al., 2023); the Ouémé Basin (Bossa et al., 2012, 2014; Danvi et al., 2018); the Volta (Kankam-Yeboah et al., 2013; Sood et al., 2013), Pra (Awotwi et al., 2021), Owabi (Osei et al., 2019), and Veia River (Larbi et al., 2021) in Ghana; and the Tougou River (Yonaba et al., 2023). The studies indicate that precipitation projections for West Africa are variable depending on the applied GCM, emission scenarios and future period. This variability translates into varying streamflow projections across the region, where the Niger Basin indicates mixed discharged trends, the Ouémé Catchment reports decreased discharges, and streamflow increases for the Mono River Catchment.

These studies mostly focus their modeling on discharge, and AET – despite being a key driver of the regional hydrological cycle – has been integrated in the model evaluation only partially. Few studies, such as Chawanda et al. (2024), calibrated the SWAT+ model against discharge and AET. Most others estimate future AET from SWAT models being optimized with discharge-only calibration approaches (Bossa et al., 2012; Sood et al., 2013; Bossa et al., 2014; Danvi et al., 2018; Larbi et al., 2021; Animashaun et al., 2023; Zouré et al., 2023). However, the modeling of AET in process-describing hydrological models, such as SWAT/SWAT+, substantially relies on parameters that also influence runoff generation, e.g., interception or soil moisture. As shown by our study in the following, calibration approaches without AET calibration result in a future AET increase of 4.0 % compared to an increase of 9.2 % when AET is integrated in the model optimization. Hence, without explicit model calibration against AET, projections of future AET can remain constrained and potentially misleading.

In this study, we examine how different calibration strategies influence simulated AET and discharge projections in a climate impact assessment context. We demonstrate how future rates of AET and discharge can differ whether AET is considered in the model calibration. In addition, this study evaluates the role of vegetation (attributed as LAI) in assessing AET. We test whether LAI can be used as a proxy to predict future AET dynamics. To date, no study has yet discussed the implications of AET being disregarded in the calibration but used for future assessments in West Africa.

We evaluate the implication of three different model calibration strategies on the climate impact assessment. The strategies include: i) a conventional single-objective optimization using only streamflow at the catchment outlet ("Q only"); ii) a multi-objective optimization considering streamflow at the outlet and LAI at the subbasin scale ("Q + LAI"); and iii) a multi-objective optimization integrating streamflow at the outlet, along with LAI and AET at the subcatchment scale ("Q + LAI + AET"). We derive multiple equally-well performing parameter sets with the ROPE algorithm to address the uncertainty from equifinality. ROPE is applied for single- (discharge) and multi-objective optimisation, where discharge, AET, and further information

like the vegetation attribute LAI are considered. These models are used for the climate impact assessment to investigate the difference between single-best and multiple near-optimal parameter estimations, with a particular focus on AET simulations.

95 As a demonstration case, we apply the SWAT-T (for tropics) model for the Bétérrou Catchment in Benin.

This study demonstrates the implications of calibration strategies on the model spread and projection for AET estimation. We make use of statistically downscaled climate model data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) that provides standardized climate impact data for cross-sectoral studies. We force the hydrological model with climate data from ISIMIP3b (five GCMs and three emission scenarios) based on the Coupled Model Intercomparison Project

100 Phase 6 (CMIP6) (Lange, 2019) to minimize uncertainties from downscaling, bias adjustment, and scenario framing.

2 Methods

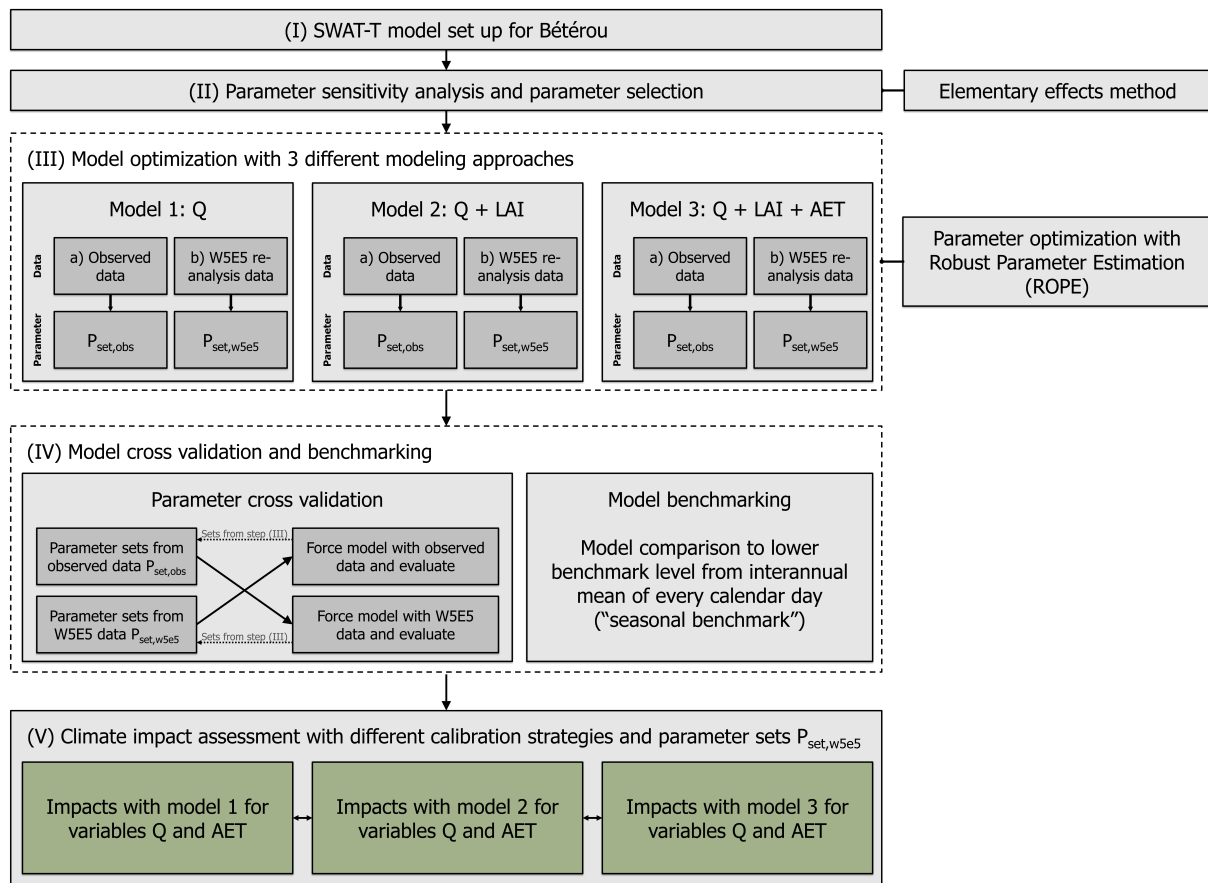


Figure 1. Methods applied in the present study to evaluate different calibration strategies for climate impact assessment.

Figure 1 gives an overview of the methods applied in this study. First, the basin-scale SWAT-T model is set up for the Bétérrou Catchment in Benin. The parameter sensitivity is quantified with the elementary effects method after Morris (Morris, 1991), and, subsequently, relevant parameters are selected. We apply the Morris method, because its computation of the elementary effects allows to quantify and rank non-linear model responses, and identify (non-) influential parameters (Morris, 1991; Campolongo et al., 2007). Three different calibration strategies are investigated: model optimization regarding discharge only; discharge and LAI; and discharge, LAI, and AET. We use the ROPE algorithm (Bárdossy and Singh, 2008) to derive multiple well-performing parameter sets and to address parameter equifinality. We force the hydrological model with observed (Galle et al., 2018; Schlueter et al., 2019; Vogel et al., 2018; Rauch et al., 2024) and the W5E5 meteorological data (Lange et al., 2021). The robustness of the model optimization is checked with a cross validation and model benchmarking. Finally, the role of the calibration strategy is evaluated with respect to the climate impact assessment, where future hydrological response (discharge and AET) predicted by each of the three approaches is evaluated. The responses for near and far future climate projections are derived and the implications of different modeling approaches are discussed.

2.1 Model description and parameter selection

The SWAT-T model is a further development of the SWAT ecohydrological model (Arnold et al., 1998). The key enhancement of SWAT-T is the modification of the plant growth module to better represent the plant phenology in tropical regions (Alemayehu et al., 2017). A detailed explanation of the advances as well as a comprehensive case study of SWAT-T is presented in Alemayehu et al. (2017). The SWAT-T model leads to more accurate predictions of AET in regions with perennial plant growth (Zhang et al., 2020; Fernandez-Palomino et al., 2021; Ferreira et al., 2021; López López et al., 2017; Merk et al., 2024). Aside from the plant module modification, SWAT-T remains identical to SWAT. The original SWAT model has been applied for river basins worldwide (Arnold and Fohrer, 2005; Tan et al., 2020), as well as regionally in West Africa and for different catchments in Benin (Akoko et al., 2021). In Benin, most studies focused on the discharge simulation for the Ouémé River basin (Bossa et al., 2014; Poméon et al., 2018) and as its subcatchments (Giertz et al., 2006; Bossa et al., 2012; Duku et al., 2016, 2018; Danvi et al., 2017; Togbévi et al., 2020). Remotely sensed AET has also been a primary model optimization target to predict streamflow (Odusanya et al., 2019, 2021). To the best of our knowledge, the SWAT-T model has only been applied in Benin for the assessment of the LAI–AET interaction (Merk et al., 2024), which demonstrates the AET prediction through LAI on the footprint scale.

The SWAT/SWAT-T model is a process-oriented ecohydrological model for the catchment-scale water balance estimation. It partitions the computation of the water balance into five storages: snow, canopy storage, soil profiles, and a shallow and a deep aquifer. The water balance in SWAT/SWAT-T is described as:

$$\Delta S = \sum_{i=1}^N (P - Q_{total} - E - w_{losses}), \quad (1)$$

where ΔS is the change in storage; N is the time in days or months; P is the precipitation; Q_{total} is the total runoff (in SWAT "water yield") as a sum of surface runoff, lateral flow, and base flow; E is AET; and w_{losses} are deep groundwater losses. We use the Soil Conservation Service (SCS) curve number (CN) method to model the surface runoff. The SWAT/SWAT-T

135 model is spatially discretized into subbasins and further subdivided into hydrological response units (HRUs). Generally, three methods are available to compute potential ET (E_0) in SWAT/SWAT-T: the Hargreaves method (Hargreaves and Samani, 1985), the Priestley-Taylor method (Priestley and Taylor, 1972), and the Penman-Monteith method (Monteith, 1965). Once E_0 is calculated, it is partitioned into potential plant transpiration (T_{plant}) and potential soil evaporation (E_{soil}). We use the Penman-Monteith method since it integrates temperature- and energy-based assumptions and vegetation. Merk et al. (2024) demonstrated that this method outperforms the other two options for AET prediction for characteristic West African land cover types (forest and shrubland), which are also most dominant in the Bétérrou Catchment. E_0 after Penman-Monteith in SWAT/SWAT-T is computed as:

$$E_0 = \frac{\Delta \cdot (R_{net} - G) + \rho_{air} \cdot c_p \cdot (e_z^0 - e_z) / r_a}{\lambda \cdot (\Delta + \gamma \cdot (1 + r_c / r_a))}, \quad (2)$$

where λ is the latent heat of vaporization; R_{net} is the net radiation; Δ is the slope of the saturation vapor pressure-temperature curve; ρ_{air} is the air density; c_p is the specific heat at constant pressure; e_z^0 is the saturation vapor pressure of air at height z ; e_z is the water vapor pressure of air at height z ; r_a is the aerodynamic resistance; and r_c is the plant canopy resistance. In SWAT/SWAT-T with E_0 after Penman-Monteith, r_a and r_c are attributed to an alfalfa grass reference with constant values (Neitsch et al., 2011). For the computation of T_{plant} , the Penman-Monteith equation is also used, and r_a and r_c are derived from an actual plant, where the plant's modeled canopy height and LAI are considered. E_{soil} is then determined as $E_{soil} = E_0 - T_{plant}$. Actual plant transpiration and soil evaporation are computed based on water availability and biophysical factors, such as LAI, root depth, and soil properties such as field capacity. The total actual evapotranspiration (AET) is the sum of actual plant transpiration and soil evaporation.

A total of 26 parameters have been investigated in this study (Table 1). The list of 26 parameters is gathered with a literature review, where selected SWAT studies in Benin (Schuol and Abbaspour, 2006; Schuol et al., 2008; Bossa et al., 2012, 2014; Duku et al., 2016; Danvi et al., 2017; Poméon et al., 2018; Houunkpè et al., 2019; Togbévi et al., 2020; Odusanya et al., 2019, 2021) and SWAT-T studies (Alemayehu et al., 2017; López-Ramírez et al., 2021; Fernandez-Palomino et al., 2021; Ferreira et al., 2021; Merk et al., 2024) have been screened. The focus was on peer-review studies, where the parameter choice and calibration strategy is transparent. All 26 parameters in Table 1 are evaluated in the sensitivity analysis. Based on the sensitivity ranking, the 15 most influential parameters are considered for the model optimization. The plant parameters FRGRW₂, LAIMX₂, DLAI, T_BASE, PHU, and GSI are specified in SWAT-T for each land cover type. The Bétérrou Catchment is primarily covered by forest, shrubland, and cropland. To avoid an excessive number of parameters (e.g., 5 plant parameters $\times$ 3 land cover types), we transfer the parameter values for FRGRW₂, LAIMX₂, DLAI, T_BASE, PHU, and GSI for each land cover type from Merk et al. (2024), who investigated specific sites within the Bétérrou Catchment. In the model optimization, each plant parameter is changed through a multiplier from 0.75 to 1.25 (see Tab. A7).

165 Insensitive parameters are not considered in the optimization but kept constant (Table 1). The parameters ALAI_MIN and BLAI are derived based on the maximal and minimal values of the GLASS-LAI time series, respectively. The multipliers for the plant parameters and constant values for insensitive parameters are used in the optimization to reduce the parameter space and address parameter equifinality.

Table 1. List of parameters used with their description and a cross ("X") if the parameter is considered in the optimization in this study. The superscripts denote the SWAT-T/West Africa study the parameter has been investigated: ¹ to ¹⁶ correspond to Schuol and Abbaspour (2006); Schuol et al. (2008); Bossa et al. (2012, 2014); Duku et al. (2016); Danvi et al. (2017); Poméon et al. (2018); Hounkpè et al. (2019); Togbévi et al. (2020); Odusanya et al. (2019, 2021); Alemayehu et al. (2017); López-Ramírez et al. (2021); Fernandez-Palomino et al. (2021); Ferreira et al. (2021); Merk et al. (2024), respectively. The table also lists the studies from which the parameters for the less sensitive parameter are transferred from.

Parameter	Description (unit)	Optimization
Parameters identified in the sensitivity analysis to be sensitive		
FRGRW ₂ ^{12,13,14,16}	Fraction of PHU as second point on the optimal LAI curve (–)	X
DLAI ^{12,13,14,16}	Fraction of total PHU when leaf area begins to decline (–)	X
T_BASE ^{12,13,14,16}	Minimum temperature for plant growth (°C)	X
PHU ^{12,13,14,16}	Total number of heat units needed for plant maturity (–)	X
GSI ^{10,12,16}	Maximum stomatal conductance (m s ^{–1})	X
CAN_MX ^{10,11,15,16}	Maximum canopy storage (mm)	X
ESCO ^{1,2,3,5,6,7,8,9,10,11,12,13,15,16}	Soil evaporation compensation factor (–)	X
EPCO ^{5,6,7,8,10,11,12,13,15,16}	Plant uptake compensation factor (–)	X
SOL_AWC ^{1,2,3,4,5,6,7,8,9,10,11,12,13,14,16}	Available water capacity of the soil layer (mm)	X
SOL_BD ^{2,7,8,11,14,16}	Moist bulk density (g cm ^{–3})	X
GW_REVAP ^{2,3,5,6,7,8,9,12,15,16}	Groundwater re-evaporation coefficient (–)	X
GWQMN ^{1,2,3,4,5,6,7,8,9,12,15}	Threshold depth of water for baseflow to occur (mm)	X
RCHRG_DP ^{1,2,3,7,8,9,12,14,15,16}	Deep aquifer percolation fraction (–)	X
REVAPMN ^{1,2,3,5,7,8,9,11,12,15,16}	Threshold depth of water for re-evaporation to occur (mm)	X
GW_DELAY ^{2,3,4,6,7,8,9,11,13,14,15}	Ground water delay (day)	X
Parameters identified in the sensitivity analysis to be less sensitive		
BLAI ^{12,13,14,16}	Maximum potential leaf area index (m ² m ^{–2})	Observed data
ALAI_MIN ^{12,13,14,16}	Minimum LAI for plant during dormant period (m ² m ^{–2})	Observed data
SOL_K ^{3,4,7,8,9,10,13,14,16}	Saturated hydraulic conductivity (mm hr ^{–1})	Judex and Thamm (2008)
FRGRW ₁ ^{12,13,14,16}	Fraction of PHU as first point on the optimal LAI curve (–)	Merk et al. (2024)
LAIX ₁ ^{12,13,14,16}	Fraction of BLAI as first point on the optimal LAI curve (–)	Merk et al. (2024)
LAIX ₂ ^{12,13,14,16}	Fraction of BLAI as second point on the optimal LAI curve (–)	Merk et al. (2024)
T_OPT ^{12,14,16}	Optimal temperature for plant growth (°C)	Merk et al. (2024)
SURLAG ^{1,2,4,5,7,8,9,12,14,15}	Surface runoff lag coefficient (–)	Bossa et al. (2014)
SOL_RD ¹⁶	Maximum rooting depth of soil profile (mm)	Merk et al. (2024)
ALPHA_BF ^{2,3,4,6,8,9,10,11,12,13,15}	Base flow alpha factor (day ^{–1})	Bossa et al. (2014)
CN2 ^{1,2,3,4,5,6,7,8,9,10,11,12,13,14,16}	Initial SCS runoff curve number (–)	Alemayehu et al. (2017)

2.2 Study site and model set up

170 The Bétérrou catchment is the Northern most headwater catchment of the Ouémé River Basin in Benin (Figure 2). It covers an area of 10100 km². The catchment is relatively flat with an altitude range from 248 m to 598 m above sea level. The land cover is a typical West African combination mainly consisting of gallery forests (52 %), savannah (33 %), and agriculture (15 %), where the landscape is marked by scattered mosaics of woody savannah with grassy understories. The region is in a natural state with a small share of urban areas (<1 %) (Judex and Thamm, 2008).

