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How sustainable land management practices may impact water resources in the Sahel: Insights from an integrated critical zone modelling approach

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ABSTRACT

Study region: The study was conducted in the south-western Sahel of Niger, within a small experimental catchment of the AMMA-CATCH observatory characterized by degraded soils, short high-intensity rainfall events, and increasing implementation of sustainable land management (SLM) practices such as micro-dams.

Study Focus: This study investigates the hydrological impacts of SLM practices on runoff generation, soil water storage, and groundwater recharge using the integrated hydrological model ParFlow-CLM combined with field observations. The model was first calibrated under pre-intervention conditions using event-based runoff observations. Micro-dams were then introduced using equivalent Manning roughness coefficients calibrated against observations to represent their hydraulic effects on a Sahelian hillslope.

New hydrological insights for the region: Results show that the model reproduces the observed reduction in event-based runoff induced by SLM practices. Under the 8% managed-area scenario, corresponding to the 8% field implementation stage (0.64 ha over the modeled 8 ha hillslope), runoff coefficients decreased from 0.24 to 0.13 in observations and from 0.25 to 0.17 in simulations. Simulations also indicate enhanced infiltration and increased event-based soil water storage in the upper soil profile, reducing soil moisture stress during dry periods. Simulations suggest that hillslope-scale, diffuse groundwater recharge increased from about 15–17% of annual rainfall, while hillslope-scale runoff declined from 15% to 9%. These findings highlight the potential of SLM interventions to improve water availability and hydrological resilience in Sahelian environments.

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1. Introduction

Land degradation is a critical global challenge that threatens ecosystems and agriculture, particularly in arid and semi-arid regions like the Sahel. In response, Sustainable Land Management (SLM) practices have been widely promoted to mitigate soil erosion, enhance vegetation cover, and restore degraded landscapes (Holt-Giménez, 2002; Branca et al., 2013; Nazoumou et al., 2016; Henry et al., 2018). Large-scale initiatives such as the Great Green Wall reflect a growing international commitment to stop desertification and improve land productivity across the Sahel (Albergel and Diop, 2012; Sacande and Muir, 2022).

While many studies have demonstrated the agronomic and ecological benefits of SLM, including increased yields, improved soil quality, and economic gains (Reij et al., 2009; Da, 2008; Danjuma and Mohammed, 2015; Zongo, 2016; Zougmoré et al., 2005), their broader hydrological consequences remain insufficiently explored (Duponnois and Dia, 2013). This is particularly important in the Sahel, where unexpected hydrological shifts (Wendling et al., 2019) have been observed in recent decades. These include rising water tables in sedimentary basins (Favreau et al., 2012), increased urban flooding (Massazza et al., 2021), and soil salinization (Ibrahim et al., 2014), despite declining rainfall and concurrent land degradation. These changes led to degraded soils where water and nutrients are flushed away, leading to less infiltrative and less fertile soils. SLM responses for runoff reduction on these degraded lands consist in agricultural practices like weeding and micro-dam networks to harvest water and favor water ponding and infiltration (Ingatan Warzagan, 2020), but also evaporation.

Specifically, in Sahelian hydrology, groundwater recharge occurs via two primary mechanisms: diffuse recharge from widespread infiltration across the landscape, and focused recharge from surface runoff accumulation in topographic depressions or endorheic ponds (Leduc et al., 2001; Massuel et al., 2011). In sedimentary Sahelian regions, land degradation has paradoxically contributed to groundwater rise, and the consequences of reversing this degradation through restoration remain uncertain (Leduc et al., 2001; Boucher et al., 2012). Distinguishing these pathways is then relevant in assessing hydrological impacts of land management at both hillslope and catchment scales as SLM may enhance local infiltration and soil water storage, but also reduce the focused recharge that previously resulted from increased surface runoff. Understanding how SLM interventions influence the water cycle seems then relevant due to their widespread dissemination (Deng et al., 2024) and their strong effects on land surface properties. To address this knowledge gap, hydrological modeling offers a powerful means to analyze the impacts of SLM on water dynamics across various components of the cycle. Numerous studies have used models to assess SLM techniques worldwide. For instance, Al-Seekh and Mohammad (2009) used runoff plots to measure post-rainstorm responses, Welderufael et al. (2008) applied the Morin and Cluff model in Ethiopia, and Verbist et al. (2009) used HYDRUS−2D to study infiltration trenches in Chile. Wildemeersch et al. (2015) evaluated soil quality changes due to water and soil conservation in Niger, and Zouré et al. (2019) showed that such practices mitigate dry spell impacts and improve crop yields.