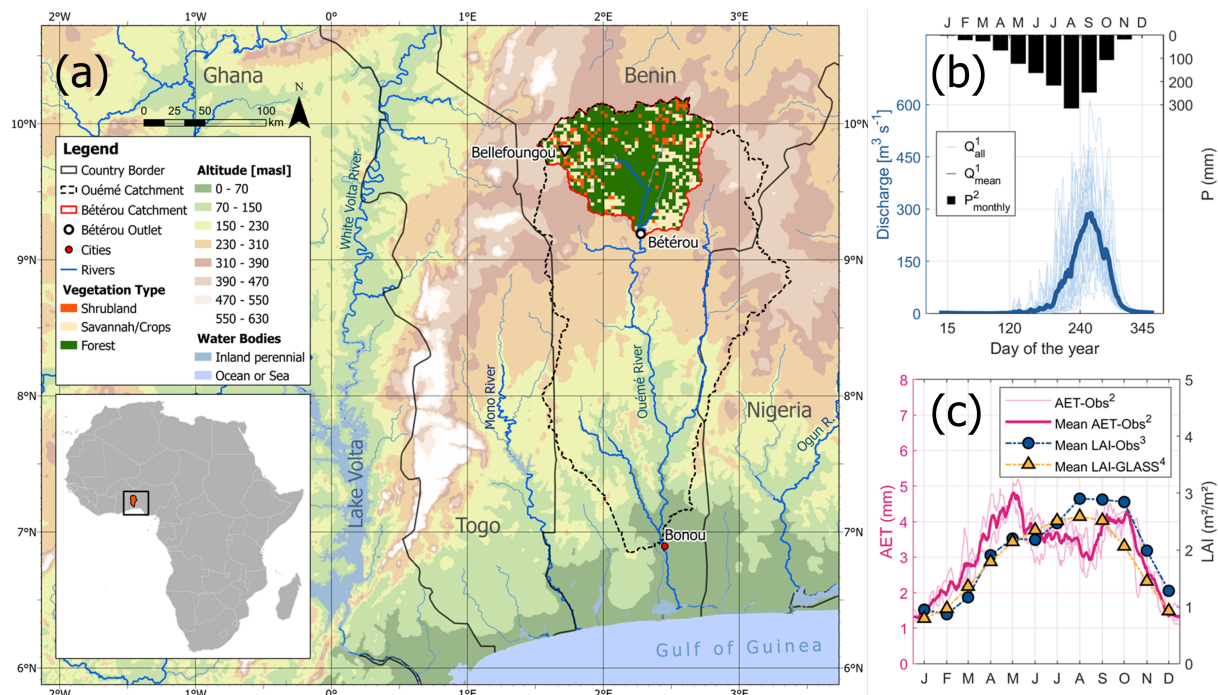


Figure 2. (a) Overview of the Bétérrou Catchment and location of the EC system in Bellefoungou; (b) monthly mean values of precipitation (Bellefoungou) and daily mean values of discharge (Bétérrou); (c) and measurements of AET and LAI in Bellefoungou: an overview of observed AET dynamics (in purple), mean monthly observed LAI (in blue) as well as the mean monthly values of GLASS LAI (in yellow). References for the data used to display the map are also listed in the Appendix (see Table A9). The superscripts in panels (b) and (c) denote the corresponding time periods: ¹ January 1996 to December 2020; ² in (b) January 2006 to December 2020; ² in (c) January 2008 to December 2010; ³ from July 2008 to May 2010; ⁴ from January 2007 to December 2015. Publisher’s remark: please note that the above figure contains disputed territories.

175 The agriculture in this region is combination of cash crops, such as cotton, and subsistence-driven smallholders. The cultivated crops are usually crops like maize, yam, sorghum, bean, millet, or cassava (Janssens et al., 2010). The cropping calender in this region follows the rainy season and can generally be dated from May to November – with crop specific variations in planting and harvesting (Forkuor et al., 2014). The distinct dry and wet streamflow seasonality is typical for catchments along

the Guinean Savanna. The maximum daily average streamflow occurs in September with an estimated value of $290 \text{ m}^3 \text{ s}^{-1}$. The climate in the Bétérou catchment is typical for Sub-Saharan, sub-humid Africa. The annual precipitation ranges from 1100 to 1500 mm (Mamadou et al., 2016; Bliefernicht et al., 2019). The precipitation pattern is unimodal, with a rainy season between April and October, whereas from November to March, the dry season occurs. The annual mean daily temperature is 25°C (Galle et al., 2018). The soils in the Bétérou catchment consist of ferric soils with loamy sand present in the upper soil horizons (Giertz and Dieckkrüger, 2003). Generally, the AET data follows the seasonal pattern of LAI (Fig. 2c). In addition, a decrease in AET in the wet season can be observed for this region. During this season, the atmospheric water demand is reduced due to high air humidity resulting in low water pressure deficits as shown by Mamadou et al. (2016).

For the model set up, we subdivided the Bétérou Catchment into 14 subbasins and 126 HRUs. The dominant land cover types forest, shrubland, and cropland are assigned to the SWAT/SWAT-T data base of "FRSD", "RNGE", and "AGRL", respectively. The share of cropland cover is relatively small (15 %) and data for detailed crop modeling is scarce. Thus, we apply a conceptual approach to integrate crops. We assign the generic plant data base "AGRL". For cropland, the plant growth is not automatically triggered by the soil moisture index but its planting and harvesting is scheduled in the management operations to follow the rainy season (Forkuor et al., 2014). We validate the conceptual approach by comparing the simulated LAI of croplands to the reference of GLASS-LAI. The simulations are run for daily timesteps.

2.3 Data used in this study

The SWAT-T model is set up using the data listed in Table 2. We force the models with daily data for precipitation, temperature, relative humidity, solar radiation, and wind speed from two data sets. The first set of forcing data is the ISIMIP3b baseline data set from ISIMIP3b (W5E5 data, Lange et al. (2021)). In ISIMIP3b, the baseline (historical) forcing is not a raw GCM historical simulation but the observation-based W5E5 dataset, to which all future GCM projections are bias-adjusted. This ensures that the statistical properties (mean, variability, and seasonality) of the future projections are consistent with the historical reference climate. For the Bétérou Catchment, the W5E5 baseline captures the main precipitation and temperature patterns reasonably well (see A9 in Appendix). Generally, the W5E5-precipitation tends to smooth individual extreme rainfall events and the W5E5-temperature reflects higher maximal daily temperatures than the monitored data.

Secondly, we use observed data (AMMA-CATCH (Galle et al., 2018) and precipitation data from KASS-D (Schlueter et al., 2019; Vogel et al., 2018)). The precipitation point observations were regionalized to a 0.05° grid (5 km resolution) using a simple nearest-neighbor interpolation approach (Rauch et al., 2024). The resulting gridded rainfall fields were then spatially averaged over each sub-catchment to produce 14 sub-catchment-specific rainfall time series, which served as precipitation inputs in the model setup. Both data sets (W5E5 and observed data) are used for a separate calibration.

As a reference to SWAT-T's simulated LAI, we use the GLASS-LAI data, because it is reasonable performance in applications worldwide (Liang et al., 2014). Typically, raw LAI data from satellite-based products (e.g., MODIS) encounter uncertainties and noise in tropical regions (Viovy et al., 1992; Atkinson et al., 2012). The GLASS-LAI algorithm provides robust LAI data through tailoring MODIS and CYCLOPES products with general regression neural networks (Liang et al., 2014). In SWAT-T, LAI is simulated for each HRU. The raster cell size of the GLASS-LAI data does not align with the HRUs.

Table 2. Overview of the data sets that are applied in this study. ¹ Observed precipitation data from Rauch et al. (2024) are gridded through nearest-neighbor from the KASS-D database; ² Observed meteorological data covered solar radiation, temperature, wind speed, and relative humidity.

Variable	Datasets/Model	Database name or source
Data for model set up		
Digital elevation model	Copernicus GLO-30 (30m x 30m)	Copernicus (2022)
Land cover map	Copernicus Global Land Service (100m x 100m)	Buchhorn et al. (2020)
Soil map	IMPETUS Soil Data Set	Judex and Thamm (2008)
Model forcing data		
Precipitation ¹	Gridded (0.05° x 0.05°) from KASS-D	Rauch et al. (2024)
Meteorological data ²	AMMA-Catch network	Galle et al. (2018)
ISIMIP3b reference data	W5E5	Lange et al. (2021)
Climate projections	ISIMIP3b: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL	Lange (2019)
Data for model performance evaluation		
Streamflow	AMMA-Catch network (pointwise)	Galle et al. (2018)
AET	FLUXCOM (rastered, 0.0833° x 0.0833°)	Jung et al. (2019)
LAI	GLASS-LAI (rastered, 250m x 250m)	Liang et al. (2021)

We compute the mean GLASS-LAI value for each subbasin by averaging the values of the raster cells that cover it. We then aggregate the simulated LAI at the subbasin scale to match the GLASS-LAI reference. For each subbasin, the subbasin-averaged LAI value is calculated based on the corresponding HRUs, with the LAI weighted by the area of each HRU within the subbasin. In the model evaluation, we compare the weighted-average subbasin values of the GLASS-LAI to simulated LAI. For AET, we use FLUXCOM-AET (Jung et al., 2019), which combines MODIS, meteorological and eddy covariance tower data to provide a global data set of energy fluxes.

We have compared the FLUXCOM-AET product and with eddy-covariance (EC) observations from the Bellefoungou flux tower (latitude 9.791°N, longitude 1.718°E) which is part of the AMMA-Catch network in the western part of the Bétérou Catchment in Benin (see Figure 2). This validation shows a reasonable fit of FLUXCOM-AET to the EC data (see Figure A10 and Table A4 in Appendix). The EC data represents a localized area and does not fully capture the spatial heterogeneity within the corresponding FLUXCOM-AET grid cell (0.083°) or the entire Bétérou catchment. Consequently, some discrepancies in both magnitude and short-term dynamics between FLUXCOM and tower-based AET can be expected. Nevertheless, FLUXCOM-AET captures the seasonal timing and variability of monitored AET reasonably well. Therefore, we apply FLUXCOM-AET as a promising validation dataset for catchment-scale AET patterns.

Similarly to LAI, the AET data is aggregated at the subbasin scale, with FLUXCOM raster cells weighted by the area of each subbasin. In SWAT-T, AET is simulated at the HRU level and averaged at the subbasin scale. We compare the weighted-

averaged AET data from both FLUXCOM and SWAT-T at the subbasin scale. We use the Kling-Gupta efficiency (E_{KGE}) after Gupta et al. (2009), percent bias (E_{PBias}), and the coefficient of determination (E_{R^2}) (see Appendix A3 for additional equations) to quantify the SWAT-T performance to model daily discharge, LAI, and AET. Observed streamflow, GLASS-LAI, and FLUXCOM-AET data is respectively available from January 1996 to December 2020, January 2001 to December 2015, and January 2001 to December 2014. Observed precipitation data is available from January 1981 to December 2017. The meteorological data from the AMMA-Catch network is available from January 2006 to December 2020.

We use the daily meteorological data of five GCMs and three scenarios from CMIP6 for the climate impact assessment. The selected scenarios refer to the low, medium-to-high, and high narrative SSP scenarios 1–2.6, 3–7.0, and 5–8.5, respectively, where number before the hyphen represents the shared socio-economic pathway narrative and the number after indicates the radiative forcing by 2100 in Wm^{-2} . We use the climate forcing data from the ISIMIP3b initiative (Lange, 2019) with five GCMs (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL), since it provides bias-adjusted, downscaled, and standardized climate data. It has been widely used by the hydrological impact modeling community, enabling cross-sectoral comparisons. For instance, Romanovska et al. (2023) report the applicability of ISIMIP3b data for West Africa, and assess uncertainties and impacts on agriculture for the region.

2.4 Sensitivity analysis with the Morris method

Table 1 lists 26 parameters that have been used to assess the vegetation, AET, and discharge simulation with SWAT/SWAT-T. We perform a sensitivity analysis to understand the parameter response complexity on the catchment-scale. Based on a sensitivity ranking, the parameter space can be reduced to the most important parameters. We apply the elementary effects (or Morris) method (Morris, 1991; Campolongo et al., 2007). The application of the Morris method allows the quantification of the parameter sensitivity through statistical means (μ^* -values) of the elementary effects (Morris, 1991; Campolongo et al., 2007). While the elementary effects are a local sensitivity measure, the computation of multiple elementary effects for varying parameter subsets enables a quasi-global sensitivity analysis (Saltelli et al., 2008). Compared to other sensitivity approaches, it is moreover computationally efficient due to its one-at-a-time sampling strategy (Pianosi et al., 2016). A brief description on the mathematical background of the Morris method can be found in A7. We apply Latin hypercube sampling to generate a distributed parameter space. We define $r = 500$ and $q = 26$ parameters with which the total sample size is $N = 13500$. The model sensitivity is evaluated with KGE. We quantify the influence of the SWAT-T parameters on streamflow, LAI, and AET separately, denoted as $E_{KGE,Q}$, $E_{KGE,LAI}$, and $E_{KGE,AET}$, respectively. Additionally, we assess the parameter sensitivity on the equally-weighted combination of all three objectives, $E_{KGE,all}$:

$$E_{KGE,all} = 1/3 \cdot E_{KGE,Q} + 1/3 \cdot E_{KGE,LAI} + 1/3 \cdot E_{KGE,AET}. \quad (3)$$

The combination of separated and composed sensitivity analysis objective enhances the understanding of the parameter response complexity. For the application of the Morris method, we integrated the approaches of Morris (1991), Campolongo et al. (2007), and Gupta et al. (2009) into a set of MATLAB scripts.

2.5 Three calibration strategies with ROPE, evaluation and robustness check

Table 3 summarizes the calibration strategies with their level of complexity. The approaches consider i) only streamflow at the catchment outlet ("Q only"); ii) streamflow at the outlet and LAI at the subcatchment scale ("Q + LAI"); and iii) streamflow at the outlet, along with LAI and AET at the subcatchment scale ("Q + LAI + AET"). For each calibration strategy, ROPE is applied and a separate objective function $E_{KGE,eff}$ is defined with an equally weighted contribution $E_{KGE,v}$ of the considered variable v (Tab. 3). We integrate the modeling of LAI as proxy of hydrological process representation spatially distributed in the entire catchment. AET data for model performance evaluation is often limited or the necessary data to compute AET, e.g., with Penman-Monteith, is lacking. Given the LAI–AET linkage in this region (Mamadou et al., 2016), we test whether a calibration approach with streamflow and LAI can be used to predict AET.

Table 3. Overview of model optimization approaches and forcing data.

Label	Target variables	Forcing data	Objective function
Q-o	Q	Observed data	$E_{KGE,eff} = E_{KGE,Q}$
QL-o	Q, LAI	Observed data	$E_{KGE,eff} = 1/2 \cdot E_{KGE,Q} + 1/2 \cdot E_{KGE,LAI}$
QLA-o	Q, LAI, AET	Observed data	$E_{KGE,eff} = 1/3 \cdot E_{KGE,Q} + 1/3 \cdot E_{KGE,LAI} + 1/3 \cdot E_{KGE,AET}$
Q-w	Q	W5E5 data	$E_{KGE,eff} = E_{KGE,Q}$
QL-w	Q, LAI	W5E5 data	$E_{KGE,eff} = 1/2 \cdot E_{KGE,Q} + 1/2 \cdot E_{KGE,LAI}$
QLA-w	Q, LAI, AET	W5E5 data	$E_{KGE,eff} = 1/3 \cdot E_{KGE,Q} + 1/3 \cdot E_{KGE,LAI} + 1/3 \cdot E_{KGE,AET}$

The robust parameter estimation (ROPE) algorithm after Bárdossy and Singh (2008) is used for the optimization of the three modeling approaches. ROPE is a depth function-based algorithm to iteratively find parameter sets that give good model predictions and are robust. The ROPE algorithm does not necessarily give the best parameter sets (global optimum), but rather an ensemble of different near-optimum parameters sets (Bárdossy and Singh, 2008). We apply ROPE to derive an ensemble of good parameter sets for climate impact assessment. In addition, the limitations and dependency on a single parameter set (equifinality) are overcome by incorporating multiple well-performing sets. We define "well-performing" if the parameter set gives satisfactory KGE values ($E_{KGE} \geq 0.6$) according to Thieme et al. (2013).

With ROPE, parameter robustness is quantified using the halfspace depth function introduced by Tukey (1975). Generally, data depth is a quantitative approach to define how central a sampled point is in a multivariate distribution. The more central and, thus, deep a point is located, the less the corresponding objective value differs if the point is subject to a small change, e.g., parameter changes (Bárdossy and Singh, 2008). The calculated parameter set depth value is denoted as L in the following.

To apply the ROPE algorithm, random samples X_N of N parameters and their bounds d are defined. The model is run for each sample and its performance is quantified. A subset X_N^* of the best performing parameters is defined, e.g., the best 10 % of X_N . The performance is evaluated with an objective function (here $E_{KGE,eff}$, Tab. 3). Based on X_N^* , M new random samples (labeled Y_M) are generated according to the corresponding depth values L . A new parameter vector of Y_M is only considered if it lays within the convex hull given by the depth values. The boundary of the convex hull is defined as $L \geq 1$.

Each new parameter vector inside the hull ($L \geq 1$) is considered for the sampling of the next iteration. The iterations of the ROPE algorithm stop as soon as a convergence criteria is reached. We figured that after 12 (20) iterations for the "Q only" and "Q + LAI" ("Q + LAI + AET") the model performance plateaus. From one iteration to the next, the 10 % best parameter values are used. After the final iteration, we consider the 20 best parameter sets for the climate impact assessment.

290 We calibrate against streamflow, GLASS-LAI, and FLUXCOM-AET. The calibration (validation) is defined from January 2008 to December 2011 (January 2012 to December 2015). We use eight years to enable a computational cost-efficient calibration for the total of six applied model optimizations. The period from 2006 to December 2015 is an adequate overlap of W5E5 and observed data to enable a fair and comprehensive comparison of the forcing data.

The model performance to predict streamflow, LAI, and AET is separately evaluated with E_{KGE} and for each forcing data
 295 set. For model validation, we evaluate the efficiencies E_{KGE} , percent bias E_{PBIAS} , and the coefficient of determination E_{R^2} of streamflow, AET, and LAI (see Appendix A3 for supplementary equations).

We assess the reliability of the derived parameter sets through a benchmark evaluation. For hydrological models, benchmarks facilitate an improved interpretation of the model performance and KGE metrics. (Schaeffli and Gupta, 2007; Seibert et al., 2018; Knoben et al., 2019, 2020). In this study, we define a lower level of expected model performance based on the interannual
 300 mean for every calendar day ("seasonal benchmark") as suggested by Knoben et al. (2020). For this purpose, we compute the daily mean seasonal values for discharge from the observed data of the period 2001 to 2015. For LAI and AET, the mean seasonal values are based on the 8-daily temporal resolution for according to the GLASS-LAI and FLUXCOM-AET data source. Each seasonality is duplicated to be as long as the evaluation period (2008 to 2015), and, thus, represents the identical temporal resolution of the model simulation. We compare the duplicated seasonality to the observed time series and
 305 compute $E_{KGE,Q}$, $E_{KGE,LAI}$, and $E_{KGE,AET}$ for the entire evaluation period. We use the duplicated seasonality ("seasonal benchmark") as a synthetic predictor to benchmark SWAT-T's modeling performance.

2.6 Model cross validation

The applicability of the parameter sets is evaluated with a cross validation. The parameter sets derived with observed data input are run with model forcing of ISIMIP3b reference data W5E5; and vice-versa the W5E5-parameters with observed data
 310 forcing. The cross validation is conducted for the evaluation period (January 2008 to December 2015) and assessed through $E_{KGE,Q}$, $E_{KGE,LAI}$, and $E_{KGE,AET}$. We focus the cross validation on the most comprehensive calibration approach "Q + LAI + AET".

2.7 Climate impact assessment

The ISIMIP3b project provides meteorological forcing data from five climate models for three future scenarios, and the corresponding baseline, or historical data. The baseline data set represents the observed climate characteristics, usually for the
 315 period from 1901 to 2015, and is used as a reference point to evaluate the future climate scenarios. For meteorological changes, we calculate the mean annual precipitation for each baseline data of the climate models. For each climate model and scenario, we compute the annual precipitation for each year of the near (2031 to 2050) and far (2070 to 2099) future periods. For each

period, the mean annual precipitation is calculated. The resulting mean annual precipitation per period is compared to the mean annual precipitation of the baseline data, and the increase or decrease (compared to the baseline data) is determined. For the temperature change, we compute the mean annual temperature for each climate model/scenario and its baseline data. The multi-model mean is calculated from all five GCMs. For hydrological changes, we evaluate the target variables AET and discharge. As baseline for AET (discharge), we use the simulated mean annual AET (discharge) from the period January 2001 to December 2015 from the W5E5 forcing.

3 Results

3.1 Sensitivity analysis

The sensitivity of the parameters is quantified with the elementary effects method after Morris (1991) whereby a ranking is possible. The higher the μ^* value of a parameter is, the higher is the parameter sensitivity (Campolongo et al., 2007; Garcia Sanchez et al., 2014). Basically, the elementary effects are calculated according to the model responses, represented as objective function KGE, to the parameter changes. Four different objectives $E_{KGE,Q}$, $E_{KGE,LAI}$, $E_{KGE,AET}$, and $E_{KGE,all}$ are defined to evaluate the parameter sensitivity when modeling discharge, LAI, AET, and the combined performance, respectively, with SWAT-T. Figure 3 shows the values μ^* . The sensitivity analysis considers the entire evaluation period from 2001 to 2015.

The parameter sensitivity for the equally-weighted objective $E_{KGE,all}$ is displayed in Figure 3a. The ranking of the first 8 parameters is similar to the discharge-only analysis in Figure 3c indicating a strong influence of the discharge performance $E_{KGE,Q}$ in $E_{KGE,all}$. The ranking 9 to 15 is assigned to relevant plant, soil, and AET parameters that are sensitive for $E_{KGE,LAI}$ and $E_{KGE,AET}$.

Figure 3b summarizes the sensitivity ranking with respect to LAI. The LAI parameters (DLAI, T_BASE, FRGRW2, PHU, LAIMX2, LAIMX1; green circles) are generally the most sensitive, together with the SOL_AWC (soil; in purple) and GSI (AET; in red) parameters. The sensitivity ranking confirms the linkage of LAI and AET in the region. The plant growth depends on water and temperature stresses in SWAT/SWAT-T. The water stress is a function of AET and water availability, in which the parameters SOL_AWC and GSI are pivotal. The other soil and AET parameters are less influential, while groundwater and runoff parameters are irrelevant for predicting LAI.

The sensitivity for the discharge modeling is summarized in Figure 3c. It can be observed that the most sensitive parameters are the groundwater (GWQMN, RCRG_DP, GW_REVAP, REVAPMN) and soil parameters (SOL_AWC, SOL_BD), where GWQMN is most influential. It governs the water depth for which baseflow can occur and partitions the flow into surface and baseflow contributions. Large GWQMN values allow more surface runoff and less baseflow – and vice versa for small values. The streamflow at the Bétérout gauge is seasonal and connected to the dry and wet precipitation periods. The groundwater parameters, and GWQMN in particular, are essential to model the low flows in the dry season. Figure 3c shows that the groundwater parameters have more impact on the discharge modeling than the runoff (CN_2, CH_K2, HRU_SLP, SURLAG, CH_N2) or plant parameters. Similar findings of the strong groundwater relevance in tropical regions are also reported in the SWAT-T application of López-Ramírez et al. (2021).

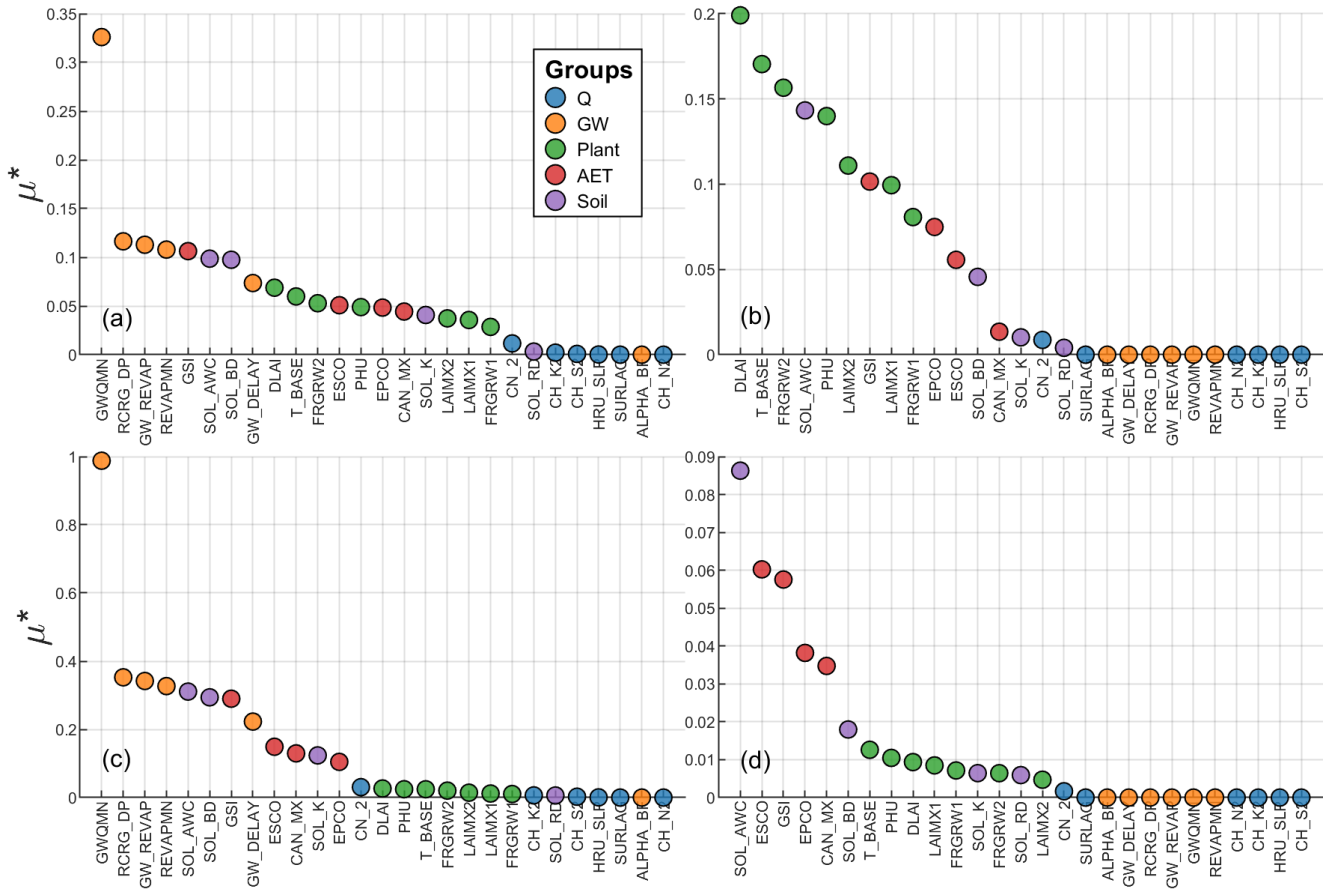


Figure 3. Ranking of the parameter sensitivity quantified with the elementary effects method. The panels (a), (b), (c), and (d) show the parameter sensitivity with respect to all variables ($E_{KGE,all}$), LAI ($E_{KGE,LAI}$), AET ($E_{KGE,Q}$), and discharge ($E_{KGE,AET}$), respectively. Each panel shows the statistical moment μ^* for each parameter on the y-axis where a higher value for μ^* indicates a higher parameter sensitivity. We use different marker colors to assign groups for which each parameter is commonly associated with. Please note the different y-axis scaling.

The sensitivity ranking in Figure 3d highlights the soil (SOL_AWC, SOL_BD) and AET (ESCO, GSI, EPCO, CAN_MX) parameters to be most sensitive for AET modeling. The AET parameters directly govern the calculation of AET. The soil parameters determine the soil water and availability and, thus, indirectly contribute to the actual amount of AET. The plant parameters are comparably less influential, yet are relevant. The contribution of the plant parameters affirm the significance of LAI for AET in this region. Groundwater and runoff parameters are not substantial for AET prediction.

The sensitivity analysis is applied to identify relevant parameters and reduce the parameter space for a more efficient optimization. Overall, 15 parameters are selected that are substantial for the prediction of discharge, LAI, and AET. The final parameters are listed in Table 1.

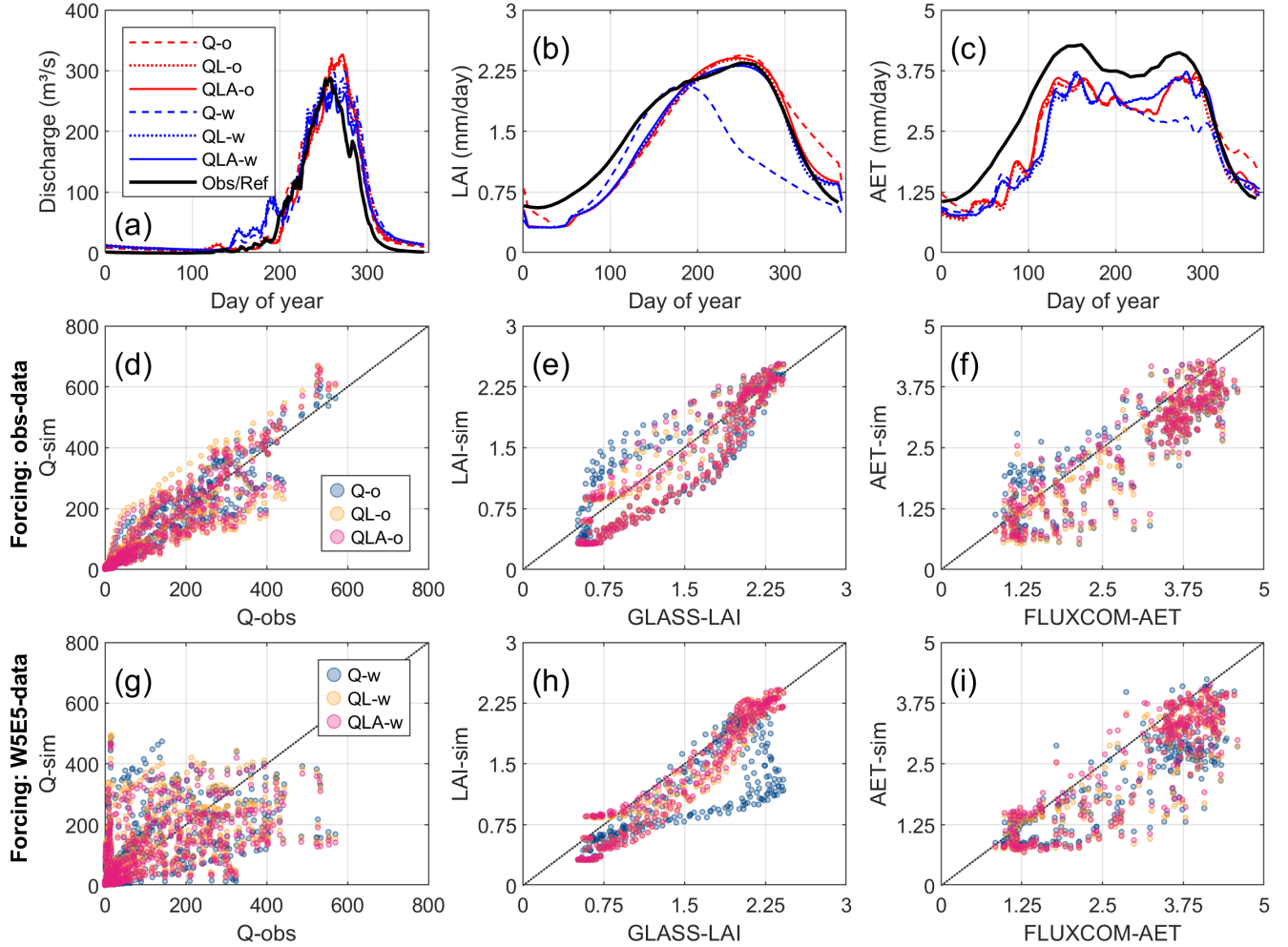


Figure 4. Mean annual seasonality of simulated (a) discharge, (b) LAI, and (c) AET from each calibration strategy. Each curve in (a), (b), and (c) represents the mean variables value (discharge, LAI, AET) from $n = 20$ parameter sets from ROPE. Panels (d), (e), and (f) show scatter plots for discharge, LAI, AET, respectively, of model forcing with observed data. Marker colors indicate the calibration strategy. The mean value of the 20 parameter sets from ROPE is displayed. Label letters represent the calibration variables (Q = discharge, L = LAI, A = AET). The suffix "-o" ("-w") indicates a model forcing with observed data (W5E5 data). Similarly to LAI, panels (g), (h), and (i) show the scatter plots for simulated discharge, LAI, AET, respectively, with model forcing with W5E5 data. The dashed gray 1:1 line in (d) to (i) represents the theoretical best fit. Scatter plots for discharge show daily, for AET and LAI 8-daily points. The time series are presented for the entire evaluation period (2008 to 2015) in all panels.

The models are forced with observed and W5E5 data. The derived parameter sets from the W5E5 forcing are used for the climate impact assessment. The purposes of the optimization with observed input data are to demonstrate the general

performance potential of the ROPE algorithm and to enable a parameter cross validation for the models with W5E5 parameters. We select the 20 best runs from the ROPE optimization for the subsequent model applications. In the following analysis, Figure 4 shows the comparison of simulated and observed discharge, LAI, and AET. Table 4 summarizes the quantitative model performance as KGE values for the calibration and validation periods.

Overall, the mean annual patterns of discharge, LAI, and AET are moderately well represented in all optimization approaches and with both forcing datasets (Fig. 4a to Fig. 4c). For discharge, the performance of the daily simulation is tied to the forcing data, as spotlighted by the scatter plots in Figure 4d and Figure 4g. The discharge simulation with observed data align well with the 1:1 line in Figure 4d, i.e., it reproduces the recorded streamflow accurately. In contrary, the discharge simulation with W5E5 shows a spread in the scatter, where single high flow events are recorded, but not modeled; and vice-versa for single simulated high flow events. The performance quantification according to KGE is given in Table 4. Model optimization with observed data ($E_{KGE,Q} = 0.49$ to 0.92 , Tab. 4, calibration and validation) outperforms the W5E5 model optimization ($E_{KGE,Q} = 0.10$ to 0.64 , calibration and validation). The variation in performance can be explained with differences in the input precipitation data sets. For instance, the precipitation intensity in 2010 is too low in W5E5 compared to the observation data (see Figure A7). In this period, the simulated discharge is underestimated with W5E5.

Table 4. Model performance for daily simulation as KGE [-] for forcing with observation network data and W5E5 data. KGE values are given for the calibration (January 2008 to December 2011) and validation (January 2012 to December 2015) for each strategy. The table lists the minimal, median, and maximal KGE values per variable and calibration (from 20 parameter sets).

Strategy	Calibration			Validation		
	Q	LAI	AET	Q	LAI	AET
Obs. data forcing						
Q	0.87, 0.88, 0.91	0.36, 0.74, 0.85	0.53, 0.73, 0.77	0.49, 0.81, 0.92	0.24, 0.73, 0.81	0.59, 0.84, 0.91
Q + LAI	0.82, 0.84, 0.85	0.81, 0.84, 0.88	0.71, 0.75, 0.80	0.57, 0.74, 0.88	0.75, 0.80, 0.82	0.81, 0.86, 0.90
Q + LAI + AET	0.82, 0.85, 0.90	0.78, 0.85, 0.87	0.75, 0.78, 0.80	0.39, 0.85, 0.90	0.75, 0.80, 0.83	0.86, 0.88, 0.90
W5E5 forcing						
Q	0.60, 0.62, 0.64	0.25, 0.62, 0.86	0.50, 0.67, 0.77	0.10, 0.43, 0.50	0.36, 0.61, 0.81	0.55, 0.71, 0.81
Q + LAI	0.59, 0.61, 0.64	0.82, 0.86, 0.88	0.68, 0.73, 0.78	0.33, 0.45, 0.49	0.74, 0.80, 0.82	0.72, 0.78, 0.83
Q + LAI + AET	0.56, 0.60, 0.63	0.84, 0.86, 0.88	0.71, 0.75, 0.77	0.41, 0.46, 0.49	0.77, 0.80, 0.83	0.77, 0.79, 0.83

Figure 4b shows the mean annual LAI pattern from all 20 parameter sets for each optimization approach. Simulated LAI is compared to GLASS-LAI (8-daily) in Figure 4e and 4h for model forcing with observed and W5E5 data, respectively. The performance to model LAI is particularly good in the modeling approaches with LAI as target variable ("Q + LAI" and "Q + LAI + AET") for both forcing data sets. In the growing phase, a small underestimation compared to GLASS-LAI is generally present. However, the plant maturity and leaf senescence are modeled well with "Q + LAI" and "Q + LAI + AET". The performance metrics $E_{KGE,LAI}$ ranges from 0.75 (validation) to 0.88 (calibration) for these approaches (Tab. 4). For "Q only", the LAI modeling is less adequate, particularly for the W5E5 forcing, where the models fail to simulate plant maturity and leaf

senescence. The LAI calibration varies from $E_{KGE,LAI} = 0.25$ to $E_{KGE,LAI} = 0.86$ (Tab. 4) for discharge-only approaches ("Q-o" and "Q-w").

Similar to LAI, Figure 4c shows the modeled mean annual AET pattern as an average of the 20 parameter sets. Overall, the simulated mean AET closely reproduces the annual pattern of FLUXCOM reference. The SWAT-T model can represent the two "AET peaks" in the beginning and end of the rainy season, as well as the "AET dip" in the middle of the rainy season. However, the FLUXCOM-AET values are continuously underestimated. It can be observed that "Q only" particularly underestimates the reference AET and even fails to mimic the second "AET peak" due to the lack of LAI representation in this period. The scatter plots in Figure 4f and Figure 4i confirm SWAT-T's capability to predict AET, but also the simulated underestimation to FLUXCOM-AET. Generally, the optimization approaches with AET ("Q + LAI + AET") result in very good performance values for both forcing data sets ($E_{KGE,AET} = 0.75$ to $E_{KGE,AET} = 0.90$, Tab. 4). If the model is calibrated with respect to discharge and LAI, adequate AET predictions are possible. For the "Q + LAI", $E_{KGE,AET}$ varies between 0.71 to 0.90 (Tab. 4).

The investigation of multiple parameter sets confirms that the modeling performance of SWAT-T is tied to the forcing data, particularly for discharge. Figure 5 shows the empirical cumulative distribution functions for the 20 best runs from the ROPE optimization for the calibration period. In the figure, the performance of the seasonal benchmark of discharge, LAI, and AET is integrated. The performance distribution of the parameter sets to model discharge is evaluated in Figure 5a. Two distinct

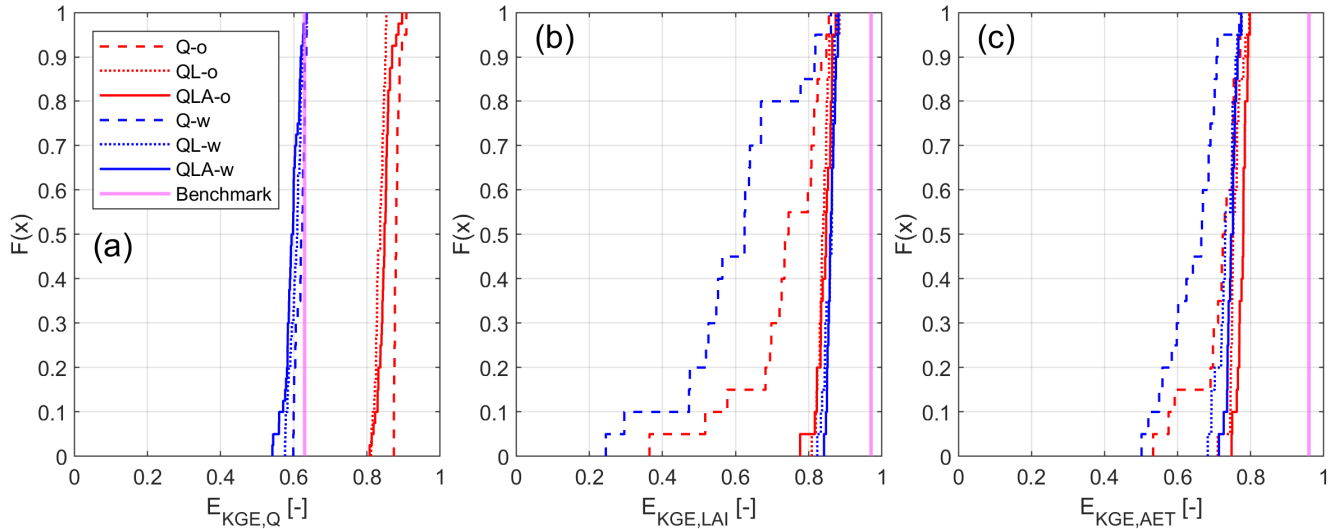


Figure 5. Empirical cumulative distribution functions (CDF) for the model performance metrics (a) $E_{KGE,Q}$, (b) $E_{KGE,LAI}$, and (c) $E_{KGE,AET}$. The CDF in each panel is computed from the KGE values of the 20 best parameter sets per calibration strategy and forcing data. The label $F(x)$ on the y-axis indicates the CDF distribution. Blue lines represent the CDFs for W5E5 forcing, red lines for observed data forcing. The line styles indicates the calibration strategy. The label letters represent calibrations variables (Q = discharge, L = LAI, A = AET). The suffix "-o" ("-w") indicates model forcing with observed data (W5E5 data). The pink line in each panel represents the KGE values for the seasonal benchmark after Knoben et al. (2020).

clusters can be identified: the distribution of the W5E5-based parameters (in blue, with $E_{KGE,Q}$ from 0.54 to 0.64) and based
 400 on the observed data set (in red, with $E_{KGE,Q}$ from 0.81 to 0.91). The W5E5 modeling results in a performance as good as the
 seasonal discharge benchmark (pink line, $KGE = 0.63$). Notably, the model outperforms the seasonal discharge benchmark,
 if the observed data set is applied. Figure 5b shows the distribution with respect to $E_{KGE,LAI}$. The values of $E_{KGE,LAI}$ from
 discharge-only (Q-o, Q-w) decline rapidly, while the other approaches yield equally good parameter sets for LAI. Figure 5c
 displays the distribution functions of $E_{KGE,AET}$. All parameter sets for the "Q + LAI" and "Q + LAI + AET" approaches result in
 405 values of $E_{KGE,AET} \geq 0.68$. In contrary, only a small subset of the "Q-only" approach yields $E_{KGE,AET} \geq 0.68$. Figure 5 highlights
 that the ROPE algorithm is applicable to derive multiple equally-good parameter sets for LAI and AET modeling. The analysis
 in Figure 5 further indicates that the integration of LAI alone does not necessarily improve the streamflow modeling with
 SWAT-T. As shown in Figure 3, the influence of LAI parameters on streamflow prediction is less sensitive. Yet, the SWAT-T
 model can't beat the benchmark for LAI or AET. GLASS-LAI and FLUXCOM-AET are reanalysis outputs based on a data
 410 assimilation of observations and satellite-based data, such as MODIS data. Both data sets inherit observed seasonal patterns
 and are processed to mimic reality (Liang et al., 2014; Jung et al., 2019). Their benchmark is thus hard to outperform for a
 physical-describing model like SWAT-T.