Despite these efforts, most studies focus on surface runoff and neglect other key processes such as evapotranspiration and groundwater recharge. Fully integrated hydrological models able to simulate coupled surface and subsurface processes are therefore valuable tools for assessing how SLM may alter hydrological fluxes. Physically based models such as ParFlow, HydroGeoSphere (HGS), and CATHY are particularly well suited for this purpose because they explicitly represent runoff generation, infiltration, evapotranspiration, and groundwater flow (Maxwell et al., 2009; Therrien et al., 2010; Gatel and Carluer, 2018; Bizhanimanzar et al., 2020) even though they are data demanding. However, their application in data-scarce regions such as the Sahel remains challenging, because reliable parameterization and evaluation require substantial hydrological, soil, vegetation, and meteorological information.

This study aims to assess the hydrological response of a small Sahelian catchment to micro-dams implementation, typical Sahelian SLM practices that mimic the natural structure of the tiger bush landscapes. Using the integrated model ParFlow-CLM, a previous dedicated field campaign (Warzagan, 2020) and the AMMA-CATCH observatory data (Galle et al., 2018), we run multi-year simulations of a representative micro catchment of the central Sahel with and without micro-dams. In our 25 m resolution simulations, micro-dams are not represented explicitly. We hypothesize that the Manning roughness coefficient can be used to represent both the effect of runoff reduction and infiltration enhancement. This approach will further allow us to represent these SLM practices at the

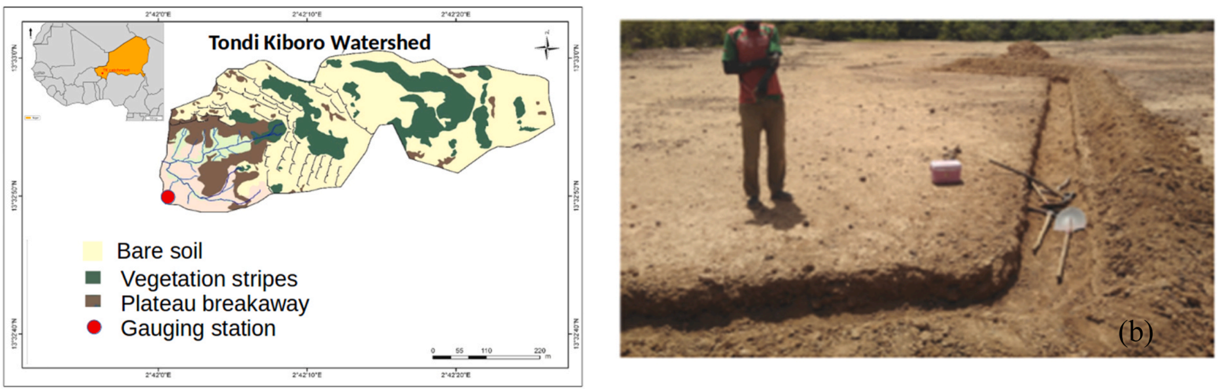

Fig. 1. Study area overview: (a) Land cover and location of the Tondi Kiboro North sub-catchment (adapted from Ingatan Warzagan et al., 2020); (b) field view of land restoration structure (reproduced from Ingatan Warzagan et al., 2019).

regional scale. We then evaluate the effects of micro-dams on event-based runoff, soil water storage, evapotranspiration and groundwater recharge.

In this study, simulated runoff and soil water storage changes are evaluated at the event scale against field observations. The non-observed simulation results (e.g. water budget, groundwater recharge, etc.) are to be interpreted as model-based hillslope-scale scenario outcomes, that is, the local hydrological response under two different SLM implementation scenarios.