3.3 Model cross validation

We assess the applicability of the W5E5-parameters with a parameter cross validation. Figure 6 shows the evaluation of the
 415 cross validation for "Q + LAI + AET". If the model is run with W5E5 parameters and observed data forcing (red dashed lines
 in Fig. 6), the resulting metrics $E_{KGE,Q}$ and $E_{KGE,AET}$ are mainly ≥ 0.6 , which aligns with a satisfactory to good modeling
 performance according to Thiemig et al. (2013). The median $E_{KGE,Q}$ for the calibration and validation period is 0.70 and 0.69,
 respectively, which also outperforms the seasonal discharge benchmark ($KGE = 0.63$). For the prediction of LAI, $E_{KGE,LAI}$
 varies for the W5E5-parameters (red dashed lines in Fig. 6b,e), where the median of $E_{KGE,LAI}$ is 0.48 (calibration) and 0.42
 420 (validation). The variation for W5E5 parameters and observed forcing can be explained through the final parameter values (see
 Tab. A7). For W5E5 optimization, the T_BASE and PHU parameter values are smaller than for observed data forcing. Lower
 T_BASE and PHU values trigger an earlier start of the plant growth along with a shorter period of maturity. If the input data is
 replaced, even small temperature changes can influence the growth start and plant maturity. Given the dependency of LAI on
 temperature in SWAT-T, its robustness for climate impact assessment is crucial. For climate impact assessment, multiple LAI
 425 parameter sets can be used to avoid the reliance on single LAI parameter sets and increase the LAI parameter robustness.

3.4 Future changes of relevant meteorological variables

Figure 7 compares the future changes of precipitation and temperature of the climate models to their baseline data. For all
 climate models and scenarios, the average temperature is projected to increase between 0.5 to 5.8 °C in the future. All climate
 models indicate a temperature increase of more than 3 °C for the higher emission scenarios (SSP3–7.0 and SSP5–8.5) in the
 430 far future (filled orange and purple symbols), with highest change values of 5.8 °C and 5.4 °C modeled by UKESM1-0-LL and
 IPSL-CM6A-LR, respectively. The temperature increase for the low emission scenario (SSP1–2.6) is comparably smaller (0.9

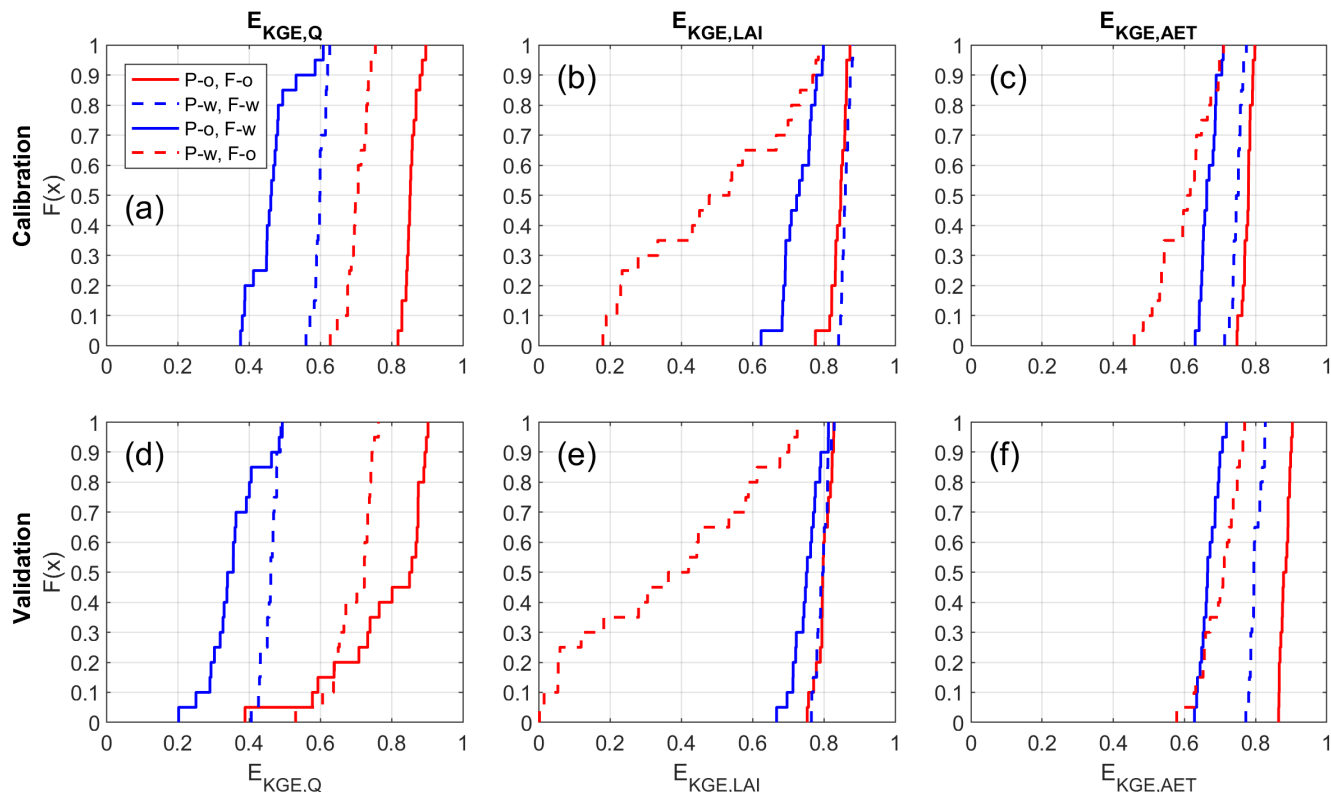


Figure 6. Cross validation of the best parameters of the "Q + LAI + AET" calibration strategy. Each line contains $n = 20$ runs from the optimization with ROPE. The label $F(x)$ on the y-axis represents the CDF distribution. The color indicates the model forcing ("F-") data, where red and blue represent forcing with observed ("-o") and W5E5 ("-w") data, respectively. The line style displays the parameter set origin ("P-"). Straight lines indicate the parameters are derived with observed forcing data ("-o"), dashed lines represent parameter sets from W5E5 forcing ("-w"). The upper and lower row show the performance for the calibration (January 2008 to December 2011) and validation (January 2012 to December 2015) period, respectively. The median of the distribution is equal to $F(x) = 0.5$.

to 2.0 °C) in the near and far future. The multi-model mean temperature change for this region ranges from 1.2 °C (SSP1–2.6, far future) to 4.2 °C (SSP5–8.5, far future). The mean temperature is expected to get warmer especially in the dry period of the year (January to June and October to December), where a prolongation of the dry and hot period (historically from February
435 to May) to January to June is projected (Figure A1).

The precipitation projection is mixed with increases and decreases in the future, where the multi-model precipitation mean varies between increases of 1.2 % (SSP1–2.6) and 7.2 % (SSP5–8.5). For the SSP1–2.6 scenarios, the precipitation changes are ± 10 % in the near and far future, except for the near future in the MRI-ESM2-0 model. Positive precipitation changes for selected scenarios are higher than 15 % in UKESM1-0-LL, IPSL-CM6A-LR, MPI-ESM1-2-HR, and MRI-ESM2-0 GCMs.
440 The GFDL-ESM4 model (circles) mainly projects precipitation decreases. The change in precipitation is most substantial in

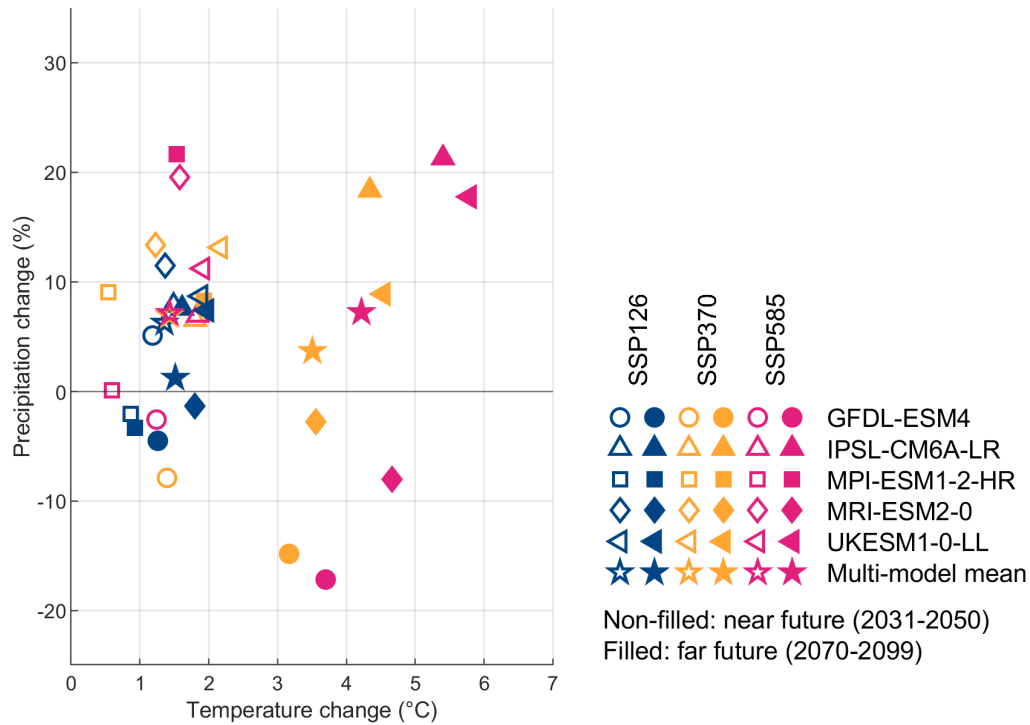


Figure 7. Mean projected meteorological changes of the daily mean temperature and annual precipitation for the near (2031-2050; no filled markers) and far (2070-2099, filled markers) future periods compared to the ISIMIP3b baseline (here 1971-2000) for five GCMs and three emission scenarios. The marker colors blue, yellow, and purple refer to SSP1–2.6, SSP3–7.0, and SSP5–8.5, respectively. Multi-model mean is the ensemble mean of the five GCMs.

the rainy season. From all GCMs, an increase in the amount of monthly precipitation is projected for August, September, and October (see Figure A2). The change values are summarized in Tab. A1. The future changes of solar radiation, relative humidity, and wind speed for the near and far future are displayed in Figure A4 to Figure A6.

3.5 Climate impact assessment and comparison of modeling approaches

445 The focus of this comparative study is the analysis of the implications of different modeling approaches on the prediction of future hydrological changes, particularly of AET and discharge. We evaluate the future discharge and AET response to climatic changes for the near (2031-2050) and far (2070-2099) future period. Generally, the climate change signal for AET is similar across all calibration strategies, where the multi-model mean values of AET indicate future increases. Yet, the future annual AET can vary dependent on the calibration strategy, the underlying GCM, the scenario, and the future period. Figure 8 shows

450 the annual AET for the applied GCM-SSP sets and the multi-model mean of all GCMs for the near and far future period. The analysis proves that the discharge only strategy ("Q only", blue boxcharts) predicts lower annual AET rates compared to the integrated optimization approaches for each applied GCM-SSP set and for the multi-model mean values for annual AET. The

lower simulated future annual AET values are lower for "Q only" (846 to 889 mm yr⁻¹, depending on the GCM-SSP scenario), while the climate sensitivity of "Q + LAI" (886 to 918 mm yr⁻¹) and "Q + LAI + AET" (904 to 932 mm yr⁻¹) is similar (Table 5). The lower rates of AET for "Q only" is furthermore evident if the future AET values are compared to the respective AET baseline. The change rates of annual AET from "Q only" to "Q + LAI + AET" are close for the near future period. While "Q only" predicts an increase of annual AET of 5.5 %, 5.7 %, and 4.2 %, "Q + LAI + AET" results in increases of 7.4 %, 7.2 %, and 5.8 % for the SSP1–2.6, SSP 3–7.0, and SSP5–8.5 scenarios (near period, multi-model mean values, Tab. 6), respectively. For the far future period, the change rates are generally higher for "Q + LAI + AET" than "Q only". However, for the SSP5–8.5 scenario, the future change of AET for "Q only" is 9.2 % compared to an increase of 8.4 % for "Q + LAI + AET". Figure 8 moreover indicates that "Q + LAI" results in predictions of annual AET which are close to "Q + LAI + AET". Thus, "Q + LAI" can approximate AET rates on the catchment scale even if AET is not integrated in the parameter estimation. The For the given setup of SWAT-T modeling in the Bétérrou Catchment, the LAI computation can be potentially used as a proxy for AET because the plant growth and AET processes are directly connected in SWAT-T on the catchment scale.

Table 5. Overview of the multi-model mean values of the future annual AET. The baseline reference is the evaluation period 2001 to 2015 simulated with W5E5. The values show the mean value for each GCM, emission scenario, and the 20 sets of parameters in mm yr⁻¹. The changes to the baseline (in brackets) are percentage changes. See Table A8 in Appendix for further future water balance components.

Future SSP scenario	Near future			Far future		
	Q	Q + LAI	Q + LAI + AET	Q	Q + LAI	Q + LAI + AET
SSP1–2.6	858 (+5.6)	900 (+5.9)	917 (+7.2)	846 (+4.0)	886 (+4.2)	925 (+8.3)
SSP3–7.0	860 (+5.7)	898 (+5.8)	915 (+7.1)	880 (+8.2)	918 (+8.0)	932 (+9.1)
SSP5–8.5	847 (+4.2)	888 (+4.5)	904 (+5.7)	889 (+9.3)	911 (+7.2)	926 (+8.3)

The future annual AET rates also depend on the GCM model. For the near future (Fig. 8), the range of predicted annual AET is smaller (750 to 1000 mm) than compared to the far future GCM model applications (710 to 1120 mm, Fig. 8). The modeling with GFDL-ESM4 and MPI-ESM-1-2-HR result in comparably smaller annual AET rates, while the simulations forced by IPSL-CM6A-LR, MRI-ESM2-0, and UKESM1-0-LL indicate higher annual AET values for the near future. For the far future period, high annual AET rates are particularly predicted with IPSL-CM6A-LR. The GCM forecasts for the far future an increase in precipitation and temperature (Fig. 7), which translates to available water and energy for AET. The simulation with forcing data from the MPI-ESM2-0 model shows distinct differences between the SSP scenarios, where the also future decreases of annual AET rates can occur. For the far future, the MPI-ESM2-0 model simulates the low temperature changes ($\Delta T \leq 2$ °C, Fig. 7), and, thus, the increase in AET is the lowest with MPI-ESM2-0 compared to the other GCM applications.

The differences in predicting annual AET are explained with variations in monthly AET dynamics. Figure 9 and Figure 10 show the monthly mean AET for the calibration approaches for the near and far future period, respectively. The figures also display the monthly mean AET values from the each model optimization forced with W5E5 data (black cross). The analysis shows for which months the calibration approaches predict different AET rates. For the near future period (Fig. 9), the monthly

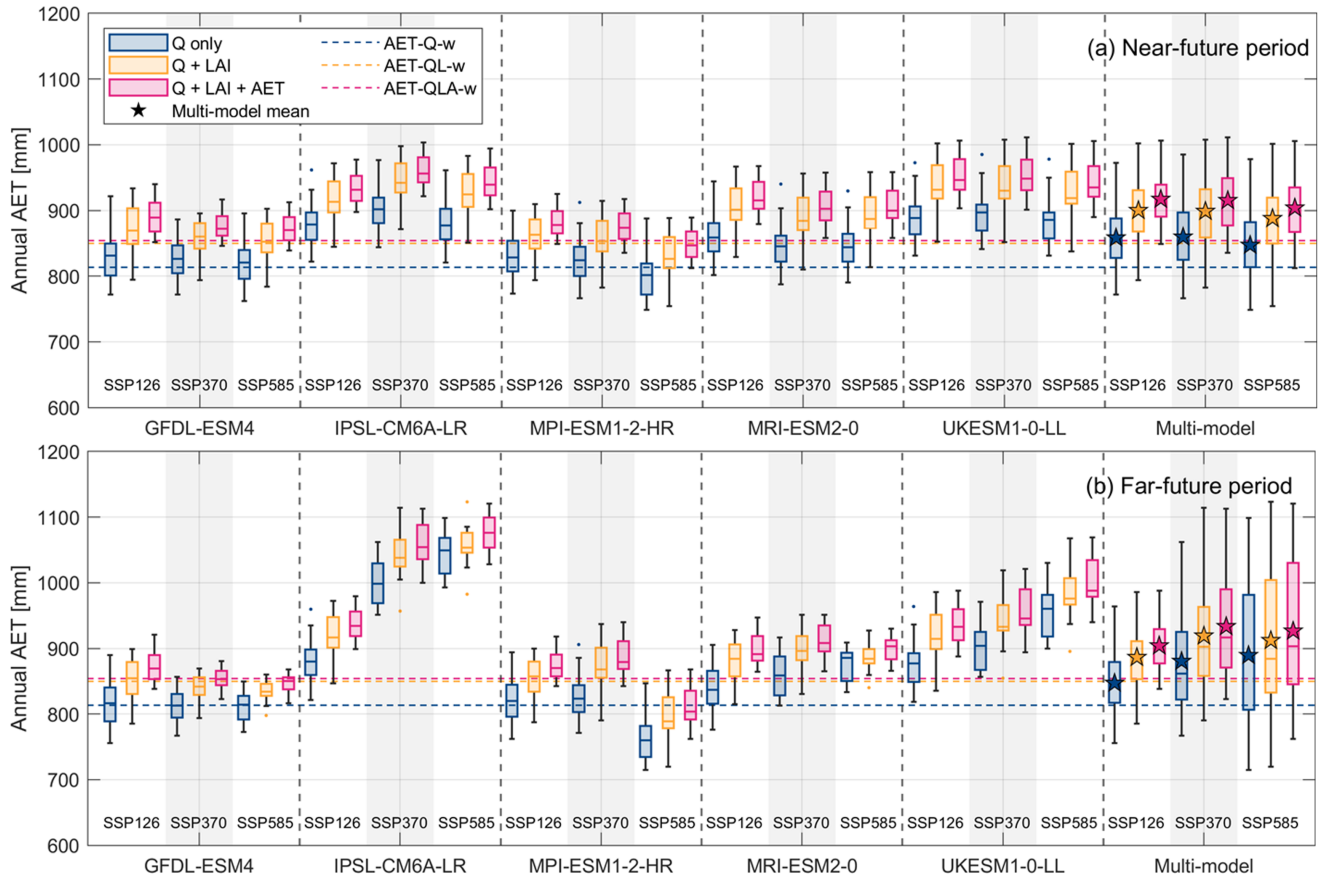


Figure 8. Future annual AET simulated with the five GCM and three SSP scenarios and the multi-model ensemble evaluation for (a) the near-future period (2031-2050) and (b) the far-future period (2070-2099). Colors indicate the calibration "Q only"/"Q-w" (blue), "Q + LAI"/"QL-w" (yellow), and "Q + LAI + AET"/"QLA-w" (pink). Each box for GCM-SSP contains $n = 20$ projected mean annual AET values from the 20 best parameter sets. For the multi-model ensembles, each box contains $n = 100$ values (5 GCMs $\times$ 20 parameter sets). Stars highlight the multi-model mean values for each calibration process and SSP scenario. Dashed horizontal lines indicate the simulated mean annual AET from the period 2001 to 2015 with W5E5 forcing. Colors represent the corresponding calibration strategy. Label letters for the horizontal lines indicate the calibrations variables (Q = discharge, L = LAI, A = AET). The suffix "-w" stands for the forcing with W5E5.

AET rates predicted with "Q only" are lower in the period from August to December. This period describes the end of the wet and transition into the dry period. Given the discharge-centered optimization, the model does not represent the plant and soil water processes in this period. The smaller AET rates for "Q only" are evident for all three SSP scenarios in the near future period. Concurrently, the predicted mean seasonal values from "Q + LAI" are close to the "Q + LAI + AET" where only small differences per month are computed.

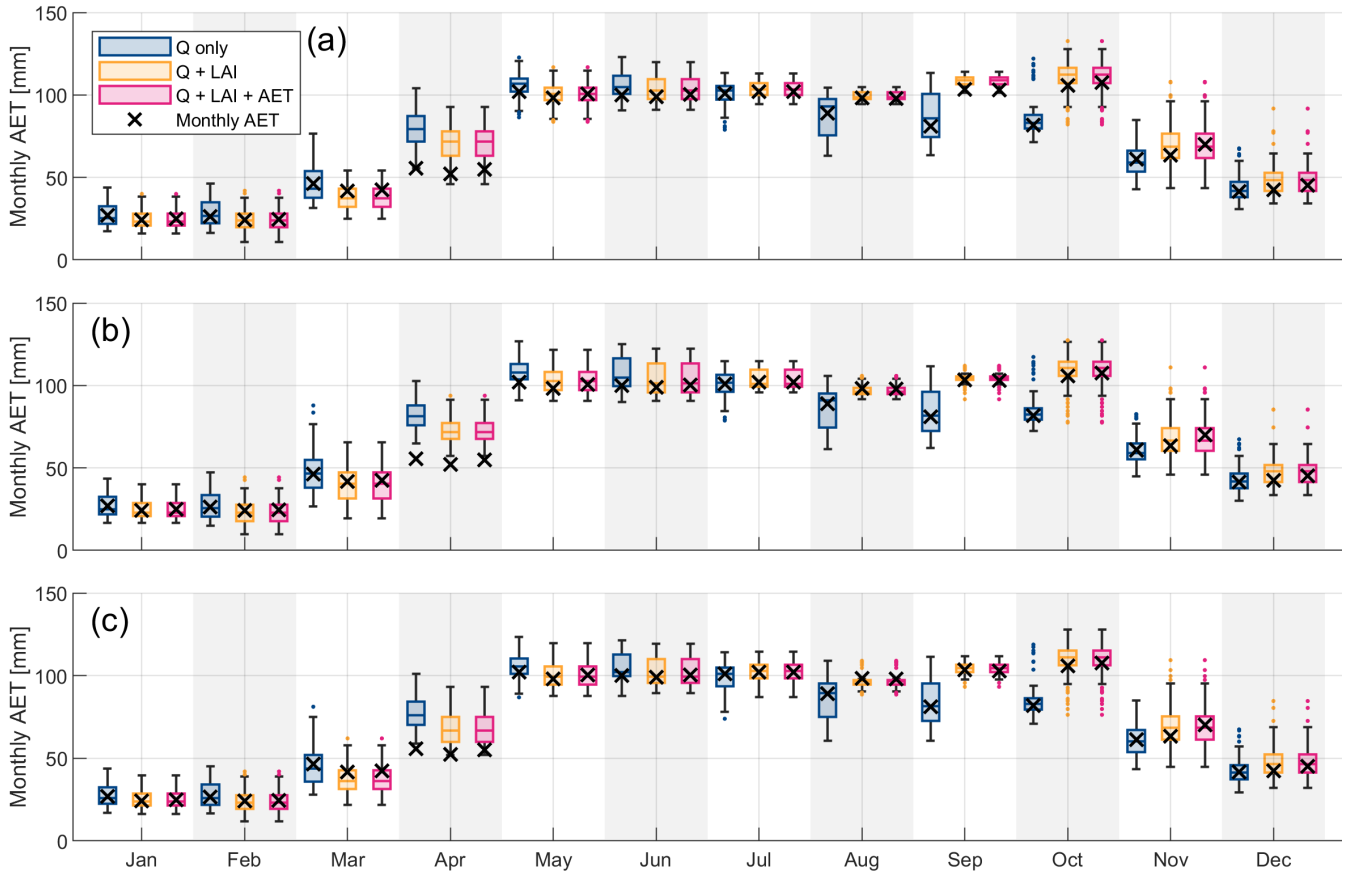


Figure 9. Future monthly AET values for the 5 GCMs and emission scenarios (a) SSP1–2.6, (b) SSP3–7.0, and (c) SSP5–8.5 for the near-future period (2031–2050). Each box contains $n = 100$ monthly AET values (5 GCMs $\times$ 20 parameter sets). Colors indicate the calibration process "Q only" (blue), "Q + LAI" (yellow), and "Q + LAI + AET" (pink). The black crosses (x) represent the monthly mean AET values from the corresponding calibration strategy (baseline monthly values).

For the far future period (Fig. 10), the pattern of monthly mean AET differences is similar to the predictions of the near future period. The monthly AET rates of "Q only" are underestimated from August to December. The analysis for the far future period moreover shows large variations within each calibration strategy itself. The box charts are wider in the far period, than in the near period evaluations, particularly for SSP5-8.5 (see Fig. 10c). The chart sizes indicate that within each calibration strategy, the range of monthly AET varies, and, thus, the forcing from the GCMs is varying, too. The comparison of future monthly mean AET values to the monthly AET rates from the W5E5 optimization points out differences particularly in April for all calibration approaches and SSP scenarios. The contrasting high rates of future monthly AET in April is related to the strong increase of temperature in the future spring months (see Fig. A1). In April, the warmer climate overlaps with the onset of the rainy season, which eventually catalyzes the AET generation.

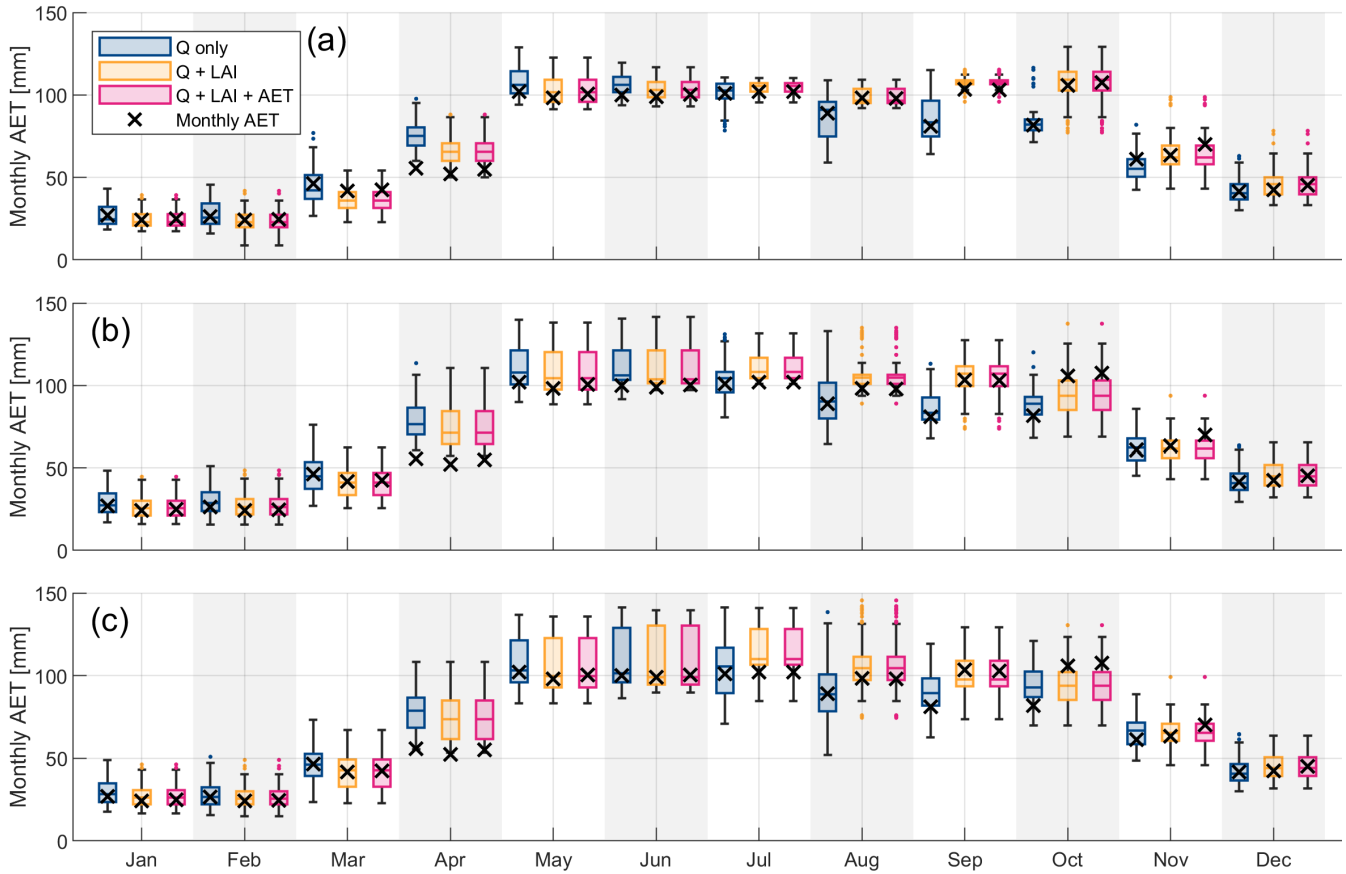


Figure 10. Future monthly AET values for the 5 GCMs and emission scenarios (a) SSP1–2.6, (b) SSP3–7.0, and (c) SSP5–8.5 for the far-future period (2070–2099). Each box contains $n = 100$ monthly AET values (5 GCMs $\times$ 20 parameter sets). Colors indicate the calibration process "Q only" (blue), "Q + LAI" (yellow), and "Q + LAI + AET" (pink). The black crosses (x) represent the monthly mean AET values from the corresponding calibration strategy (baseline monthly values).

Generally, the future rate of AET is computed to increase for the Bétérrou Catchment based on the GCMs integrated in the ISIMIP3 project. Depending on the calibration strategy and the SSP scenario, the multi-model mean changes range from 4.0 % ("Q only", SSP1–2.6, far period) to 9.2 % ("Q + LAI + AET", SSP3–7.0, far period; and "Q only", SSP5–8.5, far period) as indicated from the multi-model mean values in Figure 11 and Tab. 6. The projected changes of AET (multi-model mean) are lower for "Q only" than "Q + LAI + AET". The overview of future changes in Figure 11 and Tab. 6 indicates high AET increases particularly for the IPSL-CM6A-LR, which projects high precipitation and temperature increase. Negative AET changes are computed only partially and mainly with forcing from MPI-ESM-1-2-HR (Figure 11a).

For discharge, the future changes can be positive and negative depending on the underlying GCM forcing and calibration strategy. The application of the MPI-ESM1-2-HR model data results in a strong increase of discharge (up to 101.1 %, SSP5–8.5, "Q only"). The forcing data of GFDL-ESM4 yields mostly decreases of future discharge due to projected precipitation

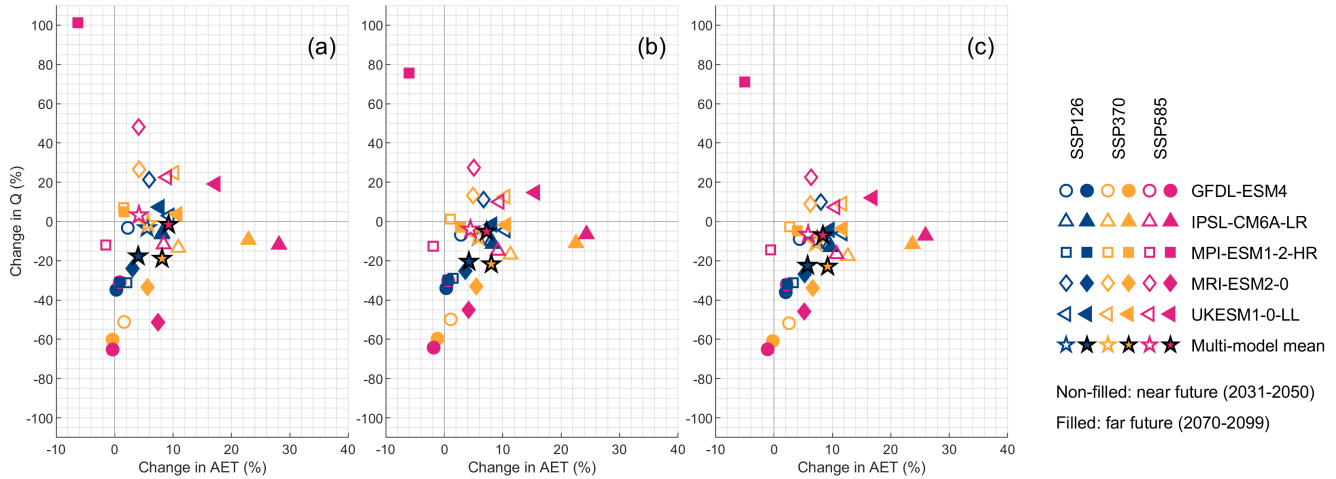


Figure 11. Mean future changes in annual AET and discharge for the GCM and emission scenarios as well as the multi-model mean for the calibration approaches (a) "Q only", (b) "Q + LAI", and (c) "Q + LAI + AET". The x-axis and y-axis denote the changes in AET and discharge in percent, respectively. Each marker represents the mean change computed from the 20 best parameter runs. The colors indicate the emission scenario. The markers represent the GCM. Filled (non-filled) corresponds to the far-future (near-future) period.

decreases and temperature increases of >3 °C. For the near future, the discharge changes from "Q only" range from -3.3 to 3.2 % (multi-model mean, Tab. 6). For "Q + LAI" and "Q + LAI + AET", the multi-model mean changes of discharges are simulated from -7.9 to -4.0 % and from -10.8 to -6.7 %, respectively. For the far-future period, the multi-model mean changes of discharge show a substantial decrease independent of the calibration strategy, where the change rates for "Q + LAI + AET" are the lowest due to the higher simulated evaporative demand. The changes are -18.9 to -1.6 % for "Q only", -21.7 to -5.1 % for "Q + LAI", and -22.9 to -7.0 % for "Q + LAI + AET".

4 Discussion

4.1 Optimization strategy and hydrological modeling

This study primarily focus on the variability of future AET depending on the calibration strategy in hydrological modeling. For this purpose, three calibration methods with different levels of complexity and information indices ("Q only", "Q + LAI", and "Q + LAI + AET") are evaluated. Similar to previous comparative studies (Huang et al., 2020; Ismail et al., 2020; Koch et al., 2020; Mishra et al., 2020; Wen et al., 2020), we investigate simple to comprehensive calibration strategies, yet with a particular focus on AET. The different calibration complexities from "Q only" to "Q + LAI + AET" also serve as a proxy for a benchmark test with lower and upper arguments, as suggested by Seibert et al. (2018). The integration of an "AET only" approach may add another layer of "upper benchmark". Yet, we also assess the calibration strategy impacts on discharge changes for the region. Disregarding discharge in the hydrological modeling can imply large discharge variability (Odusanya et al., 2019; Sarmiento

Table 6. Mean future changes in annual AET ΔE and discharge ΔQ for the GCM and emission scenarios as well as the multi-model mean for the calibration approaches "Q only", "Q + LAI", and "Q + LAI + AET". The mean changes are computed from the 20 best parameter runs. The annual AET changes are denoted as ΔE in this table for readability.

GCM	Q only				Q + LAI				Q + LAI + AET			
	Near		Far		Near		Far		Near		Far	
	ΔQ	ΔE	ΔQ	ΔE	ΔQ	ΔE	ΔQ	ΔE	ΔQ	ΔE	ΔQ	ΔE
SSP1-2.6												
GFDL-ESM4	-3.2	2.3	-34.8	0.3	-6.8	2.8	-34.0	0.3	-9.0	4.4	-36.0	2.0
IPSL-CM6A-LR	-6.5	8.1	-6.0	8.1	-9.8	8.0	-11.4	8.3	-11.6	9.5	-13.1	9.7
MPI-ESM-1-2-HR	-31.1	2.1	-31.1	0.9	-29.0	1.5	-29.9	0.6	-31.2	3.3	-32.0	2.3
MRI-ESM2-0	21.4	5.9	-23.9	3.1	11.1	6.7	-25.2	3.6	9.8	8.1	-26.9	5.2
UKESM1-0-LL	2.9	9.4	7.3	7.7	-4.5	10.5	-1.6	8.2	-6.0	11.8	-4.3	9.6
Multi-model mean	-3.3	5.5	-17.7	4.0	-7.8	5.9	-20.4	4.2	-9.6	7.4	-22.4	5.8
SSP3-7.0												
GFDL-ESM4	-51.2	1.6	-60.1	-0.4	-49.9	1.1	-59.7	-1.2	-51.8	2.6	-60.9	-0.2
IPSL-CM6A-LR	-13.4	10.9	-9.4	22.9	-16.9	11.3	-11.0	22.5	-17.7	12.6	-11.6	23.7
MPI-ESM-1-2-HR	7.0	1.6	4.9	1.6	1.3	1.0	-3.0	2.8	-2.6	2.7	-4.7	4.0
MRI-ESM2-0	26.7	4.2	-33.5	5.7	13.1	4.9	-33.1	5.5	8.8	6.3	-33.8	6.7
UKESM1-0-LL	24.8	10.2	3.7	10.8	12.7	10.5	-1.8	10.6	9.1	11.7	-3.6	11.8
Multi-model mean	-1.2	5.7	-18.9	8.1	-7.9	5.8	-21.7	8.0	-10.8	7.2	-22.9	9.2
SSP5-8.5												
GFDL-ESM4	-30.9	0.9	-65.2	-0.3	-30.1	0.7	-64.2	-1.8	-32.1	2.2	-65.1	-1.1
IPSL-CM6A-LR	-11.7	8.4	-11.8	28.1	-14.9	9.2	-6.5	24.3	-16.6	10.7	-7.2	25.9
MPI-ESM-1-2-HR	-12.0	-1.5	101.1	-6.3	-12.7	-2.0	75.6	-6.1	-14.5	-0.6	71.0	-5.0
MRI-ESM2-0	48.1	4.1	-51.2	7.4	27.5	5.1	-45.1	4.2	22.5	6.4	-45.9	5.2
UKESM1-0-LL	22.5	9.0	19.1	17.3	10.0	9.5	14.8	15.6	7.3	10.5	12.1	16.9
Multi-model mean	3.2	4.2	-1.6	9.2	-4.0	4.5	-5.1	7.2	-6.7	5.8	-7.0	8.4

et al., 2025). We have thus avoided to include "AET only" to minimize discharge uncertainties. The investigation of a Q+AET calibration could also serve as an upper benchmark and is expected to reproduce AET rates well. It is however not considered in the present study, because it would potentially neglect vegetation dynamics to satisfy the atmospheric water demands. Isolating Q+AET from LAI adds a further layer in understanding the role of vegetation processes in AET-focused calibrations. Looking ahead, future work could explicitly explore Q+AET as a further upper limit together with Q+LAI+AET.