2. Data and methodology

2.1. Study area description

The study area is located within the Tondi Kiboro (TK) experimental catchments (Amogu et al., 2015), in the southwestern Sahel region of Niger, about 70 km east of Niamey (Fig. 1a). It is a representative micro-catchment of the central Sahel part of the regional and long-term AMMA-CATCH observatory (http://www.amma-catch.org; Cappelaere et al., 2009; Lebel et al., 2009; Galle et al., 2018) which have been studied extensively since the 1990s. Tondi Kiboro experimental site consists of catchments (TK North and South) with nested sub-catchments. The present study focuses on the upstream sub-catchment TK North (23.4 ha). The main surface features in the catchment are typical of the south-west Niger landscape and include tiger bush relic and bare soils on the plateau, slope breaks at the plateau edge covered with sparse bushes and transitioning from the low angle plateau slope (0.2–0.6%) to the average hillslope (5–20%), with sandy structured soils in cultivated and fallow areas, and crusted soils in degraded hillslope fallows (Peugeot et al., 1997; Vandervaere et al., 1998). Strong runoff generation contrasts exist between crusted and more permeable zones. Based on variations in vegetation, soil characteristics, and slope, land use in the catchment can be divided into three major hydrological units: bare soil, vegetated strips, and plateau breakaway zones (Fig. 1b). These catchments are representative of the lateritic plateau and associated hillslopes encountered in south-west Niger.

Between 2009 and 2016, micro-dams were constructed on bare soils upstream of the plateau breakaway to reduce runoff and enhance water infiltration (Fig. 1b). These structures consist of trapezoidal trenches, approximately 50 cm wide and 30 cm deep, dug into the lateritic soil. The excavated material is used to build downslope embankments, which can extend up to 80 m in length (Ingatan Warzagan, 2020).

Hydrological data are available at multiple scales within the basin and have been documented by Warzagan et al. (2019). At the plot scale, event-based measurements of soil water storage changes were collected (Ingatan Warzagan, 2020), before and after the event, using a neutron probe, which indirectly estimates volumetric water content after field calibration against gravimetric measurements from undisturbed soil samples. Observations were conducted every 10 cm down to 2 m in depth, on 3 micro-dams (MD1 MD2 and MD3), upstream and downstream, and on an untreated (control) plots. Following Warzagan (2020), observed soil water storage changes were computed over the 0–135 cm soil profile, where most event-scale storage variations were observed. In the model, the closest corresponding depth interval was the upper 0–150 cm profile, due to vertical discretization constraints. Simulated and observed storage changes were therefore compared using these two closely matching depth intervals. At the catchment scale, event-based water volumes were monitored from 2004 to 2017 at the TK upstream North outlet using a hydrometric station equipped with a rectangular measuring flume with a "Parshall" design and a float-operated limnigraph. These data are available through the AMMA-CATCH runoff dataset (https://doi.org/10.17178/AMMA-CATCH.CE.Run_Nct). Water level was recorded at a 1-minute time step, allowing quasi-continuous monitoring of runoff events. Discharge was derived from a rating curve established from current-meter gauging measurements, following the protocol described by Warzagan (2020). Local rainfall at TK North was documented using direct-reading rain gauges, read after each event, and tipping-bucket recording rain-gauges, used to characterize rainfall timing and intensity for event-scale runoff analysis.

The period prior to any interventions (2004–2008) is used as baseline to characterize the natural hydrological response. Micro-dams were first installed in 2009 and two post-restoration implementation levels are considered in this study, corresponding to the **3% and 8% managed-area scenarios (**Table 1**)**. During the study period, up to 2016, limited vegetation growth was observed on the

Table 1
Annual rainfall and number of rainfall events from 2004 to 2016.

Year	Annual Rainfall (mm)	Nb of events	treated area(%)
2004	533	25	0
2005	400	33	0
2006	561	33	0
2007	524	28	0
2008	611	32	0
2009	437	31	3
2010	428	30	3
2011	290	12	3
2012	493	24	3
2013	528	21	8
2014	512	26	8
2015	692	37	8
2016	502	27	8
Average	499	27	

micro-dams (Ingatan Warzagan, 2020).

Meteorological data (Fig. 2) were obtained from the AMMA-CATCH Wankama site (13 km from the Tondi Kiboro site) at 30-minute temporal resolution for the 2006–2009 time period, using the AMMA-CATCH water and energy flux dataset (https://doi.org/10.

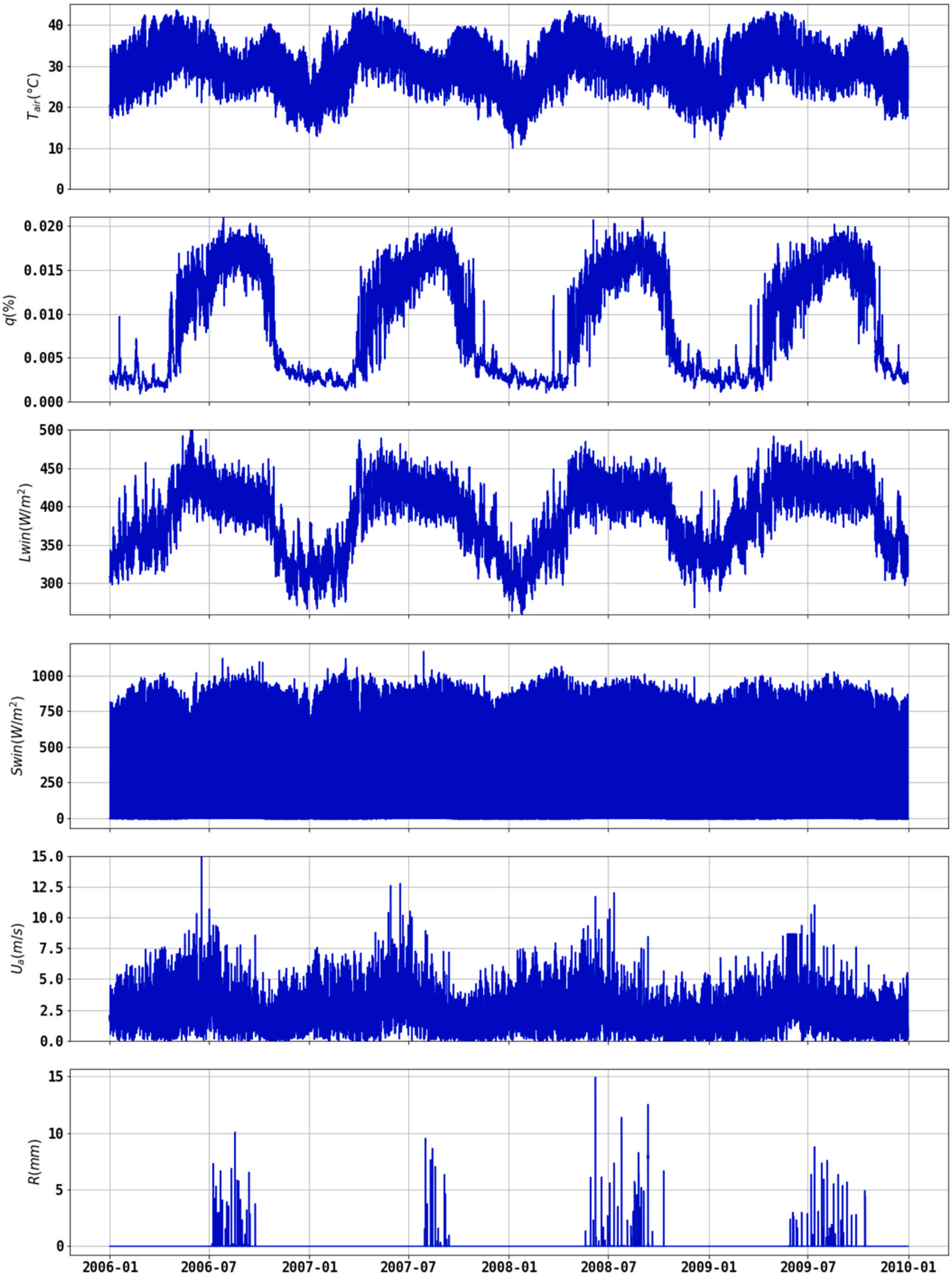

Fig. 2. Model forcing. From the top panel to the bottom, Tair: air temperature, q: specific humidity, LWin: incoming long waves, SWin: incoming short waves, Ua: wind speed, R: daily precipitation.