Model evaluation in this study is based on in-situ monitoring and satellite-derived reanalysis datasets (GLASS-LAI and FLUXCOM-AET). GLASS-LAI and FLUXCOM-AET have been validated by Merk et al. (2024) for two distinct loca-

525 tions within the Bétérrou Catchment. GLASS-LAI and FLUXCOM-AET rely on models and assumptions, and are provided at a coarser resolution than the hydrological model. To address scale differences, the SWAT-T outputs, GLASS-LAI and FLUXCOM-AET data were spatially projected onto the same units. While this approach allows for a spatially explicit evaluation that reflects land cover variability within the Bétérrou catchment, it also introduces some information loss, e.g., from the aggregation of AET heterogeneity. This is particularly important in the process representation of the LAI-AET interaction
530 for localized land-atmosphere feedbacks. The subbasin-level evaluation offers a practical compromise, where spatial context is preserved at a scale appropriate for hydrological modeling. Smaller scales (e.g., HRU levels) and dynamic land use changes have not been considered given the spatial mismatch of modeled and simulated LAI and AET. As demonstrated in Yonaba et al. (2021), dynamic land use modeling can further enhance the process representation of surface runoff and AET in the region. Future research can consider a coupling of detailed LAI, AET, and dynamic land use modeling to further enhance robust
535 hydrological modeling for the region.

The application of satellite-based GLASS-LAI and FLUXCOM-AET data for a tropical catchment like the Bétérrou Catchment carries uncertainties. Generally, GLASS-LAI and FLUXCOM-AET are both widely used and are considered high quality. Yet, satellite-based datasets in tropical regions can be subject to cloud contamination and reflectance noise (Viovy et al., 1992; Atkinson et al., 2012) or the lack of observation networks for validation (Weerasinghe et al., 2020). For the Bétérrou region, the
540 GLASS-LAI dataset shows promising applicability when compared to monitored data (Merk et al., 2024). FLUXCOM-AET has been extensively validated against eddy covariance (EC) measurements across a wide range of climatic conditions, supporting its general reliability (Jung et al., 2019). This study relies on a pointwise validation of FLUXCOM-AET and GLASS-LAI. While this approach does not fully capture spatial heterogeneity or all sources of uncertainty, it provides a consistent and pragmatic basis for model evaluation in data-scarce tropical regions. This approach ensures that the validation framework remains
545 robust and fit for purpose.

The hydrological cycle in the Western African region is driven by precipitation, AET, and discharge (Rodell et al., 2015). Although soil moisture is a key internal state variable in hydrological modeling, we have not included soil moisture products for the model validation. Accurate simulations of the dynamics of AET and discharge has been shown to reliably represent the hydrological behavior in the Ouémé catchment (Odusanya et al., 2021). We thus focused the model evaluation on discharge,
550 AET, and LAI, and excluded soil moisture to minimize additional uncertainty and potential conflicts between observational variable constraints.

We integrate LAI as a proxy for vegetation in the hydrological modeling. The relevance of LAI on the AET and discharge estimation in sub-humid regions has been highlighted prior, e.g., in Alemayehu et al. (2017); Hoyos et al. (2019); Ferreira et al. (2021); López-Ramírez et al. (2021). Previous studies for the region, like Poméon et al. (2018) or Odusanya et al. (2021),
555 include AET in the hydrological modeling of the Ouémé River in Benin, while others have focused on "Q only" approaches (Bossa et al., 2014; Danvi et al., 2018). We demonstrate that a detailed LAI modeling can predict adequate AET outputs.

The evaluation of modeled discharge from the ROPE application yields different KGE ranges depending on the forcing data. For calibration with data from the observation network, the maximum $E_{KGE,Q}$ (validation) is 0.91 (0.92), 0.85 (0.88), and 0.90 (0.90) for "Q only", "Q + LAI", and "Q + LAI + AET", respectively. These results align with findings from other studies;

560 for instance, Afféwé et al. (2025) report 0.83 (0.77) with HBV model, or Herzog et al. (2021) validate the Parflow-CLM model with a mean KGE value of 0.82. The strong KGE performance confirms that the ROPE algorithm and the SWAT-T are well-suited for discharge calibration in the Bétérou Catchment.

However, it is still essential to calibrate the hydrological impact model with the W5E5 forcing dataset if the bias-adjusted ISIMIP3b GCM outputs are used. In this study, the maximum $E_{KGE,Q}$ from calibration (validation) are 0.64 (0.50), 0.64 (0.49), and 0.63 (0.49) for "Q only", "Q + LAI", and "Q + LAI + AET", respectively. We assume the KGE values are smaller compared to the observed data due to the W5E5 data forcing, particularly precipitation. The W5E5 data set represents the seasonality accurately well, but it lacks the depiction on sub-seasonal variations and single rainfall events for the Bétérou Catchment in West Africa. Similar results with CMIP6 are reported by Wang et al. (2022) for the Congo River in Africa who figured challenges in discharge representation through CMIP6 climate data. However, we benchmark the discharge performance with the seasonal benchmark after Knoben et al. (2020), which shows an adequate behavioral modeling of discharge. Combined with the parameter cross validation, the W5E5-models are applicable and can still represent the mean seasonal patterns of the hydrological cycle in Bétérou. We thus recommend benchmarking and cross validation with observed data if the ISIMIP3b is used for future studies in West Africa.

The benchmarking moreover contains a Julian Day method for FLUXCOM-AET and GLASS-LAI, where a relatively strong performance for both datasets can be observed. The remotely sensed FLUXCOM-AET and GLASS-LAI products are subject to temporal smoothing and gap-filling, which can regularizes the signal and enhances the skill of a climatological benchmark. Therefore, the benchmark performance should be cautiously interpreted as it is not an evidence of superior model process representation. It is possible that satellite-based datasets do not fully capture the dynamic year-to-year variability in vegetation and evapotranspiration, particularly during cloudy periods (Viovy et al., 1992; Atkinson et al., 2012) or in highly dynamic land surface conditions (Weerasinghe et al., 2020). The retrieval algorithms and data assimilation for both FLUXCOM-AET and GLASS-LAI rely on temporal compositing and interpolation. Thus, the processing influences and smooths the real interannual fluctuations and make the reference signal appear more repeatable from year to year. It is likely that this regularization of the observational data contributes to the high skill of the Julian Day benchmark for FLUXCOM-AET and GLASS-LAI.

The model optimization and selection of the 20 parameter sets for the climate impact assessment are based on the performance metrics KGE, which is a robust criteria to asses the runoff generated within a catchment (Gupta et al., 2009). Single metrics can however overlook pitfalls of the model structure and defer the model and parameter choice (Schaeffli and Gupta, 2007; Knoben et al., 2019; Hallouin et al., 2020; Cinkus et al., 2023). We apply multiple parameter sets, the benchmarking after Knoben et al. (2020), and parameter cross validation to increase the reliability of the single-metrics based model choice for climate impact assessments. Looking ahead, the model optimization can include further performance criteria to assess specific features of hydrological process in the region, such as the Nash-Sutcliffe Efficiency (NSE) or the logarithmic NSE, among many others, to better include high or low flows, respectively.

The evaluation of LAI as proxy for AET is site- and model-specific. Although the Bétérou Catchment is representative of parts of West Africa, it captures only a subset of the region's diverse hydrological, phenological, and climatic conditions. The ET dynamics in the region can be generally considered water-limited, since the strong seasonal water deficit governs ecosystem

595 functioning (Mamadou et al., 2016). From a modeling perspective, LAI can be expected to serve as a proxy for AET primarily
in physical-oriented hydrological models that use LAI as a vegetation attribute in the framework of ET computation, such as
the Penman-Monteith method. In contrast, the relation of LAI and AET is weaker in hydrological models that estimate ET
using more simplified or empirical approaches, such as the Hargreaves method. In such models, the suitability of LAI as a
proxy for AET is limited. Consequently, the conclusions regarding the suitability of LAI as a proxy for AET may be specific to
600 water-limited environments and should be evaluated in regions with different hydroclimatic regimes as well as the hydrological
model applied.

4.2 Climate future data and meteorological changes

We used five GCMs with three SSP scenarios from ISIMIP3b (based on CMIP6) equally weighted, where we followed the con-
ventional model democracy approach. Model democracy in climate impact studies can be crucial (Knutti, 2010). However, the
605 use of multiple GCM-scenario combinations helps to reduce structural GCM model uncertainty, while enhancing transparency
and comparability. For example, the application of CMIP6 data in this study for the Bétérou Catchment in Benin enables com-
parisons with similar assessments in this region, such as the findings of Yonaba et al. (2023) for the Tougou Basin in Burkina
Faso. Both studies indicate substantial increases in projected discharge under the MPI-ESM1-2-HR model, with changes up to
101.1 % in this study and up to 117 % in (Yonaba et al., 2023).

610 However, assuming all GCM models perform reasonably well globally is critical, since poorly performing GCMs can in-
fluence ensemble-based hydrological impact statements (Flato et al., 2014). Hattermann et al. (2018) highlight that GCMs
are major source of uncertainty in the climate-hydrological impact modeling. Consequently, the influence of the calibration
strategy on future AET is likely to be smaller compared to the GCM model uncertainty. Nevertheless, our study demonstrates
that the future changes of AET strongly depend on the calibration strategy. Thus, disregarding AET during model calibration
615 may introduce an additional layer of uncertainty other than the GCM uncertainty.

The application of multiple ISIMIP3b GCMs offers a transparent and standard way to understand climate changes and hy-
drological responses across studies, and to avoid uncertainties from individual downscaling and bias corrections. Romanovska
et al. (2023) demonstrate the potential benefits of the ISIMIP3b climate data since its multi-model mean ensembles can even
outperform individual models when compared to observed precipitation in Western Africa. The seasonal patterns of temper-
620 ature and precipitation in the GCM historical data closely align with those observed in the monitoring network. The monthly
values are similar, and qualitatively meet the criteria suggested by (Krysanova et al., 2017; Hattermann et al., 2018). The me-
teorological changes for the Bétérou Catchment in Benin indicate a clear projection for temperature, but a divers picture for
precipitation. For temperature, all GCMs forecast increases of 0.5 to 5.8 °C, which generally aligns with the changes projected
with CMIP6 for the West African Region (Almazroui et al., 2020).

625 The projected precipitation derived from the ISIMIP3b data set indicates a diversified scatter of changes. The multi-model
mean values indicate small (1.2 %, SSP1–2.6) to large (7.2 %, SSP5–8.5) precipitation increases. Yet, the variability between
single models is distinct. Substantially wetter periods are indicated by MPI-ESM1-2-HR, IPSL-CM6A-LR, and UKESM1-
0-LL, while GFDL-ESM4 and MRI-ESM2-0 project drier future rainfall. The ensemble spread in CMIP6 precipitation pro-

jections can be attributed to differences in how models simulate the West African Monsoon (Almazroui et al., 2020). Similar
630 precipitation variability for West Africa has also been reported in other climate forcing datasets. For example, Nikulin et al.
(2012) found substantial spreads in CORDEX precipitation projections that are also linked to the complex monsoon dynamics.

4.3 Hydrological changes

The annual AET is generally predicted to increase independent of the GCM, the time period (near-, far future), or the calibration
strategy ("Q only", "Q + LAI", "Q + LAI + AET"). For the low emission scenario (SSP1–2.6), the multi-model mean changes
635 range from 4.0 % to 7.4 % across all calibration strategies. The high emission scenario (SSP5–8.5) predicts multi-model mean
changes of 4.2 % to 9.2 %. Previous impact studies for the Ouémé region report increases, but also decreases in future AET for
the region (Bossa et al., 2012, 2014; Danvi et al., 2018). However, these studies relied on models calibrated against discharge,
without explicitly including AET in the calibration. As our results demonstrate, disregarding AET from calibration can defer
the simulated amount of future AET, where "Q only" simulates lower future annual AET changes than "Q + LAI" or "Q + LAI
640 + AET". These findings align with Mishra et al. (2020), who demonstrate the influence of the AET calibration strategy on the
climate impact assessment for the Upper Godavari in India.

Differences in projected AET across the calibration approaches are most pronounced between August and December. The
calibration strategy has a smaller impact on AET simulation during the early part of the year, which is the shift from dry to wet
period. The seasonal AET pattern in Bétérrou is characterized by two peaks (April to June and September to November) with a
645 notable dip during the peak rainy season (June to September). This mid-season decline is primarily caused by cloud cover and
rainfall, which limit solar radiation and thus reduce AET. SWAT-T can simulate AET dynamics in the beginning of the season
(January to July), which is largely independent of the calibration strategy. However, from August onward, the AET simulation
becomes more sensitive to the calibration strategy, demonstrating the need for carefully adjusted model parameters. The soil
(e.g., SOL_AWC, SOL_BD), AET (e.g., GSI), and plant growth (DLAI, T_BASE, FRGRW2) parameters can be essential to
650 realistically represent post-monsoon and dry-season AET in Bétérrou.

The analysis of future discharge changes shows increases and decreases depending on the GCM, emission scenario, and eval-
uation period. The different projections are largely attributed to the complexity of how GCMs simulate precipitation dynamics
and projections of the West African Monsoon (Paeth et al., 2011). Consequently, the model forcing with MPI-ESM-1-2-HR
outputs can also result in high future discharges (change of 101.1 % for "Q only", SSP5–8.5, far future). Similar substantial
655 discharge changes with MPI-ESM-1-2-HR are also reported by Yonaba et al. (2023) for a catchment in Burkina Faso. This
GCM projects substantial precipitation increases with minor temperature changes for the West African region. Overall, the
analysis of the multi-model mean for future discharge changes essentially indicates a decrease of discharge for the Bétérrou
region. The multi-model mean changes vary from 22.9 % to 3.2 %. Discharge decreases for the Ouémé region have also been
found in other studies (Bossa et al., 2012, 2014; Danvi et al., 2018). The decreases can potentially be attributed to the increase
660 in temperature, which intensify the evaporative demand.

In this study, the evaluation of hydrological changes is focused on the primary components of the hydrological cycle AET
and discharge in the Bétérrou Catchment. These variables provide a robust basis for interpretation, since they are reasonably

well constrained by observations. Other water balance components, such as the partitioning into surface runoff, lateral flow, and baseflow, are not specifically investigated at this stage. Soil moisture dynamics are not analyzed in detail, because no particular calibration or validation has been conducted. Looking ahead, a comprehensive analysis of the water balance components will be conducted with a special focus on soil moisture, the partitioning of the flow components, and hydrological variables.

5 Conclusion

The broad implication of this research is the demonstration of how different the response of future AET to climate change can be depending on the calibration strategy with an ecohydrological impact model. Although being a key component of the hydrological cycle and commonly used as an indicator for water availability, AET often remains disregarded in model calibration in climate impact assessment frameworks in West Africa. We investigate the role of different calibration strategies on future AET projections under different GCM and emission scenario combinations for the demonstration site Bétérrou in West Africa using the ecohydrological model SWAT-T.

This study couples comprehensive parameter estimation with climate impact assessment, and uses multiple near-optimal parameter sets for each calibration strategy. This ensemble-based approach avoids reliance on a single best-fit solution and explicitly accounts for model parameter equifinality. As a result, the robustness of simulated AET dynamics and associated hydrological projections is improved, and the influence of calibration strategy can be more clearly isolated.

The analysis shows that the calibration strategy calibration approach can influence the future AET projections. The simulated mean annual AET substantially varies depending on the calibration strategy for the baseline (2001 to 2015) and future periods (2031 to 2050 and 2070 to 2099). The annual AET is smaller for discharge-only calibration compared to Although the applied strategies "Q only", "Q + LAI", and "Q + LAI + AET" indicate increasing future rates of AET, "Q + LAI" and "Q + LAI + AET" show similar climate sensitivities. Across all GCM and SSP scenarios, the annual AET is smaller for "Q only" (846 to 889 mm yr⁻¹) compared to "Q + LAI" (886 to 918 mm yr⁻¹) and "Q + LAI + AET" (904 to 932 mm yr⁻¹) approaches. The relative future AET changes of the GCM-ensemble mean for low emission scenarios (SSP1–2.6) range from $\Delta E = 4.0\%$ (discharge only) to $\Delta E = 7.4\%$ (AET in calibration) in the near future period. For high emission scenarios (SSP5–8.5) and the far future period, the future change of AET is $\Delta E = 9.2\%$ (disregarding AET in model calibration) to $\Delta E = 8.4\%$ (AET in calibration). The differences in future AET changes from the calibration strategy are tied to the simulation of the mean seasonal AET values. Disregarding AET in calibration results in lower AET predictions for the wet to dry transition period (August to December). This study moreover

Further, this study highlights the value of plant growth (LAI) for AET estimation. Given the high transpiration rates in the region, vegetation dynamics (LAI) can, particularly when applying the ecohydrological model SWAT-T. It shows that the combined "Q + LAI" (disregarding AET in calibration) yields similar AET representation to "Q + LAI + AET" and improves the performance of modeling the AET seasonal pattern compared to "Q only" for the Bétérrou Catchment in Benin. Nevertheless, additional research is needed to determine whether LAI can consistently serve as a proxy for AET when direct calibration is not feasible across different catchments, climatic conditions, and hydrological models.

This study aligns with the well-documented findings that the application of the ISIMIP3b (CMIP6) data can have for climate impact assessment in West Africa. The baseline forcing data set W5E5 captures the precipitation pattern of the Bétérou Catchment reasonably well, yet can have implications in representing individual rainfall events. For instance, model calibration using W5E5 forcing shows lower performance compared to simulations driven by observed meteorological data for discharge simulation. 700 Additionally, some GCMs can be more sensitive to the regional affecting West African Monsoon. This leads to higher precipitation projections, which consequently results in high future discharge increases (up to $\Delta Q = 101.1\%$ for certain GCMs; "Q only").

In hydrological climate impact assessment, GCM uncertainty remains most challenging. Yet, our findings underscore the value of a robust hydrological model calibration for impact assessment. We address calibration strategy and parameter un- 705 certainty in this study to demonstrate how disregarding AET in calibration can bias simulated AET dynamics and influence associated hydrological projections. ~~The presented methodology can be transferred to other AET-dominant regions.~~ Looking ahead, integrating additional remotely sensed or satellite-based data, such as soil moisture or ensemble AET data, can further reduce modeling uncertainties and improve the reliability of future AET and discharge assessments.

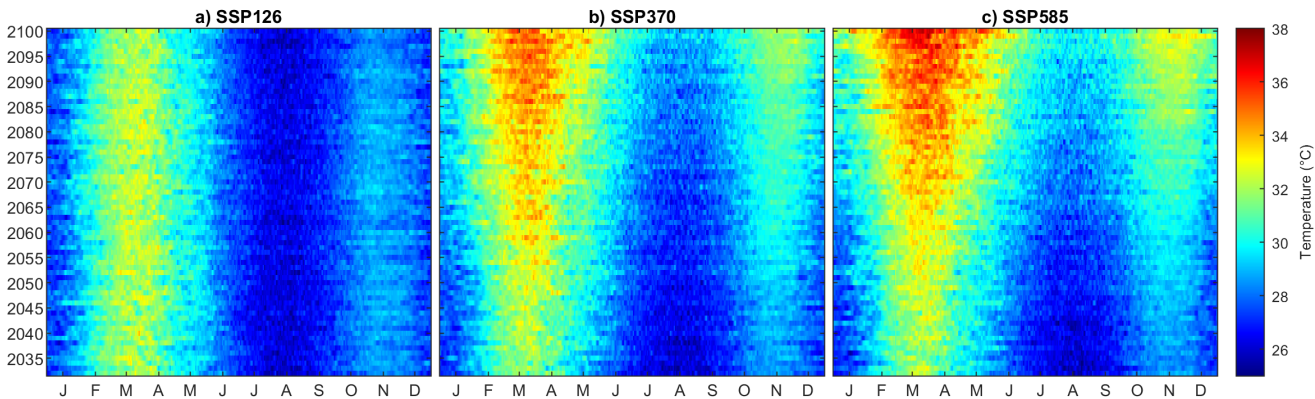


Figure A1. Daily average temperature projections (multi-model mean) in three climate change scenarios (SSP1–2.6, SSP3–7.0, SSP5–8.5).

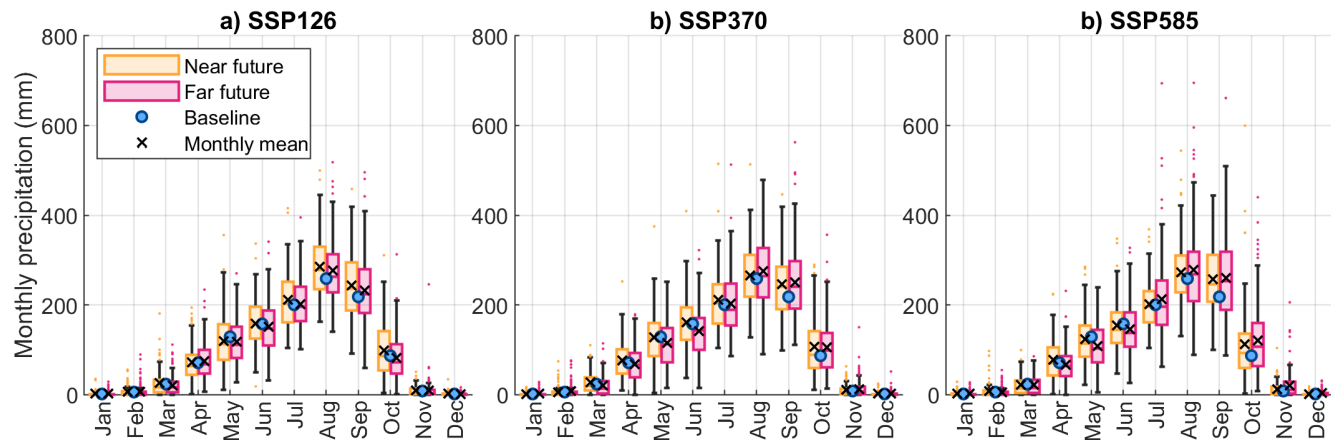


Figure A2. Seasonal cycle of monthly precipitation projections (multi-model mean) in three climate change scenarios (SSP1–2.6, SSP3–7.0, SSP5–8.5). Blue circles represent the monthly mean precipitation from ISIMIP3b baseline (1951 to 2015). Black crosses are used to highlight the multi-model monthly mean values.

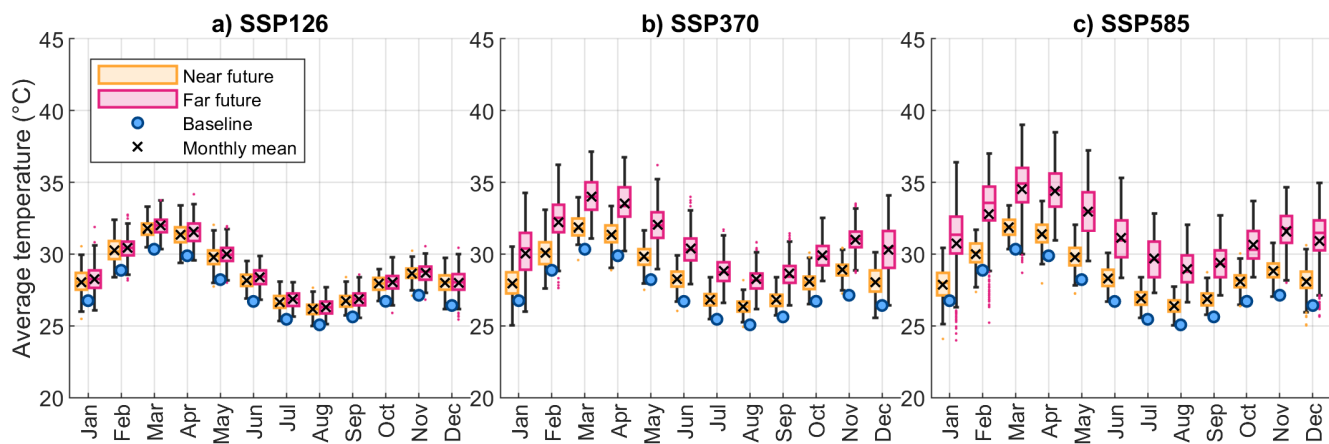


Figure A3. Seasonal cycle of average temperature projections (multi-model mean) in three climate change scenarios (SSP1–2.6, SSP3–7.0, SSP5–8.5). Blue circles represent the monthly mean temperature from ISIMIP3b baseline (1951 to 2015). Black crosses are used to highlight the multi-model monthly mean values.

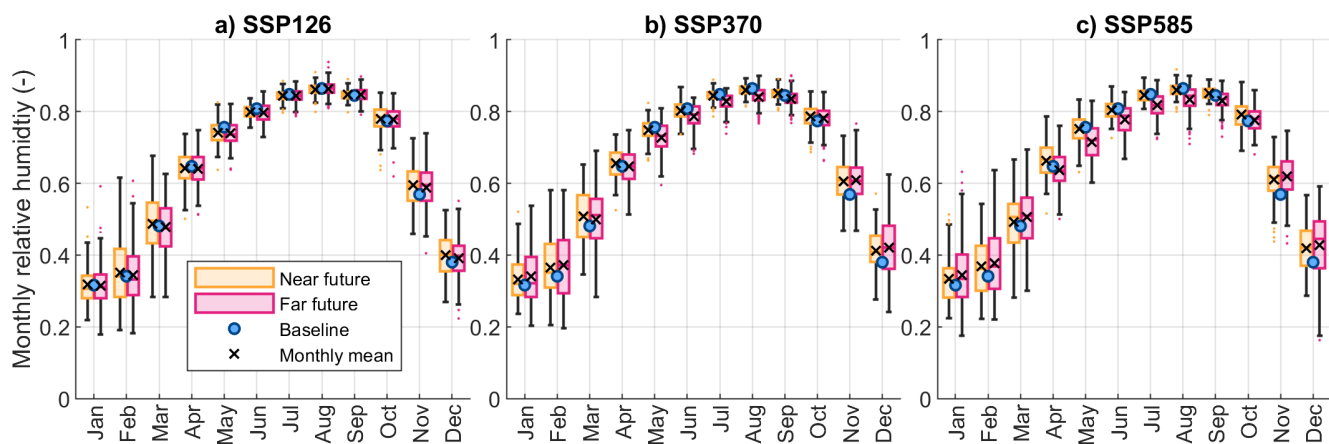


Figure A4. Seasonal cycle of monthly humidity projections (multi-model mean) in three climate change scenarios (SSP1–2.6, SSP3–7.0, SSP5–8.5). Blue circles represent the monthly mean humidity from ISIMIP3b baseline (1951 to 2015). Black crosses are used to highlight the multi-model monthly mean values.

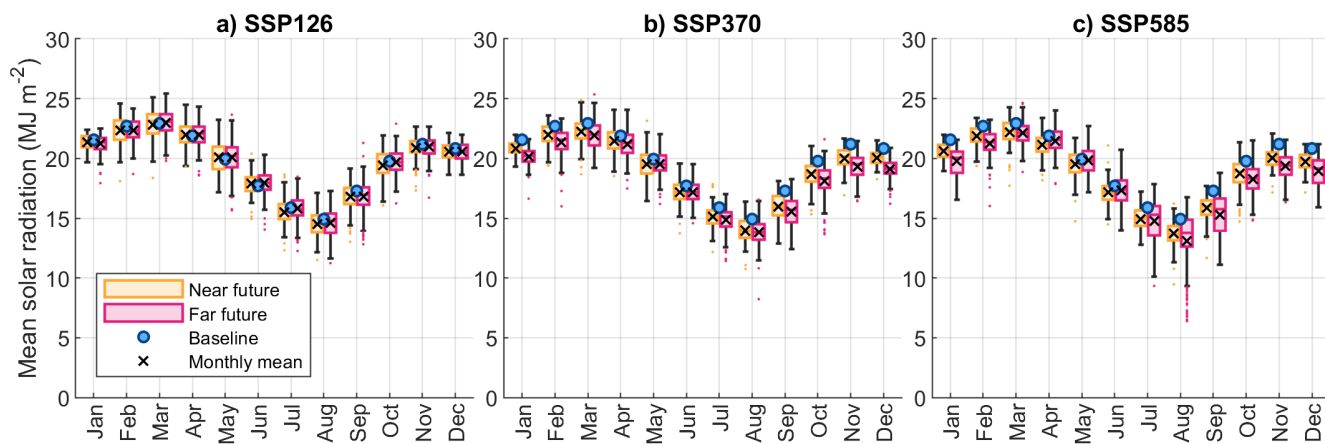


Figure A5. Seasonal cycle of monthly solar radiation projections (multi-model mean) in three climate change scenarios (SSP1–2.6, SSP3–7.0, SSP5–8.5). Blue circles represent the monthly mean radiation from ISIMIP3b baseline (1951 to 2015). Black crosses are used to highlight the multi-model monthly mean values.

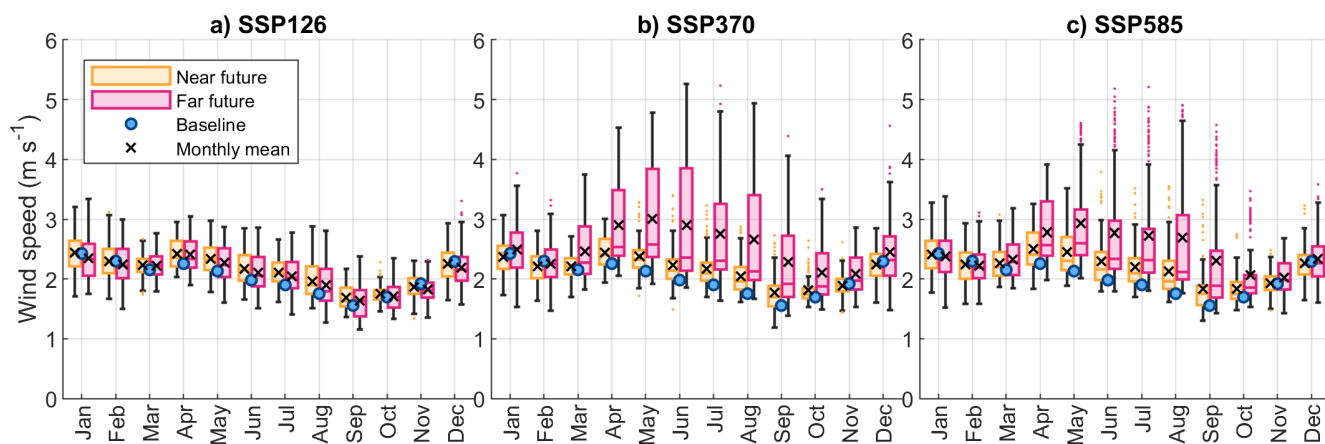


Figure A6. Seasonal cycle of monthly wind speed projections (multi-model mean) in three climate change scenarios (SSP1–2.6, SSP3–7.0, SSP5–8.5). Blue circles represent the monthly mean wind speed from ISIMIP3b baseline (1951 to 2015). Black crosses are used to highlight the multi-model monthly mean values.

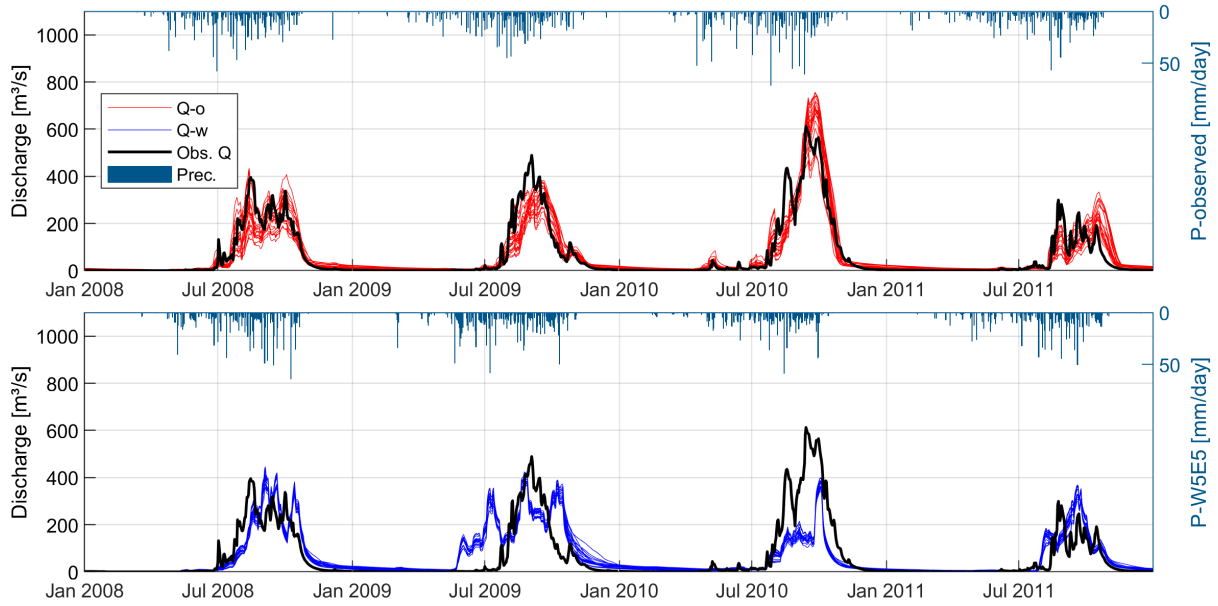


Figure A7. Hydrograph for the calibration period for observed forcing data (W5E5 forcing data) in the upper (lower) panel. Each panel shows the simulated hydrograph for the 20 best parameters of the "Q + LAI + AET" approach, the observed streamflow, and precipitation.

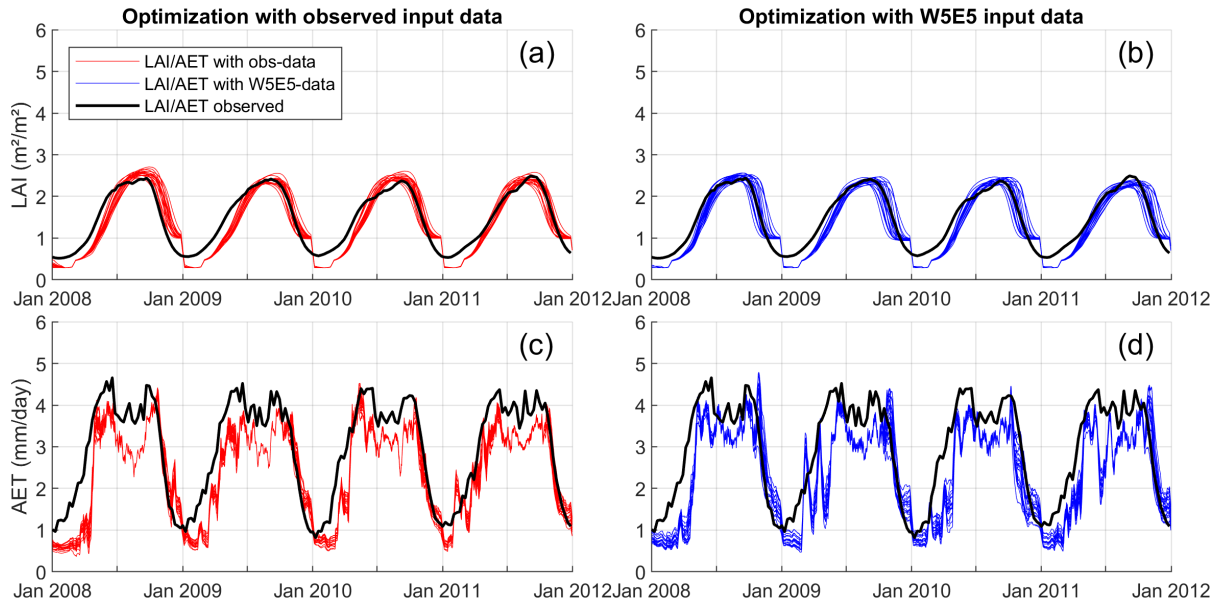


Figure A8. Time series of LAI/AET for the calibration period for observed forcing data (W5E5 forcing data) in the left (right) panels. Each panel shows the simulated LAI/AET for the 20 best parameters of the "Q + LAI + AET" approach and the references GLASS-LAI/FLUXCOM-AET.

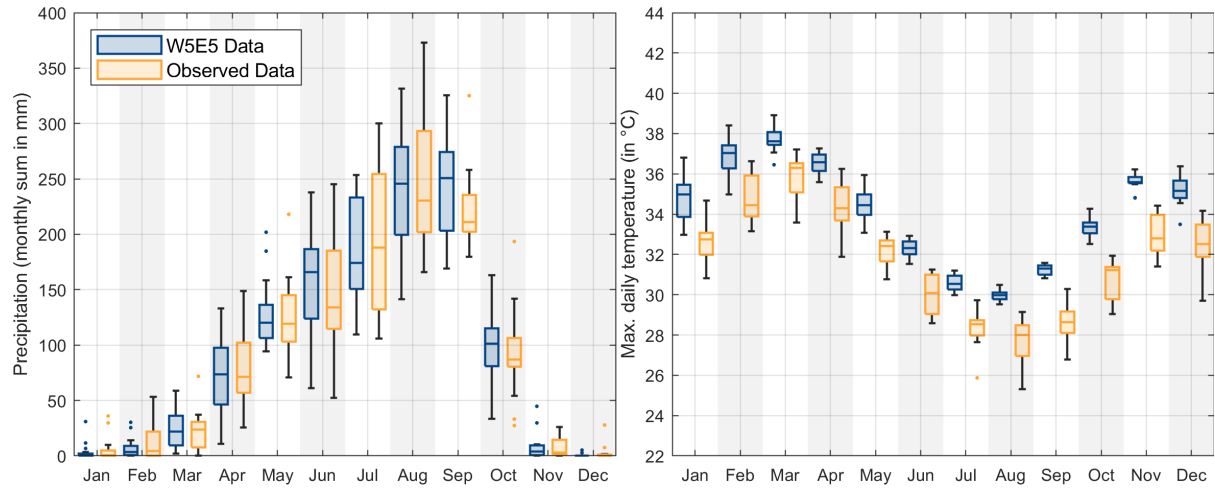


Figure A9. Comparison W5E5 and observed data for monthly precipitation sums (left) and daily maximal temperature (right).