17178/AMMA-CATCH.AE.H2OFlux_Ncw), and have been described in Velluet et al. (2014). Precipitation falls when the monsoon flux reaches the Sahel from June to October. Annual precipitation varies between 300 and 600 mm on average (Table 1) from 12 to 37 events a year. This rain distribution is sparse enough to support the hypothesis of no soil moisture memory effect from one event to the other. Fig. 2 illustrates the seasonal and annual variability of rainfall in the region. Daily surface air temperature is rather high with a significant seasonal variability (between 20°C to 35°C) and daily values which reach more than 40°C before the rainy season. Specific humidity is also seasonally variable from 4 g/kg during the dry season to 20 g/kg during the wet season. This contributes to high longwave radiation inputs during the rainy seasons because of high temperature and specific humidity values.

Due to missing synchronous data at Tondi Kiboro, a composite four year forcing was built using rainfall from the Wankama Plateau gauge, available through the AMMA-CATCH rainfall dataset (https://doi.org/10.17178/AMMA-CATCH.CE.Rain_Nc), located 700 m from the Wankama northern Eddy Flux station from which the other meteorological variables were taken. This ensures temporal consistency between rainfall and radiation and other meteorological input variables, essential for accurate evapotranspiration modeling.

Vegetation dynamics for the plateau breakaway was represented using observation-based LAI (Leaf Area Index) time series from fallow site of Wankama (Velluet et al., 2014), while the vegetated strips on the plateau received a value twice as high to account for denser woody cover. All these forcing data were linearly interpolated at 5 min temporal resolution to better capture the rapid runoff response associated with short-duration rainfall events typical of the Sahel.

2.2. Methodology

As a preliminary step, we built on the work of Velluet et al. (2014) who modeled a typical Sahelian agro-ecosystem using SiSpat (Braud et al., 1995b), a 1D soil vegetation atmosphere model (similar to ParFlow-CLM in that it solves the water and energy budget and short temporal and spatial scales), validated against long-term AMMA-CATCH observations in the Wankama site. We reproduced their results on soil columns using the ParFlow-CLM model after adjusting some internal parameterizations as soil color-albedo associations and root depth (not shown).

We then conceptualized the TK North sub-catchment as a 2D-equivalent functional hillslope unit with three typical land covers: bare soils and vegetated strips on the plateau to mimic the tiger bush relic of this site, and patchy bushy vegetation on the plateau breakaway. We first calibrated the bare soil properties through ParFlow-CLM column simulations using a runoff observation dataset (Peugeot, 1995) at the plot scale, and we then built an idealized 2D numerical model for the TK North hillslope system that we calibrated on before-restoration runoff and soil water storage data.

We then tested and validated an equivalent Manning parameter to represent subscale effects of micro-dams on the runoff. This allowed us to simulate observed runoff decrease and storage increase for two micro-dams density levels at the catchment scale and we finally compared with the water budget components for each restoration level and the no micro-dam situation. In the following, the 3% and 8% scenarios refer to two field-based implementation stages, represented in the numerical model by two different equivalent Manning roughness values applied to the same treated cells.

2.2.1. ParFlow-CLM

ParFlow-CLM is an integrated surface-subsurface coupled hydrological model designed to simulate hydrological processes in the critical zone, integrating both surface and subsurface water flow in three dimensions (Ashby & Falgout, 1996; Jones & Woodward, 2001; Kollet et al., 2017; Maxwell et al., 2014). The ParFlow model solves the three-dimensional Richards equation for variably saturated flow using a cell-centered finite difference approach. The model also incorporates a terrain-following grid that accounts for