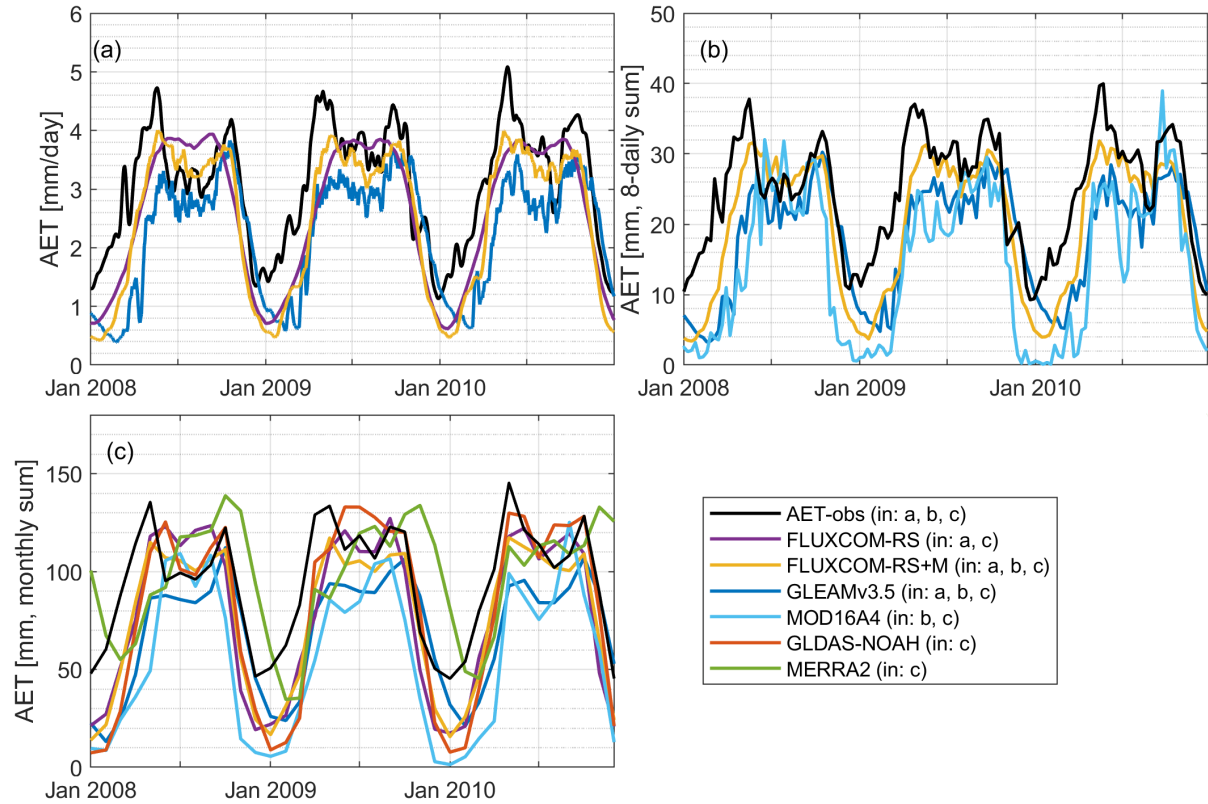


Figure A10. Comparison of monitored AET (AET-obs, black line; location: Bellefoungou, Benin) to multiple satellite-based and reanalysis AET products for different temporal scales a) daily, b) 8-daily sum, and c) monthly sum. Please note the varying y-axis scales for readability.

A2 Appendix A2 - Tables

Table A1. Projected changes of precipitation (ΔP) and temperature (ΔT) for the underlying GCM, emission scenario, and future period.

GCM	SSP1–2.6				SSP3–7.0				SSP5–8.5			
	Near		Far		Near		Far		Near		Far	
	ΔP	ΔT	ΔP	ΔT	ΔP	ΔT	ΔP	ΔT	ΔP	ΔT	ΔP	ΔT
GFDL-ESM4	5.1	1.2	−4.5	1.3	−7.9	1.4	−14.8	3.2	−2.6	1.2	−17.2	3.7
IPSL-CM6A-LR	7.9	1.5	7.6	1.6	6.6	1.8	18.4	4.3	7.0	1.8	21.3	5.4
MPI-ESM-1-2-HR	−2.1	0.9	−3.3	0.9	9.1	0.5	8.3	1.9	0.1	0.6	21.7	1.5
MRI-ESM2-0	11.5	1.4	−1.3	1.8	13.3	1.2	−2.7	3.6	19.6	1.6	−8.0	4.7
UKESM1-0-LL	8.7	1.9	7.4	2.0	13.2	2.2	8.9	4.5	11.2	1.9	17.8	5.8
Multi-model mean	6.3	1.4	1.2	1.5	7.0	1.4	3.7	3.5	7.2	1.4	7.2	4.2

Table A2. Overview of the mean E_{PBias} values (in %) of the 20 parameter sets.

Approach	Observation Network						W5E5 dataset					
	Calibration			Validation			Calibration			Validation		
	Q	LAI	AET	Q	LAI	AET	Q	LAI	AET	Q	LAI	AET
Q	−1.2	3.4	15.8	−13.6	7.7	6.6	−6.8	25.5	24.6	−25.5	24.8	21.5
Q + LAI	−2.5	8.7	20.2	−18.2	11.4	10.3	−8.9	10.8	20.6	−19.6	11.3	17.3
Q + LAI + AET	0.8	7.2	17.5	−11.1	10.9	7.6	−3.5	9.6	18.8	−10.4	10.4	15.7

Table A3. Overview of the mean E_{R2} values (no unit) of the 20 parameter sets.

Approach	Observation Network						W5E5 dataset					
	Calibration			Validation			Calibration			Validation		
	Q	LAI	AET	Q	LAI	AET	Q	LAI	AET	Q	LAI	AET
Q	0.79	0.70	0.68	0.85	0.59	0.74	0.40	0.53	0.65	0.26	0.58	0.71
Q + LAI	0.73	0.90	0.82	0.80	0.81	0.87	0.40	0.93	0.73	0.24	0.89	0.81
Q + LAI + AET	0.75	0.90	0.82	0.82	0.80	0.85	0.38	0.92	0.73	0.23	0.88	0.81

Table A4. Overview of the compared AET data sets from Figure A10 and the performance metrics E_{R2} (no unit) for the daily, 8-daily sum, and monthly evaluation.

Product	Daily	8-daily sum	Monthly	Temporal Scale	Spatial Scale
FLUXCOM-RS	0.55	<i>not applied</i>	0.71	8-daily interval	0.0833° ($\approx$ 9.3 km)
FLUXCOM-RS+Meteo	0.53	0.5	0.77	daily	0.5° ($\approx$ 55 km)
GLEAMv3.6	0.33	0.33	0.53	daily	25 km
MOD16A4	<i>not applied</i>	0.31	0.60	8-daily sum	0.5 km
GLDAS-NOAH	<i>not applied</i>	<i>not applied</i>	0.70	monthly	0.25° ($\approx$ 27.5 km)
MERRA2	<i>not applied</i>	<i>not applied</i>	0.11	monthly	0.5° ($\approx$ 55 km)

Table A5. Meteorological (ΔP for precipitation change in percent; ΔT for temperature change in degree Celsius) and hydrological changes (ΔQ and ΔE for discharge and AET changes in percent, respectively) for the GCMs and SSP scenarios (short names for GCMs and SSPs are used for layout purposes; MMM = multi-model mean) and the underlying calibration strategies (1=Q-only; 2=Q+LAI; 3=Q+LAI+AET) for the near-future period.

GCM	SSP	ΔP	ΔT	$\Delta Q - 1$	$\Delta Q - 2$	$\Delta Q - 3$	$\Delta E - 1$	$\Delta E - 2$	$\Delta E - 3$
GFDL	SSP1	5.1	1.2	-3.2	-6.8	-9.0	2.3	2.8	4.4
GFDL	SSP3	-7.9	1.4	-51.2	-49.9	-51.8	1.6	1.1	2.6
GFDL	SSP5	-2.6	1.2	-30.9	-30.1	-32.1	0.9	0.7	2.2
IPSL	SSP1	7.9	1.5	-6.5	-9.8	-11.6	8.1	8.0	9.5
IPSL	SSP3	6.6	1.8	-13.4	-16.9	-17.7	10.9	11.3	12.6
IPSL	SSP5	7.0	1.8	-11.7	-14.9	-16.6	8.4	9.2	10.7
MPI	SSP1	-2.1	0.9	-31.1	-29.0	-31.2	2.1	1.5	3.3
MPI	SSP3	9.1	0.5	7.0	1.3	-2.6	1.6	1.0	2.7
MPI	SSP5	0.1	0.6	-12.0	-12.7	-14.5	-1.5	-2.0	-0.6
MRI	SSP1	11.5	1.4	21.4	11.1	9.8	5.9	6.7	8.1
MRI	SSP3	13.3	1.2	26.7	13.1	8.8	4.2	4.9	6.3
MRI	SSP5	19.6	1.6	48.1	27.5	22.5	4.1	5.1	6.4
UKESM	SSP1	8.7	1.9	2.9	-4.5	-6.0	9.4	10.5	11.8
UKESM	SSP3	13.2	2.2	24.8	12.7	9.1	10.2	10.5	11.7
UKESM	SSP5	11.2	1.9	22.5	10.0	7.3	9.0	9.5	10.5
MMM	SSP1	6.3	1.4	-3.3	-7.8	-9.6	5.5	5.9	7.4
MMM	SSP3	7.0	1.4	-1.2	-7.9	-10.8	5.7	5.8	7.2
MMM	SSP5	7.2	1.4	3.2	-4.0	-6.7	4.2	4.5	5.8

Table A6. Same analysis as in Table A5 for the far-future evaluation.

GCM	SSP	ΔP	ΔT	$\Delta Q - 1$	$\Delta Q - 2$	$\Delta Q - 3$	$\Delta E - 1$	$\Delta E - 2$	$\Delta E - 3$
GFDL	SSP1	-4.5	1.3	-34.8	-34.0	-36.0	0.3	0.3	2.0
GFDL	SSP3	-14.8	3.2	-60.1	-59.7	-60.9	-0.4	-1.2	-0.2
GFDL	SSP5	-17.2	3.7	-65.2	-64.2	-65.1	-0.3	-1.8	-1.1
IPSL	SSP1	7.6	1.6	-6.0	-11.4	-13.1	8.1	8.3	9.7
IPSL	SSP3	18.4	4.3	-9.4	-11.0	-11.6	22.9	22.5	23.7
IPSL	SSP5	21.3	5.4	-11.8	-6.5	-7.2	28.1	24.3	25.9
MPI	SSP1	-3.3	0.9	-31.1	-29.9	-32.0	0.9	0.6	2.3
MPI	SSP3	8.3	1.9	4.9	-3.0	-4.7	1.6	2.8	4.0
MPI	SSP5	21.7	1.5	101.1	75.6	71.0	-6.3	-6.1	-5.0
MRI	SSP1	-1.3	1.8	-23.9	-25.2	-26.9	3.1	3.6	5.2
MRI	SSP3	-2.7	3.6	-33.5	-33.1	-33.8	5.7	5.5	6.7
MRI	SSP5	-8.0	4.7	-51.2	-45.1	-45.9	7.4	4.2	5.2
UKESM	SSP1	7.4	2.0	7.3	-1.6	-4.3	7.7	8.2	9.6
UKESM	SSP3	8.9	4.5	3.7	-1.8	-3.6	10.8	10.6	11.8
UKESM	SSP5	17.8	5.8	19.1	14.8	12.1	17.3	15.6	16.9
MMM	SSP1	1.2	1.5	-17.7	-20.4	-22.4	4.0	4.2	5.8
MMM	SSP3	3.7	3.5	-18.8	-21.7	-22.9	8.1	8.0	9.2
MMM	SSP5	7.2	4.2	-1.6	-5.1	-7.0	9.2	7.2	8.4

A3 Appendix A3 - Supplementary equations

The equations for the Kling-Gupta efficiency E_{KGE} , percent bias (E_{PBIAS}), and coefficient of determination E_{R2} are shown in the following. In this, r is the linear correlation between observations and simulations; σ_{sim} and σ_{obs} are the standard deviation of the simulations and observations, respectively; and μ_{sim} and μ_{obs} are the mean value for the simulations and observation, respectively; n is the number of observations; and $Q_{sim,i}$ ($Q_{obs,i}$) is the simulated (observed) discharge at time i .

$$E_{KGE} = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{sim}}{\sigma_{obs}} - 1\right)^2 + \left(\frac{\mu_{sim}}{\mu_{obs}} - 1\right)^2}, \quad (A1)$$

$$E_{PBIAS} = 100 \times \frac{\sum_{i=1}^n (Q_{sim,i} - Q_{obs,i})}{\sum_{i=1}^n Q_{obs,i}}, \quad (A2)$$

$$E_{R2} = \left(\frac{\sum_{i=1}^n (Q_{obs,i} - \mu_{obs})(Q_{sim,i} - \mu_{sim})}{\sqrt{\sum_{i=1}^n (Q_{obs,i} - \mu_{obs})^2} \sqrt{\sum_{i=1}^n (Q_{sim,i} - \mu_{sim})^2}} \right)^2. \quad (A3)$$

Table A7. Final parameters for each calibration approach and forcing data. The table lists the minimal, median, and maximal parameter value from the best performing 20 sets. The superscripts denote: ¹ parameter change is a multiplier, i.e., the original parameter p is multiplied: $p_{new} = p_{orig} + p_{orig} \times p_{change}$, based on the parameter values from Judex and Thamm (2008); ² parameter change is a multiplier, i.e., the original parameter p is multiplied: $p_{new} = p_{orig} \times p_{change}$, based on the parameter values from Merk et al. (2024).

Parameter	Forcing: observed data			Forcing: W5E5 data		
	Q only	Q + LAI	Q + LAI + AET	Q only	Q + LAI	Q + LAI + AET
ESCO	0.16, 0.45, 0.80	0.28, 0.54, 0.78	0.14, 0.34, 0.77	0.28, 0.49, 0.80	0.19, 0.57, 0.85	0.25, 0.64, 0.86
EPCO	0.20, 0.40, 0.84	0.27, 0.42, 0.77	0.21, 0.47, 0.58	0.42, 0.56, 0.75	0.24, 0.40, 0.70	0.23, 0.43, 0.52
GWQMN	1325, 1642, 1857	1345, 1593, 1713	952, 1318, 1649	1012, 1197, 1514	1147, 1311, 1479	1141, 1303, 1483
GW_DELAY	1.2, 16.7, 43.3	6.0, 21.4, 40.1	7.7, 45.9, 56.2	5.4, 8.1, 11.0	8.0, 10.1, 16.0	5.3, 8.3, 16.3
GW_REVAP	0.04, 0.10, 0.13	0.04, 0.12, 0.19	0.07, 0.14, 0.18	0.07, 0.10, 0.13	0.07, 0.11, 0.15	0.08, 0.10, 0.13
RCHRG_DP	0.03, 0.12, 0.18	0.06, 0.11, 0.17	0.06, 0.15, 0.19	0.04, 0.07, 0.13	0.05, 0.11, 0.14	0.04, 0.07, 0.16
REVAPMN	515, 751, 955	399, 754, 1137	464, 855, 1280	506, 703, 1169	640, 788, 1132	671, 895, 1213
SOL_AWC ¹	-0.23, 0.19, 0.44	-0.09, 0.14, 0.28	0.04, 0.21, 0.45	-0.10, 0.08, 0.34	-0.31, -0.08, 0.33	-0.19, 0.17, 0.40
SOL_BD ¹	0.09, 0.20, 0.32	0.16, 0.30, 0.38	0.25, 0.30, 0.32	0.05, 0.15, 0.28	-0.04, 0.12, 0.26	-0.13, 0.08, 0.29
CAN_MX	0.94, 4.47, 7.68	1.94, 5.72, 7.86	2.38, 4.39, 8.42	1.42, 3.56, 6.49	1.57, 5.37, 7.77	2.74, 6.36, 9.31
FRGRW ₂ ²	0.81, 0.91, 1.04	0.82, 0.90, 1.00	0.78, 0.86, 0.96	0.85, 0.92, 1.07	0.75, 0.91, 1.03	0.77, 0.88, 0.98
DLAI ²	0.77, 0.89, 1.06	0.86, 0.97, 1.02	0.87, 0.98, 1.06	0.80, 0.94, 1.04	0.83, 0.96, 1.03	0.83, 0.94, 1.03
T_BASE ²	0.78, 0.97, 1.16	0.99, 1.10, 1.22	0.87, 1.04, 1.21	0.91, 1.02, 1.16	0.85, 1.00, 1.13	0.84, 0.94, 1.12
GS1 ²	0.84, 1.03, 1.18	0.82, 1.02, 1.19	0.81, 1.03, 1.13	0.86, 0.95, 1.05	0.88, 1.00, 1.12	0.84, 1.04, 1.10
PHU ²	0.86, 0.94, 1.16	1.05, 1.12, 1.20	1.01, 1.14, 1.23	0.97, 1.08, 1.14	0.91, 0.99, 1.13	0.94, 1.06, 1.14

A5 Appendix A5 - Water balance components

Table A8. Overview of the multi-model mean values of the water balance components. The baseline reference is the evaluation period 2001 to 2015 simulated with W5E5. The values show the mean value for each GCM, emission scenario, and the 20 sets of parameters in mm yr⁻¹. The changes to the baseline (in brackets) are percentage changes. Precipitation is the mean annual precipitation for the near- and far-future period. SWAT-T computes "Water Yield" as the sum of surface runoff, lateral flow, and baseflow. Percolation serves as proxy for groundwater recharge when using SWAT-T.

	Near future			Far future		
	Q	Q + LAI	Q + LAI + AET	Q	Q + LAI	Q + LAI + AET
SSP1–2.6						
Precipitation	1246	1246	1246	1175	1175	1175
AET	858 (+5.6)	900 (+5.9)	917 (+7.2)	846 (+4.0)	886 (+4.2)	925 (+8.3)
Water Yield	182 (–15.6)	180 (–18.4)	168 (–18.8)	181 (–15.6)	180 (–18.4)	201 (–3.0)
Percolation	221 (–6.6)	162 (–9.2)	158 (–9.8)	185 (–22.0)	130 (–26.7)	154 (–12.0)
SSP3–7.0						
Precipitation	1238	1238	1238	1203	1203	1203
AET	860 (+5.7)	898 (+5.8)	915 (+7.1)	880 (+8.2)	918 (+8.0)	932 (+9.1)
Water Yield	180 (–16.7)	177 (–19.6)	167 (–19.2)	179 (–16.8)	177 (–19.6)	167 (–19.2)
Percolation	216 (–8.6)	160 (–10.1)	157 (–10.3)	180 (–23.9)	127 (–28.3)	124 (–29.4)
SSP5–8.5						
Precipitation	1241	1241	1241	1244	1244	1244
AET	847 (+4.2)	888 (+4.5)	904 (+5.7)	889 (+9.3)	911 (+7.2)	926 (+8.3)
Water Yield	216 (+0.5)	213 (–3.0)	200 (–3.0)	217 (+0.5)	213 (–2.9)	201 (–3.0)
Percolation	227 (–4.4)	169 (–5.2)	166 (–5.1)	201 (–15.1)	157 (–11.8)	153 (–12.0)

A6 Appendix A6 - References of the study site map

Table A9. Overview of the data use for the study site map.

Data	Database name or source
Topography	Copernicus GLO-30 (Copernicus, 2022)
Land use map	Copernicus Global Land Service (Buchhorn et al., 2020)
Water bodies	ArcGIS Pro 2.7.3 (ESRI)
Countries and cities	ArcGIS Pro 2.7.3 (ESRI)
Catchment extents	Derived with ArcGIS Pro 2.7.3 (ESRI)

A7 Appendix A7 - Supplemental Information for Morris Method

Generally, the Morris method quantifies the parameter sensitivity according to the elementary effect d_i :

$$d_i(q) = \frac{f(q_i, \dots, q_{i-1}, q_i + \Delta, q_{i+1}, \dots, q_k) - f(q)}{\Delta} = \frac{f(q + \Delta e_i) - f(q)}{\Delta}, \quad (\text{A4})$$

where Δ is the parameter step size; $q + \Delta e_i$ is the transformed parameter point; $q = [q_i, \dots, q_k]$ is any parameter of the total sample size N ; and e_i consists of a vector of zeros but one in the i^{th} unit vector. For the computation of d_i , a total sample size N is generated based on the number of parameters k . The parameters $q = [q_i, \dots, q_k]$ are changed one-at-a-time with the parameter step size Δ , i.e., one parameter is varied while the others remain constant. The sample size $N = r(k + 1)$ is determined based on r defined levels and parameters q . The local sensitivity of parameter q_i is quantified as $d_i(q)$. To quantify and rank the sensitivity in this study, the statistical moment μ_i as mean of the total sample simulation are considered (Morris, 1991). Campolongo et al. (2007) suggest to use the absolute mean μ^* to not oversee non-monotonic model responses because of opposite signs. The statistical moments for each set j are:

$$\mu_i^*(q) = \frac{1}{r} \sum_{i=1}^r |d_i^j(q)|. \quad (\text{A5})$$

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Competing interests. The authors declare that they have no conflict of interest.

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