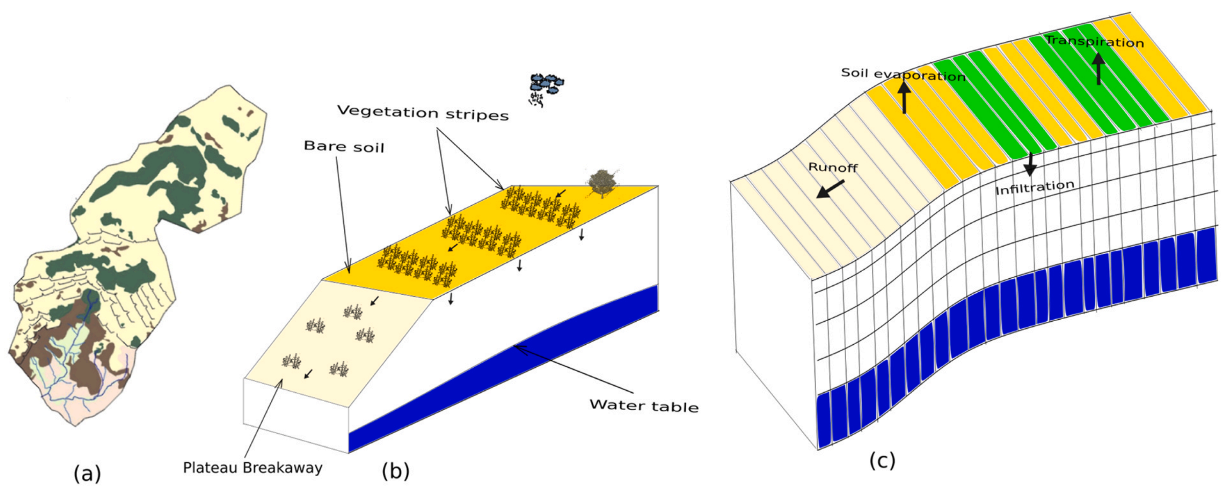

Fig. 3. Model building methodological steps for the study area: (a) physical environment, (b) 2D conceptual model and (c) numerical model.

topographic effects and uses a kinematic wave equation to handle overland flow, linking surface and subsurface processes seamlessly (Maxwell et al., 2014; Kollet et al., 2017). ParFlow is coupled with the Community Land Model (CLM), which calculates the land-water-energy exchanges, including evapotranspiration which acts as a sink in the Richards equation, according to the root distribution (Dai et al., 2003; Maxwell & Miller, 2005). CLM also handles various surface characteristics such as vegetation, albedo and temperature, influencing surface energy and water fluxes (Dai et al., 2003). This coupling allows the model to represent complex interactions between groundwater and surface water, including the generation of runoff through Hortonian or saturation excess mechanisms (Kollet et al., 2017; Dunne, 1983; Horton, 1933). ParFlow-CLM's ability to simulate detailed hydrological processes without prior specification makes it particularly suitable for studies in regions like the Sahel.

The model version used in this study is available at https://github.com/ige-parflow/parflow-master/releases/tag/v1.0-sahel-min (last accessed: 18 April 2025), where minor modifications were made to adjust vegetation root depth and to refine bare soil albedo constants and surface moisture–albedo relationships based on observed values and following the work of Velluet et al. (2014), together with allowing the ParFlow model component to run at the minute time unit.

2.2.2. Model setup

In this study, the hydrological model described in the previous section is used to model the TK North sub-catchment as a simplified 2D equivalent hillslope system as illustrated in Fig. 3. This simplification is chosen in order to set up a more general model allowing future work to explore the impacts of SLM techniques under various conditions and at larger scales. The conceptual model is built upon real-world features of the studied sub-catchment, including topography, soil properties, and land use zones. This conceptual model is then implemented as an idealized numerical domain in PF-CLM, with configuration and discretization summarized in Table 2. It consists in a 800 m (length) x 100 m (width) x 30 m (depth) 2D domain, subdivided into 25 m long x 100 m wide rectangular grid cells and a variably vertical resolution from 1 cm at the surface to 20 m for the deepest cell (Fig. 3). This 2D setup should therefore be interpreted as an idealized functional representation of the studied hillslope system, rather than as a geometrically exact reproduction of the full sub-catchment. Details of the different horizons considered are given in Table 2 and Table 3 details the soil parameters. No-flow boundary conditions are applied on the hillslope edges and a constant 23 m deep water table has been imposed at the bottom of the model as a pressure condition, in agreement with a well nearby the catchment. Water can then leave the domain by overland flow at the catchment outlet, by evapotranspiration (AET) from any root zone cells (29 first vertical cells), and through the bottom edge. Simulations were initialized with a hydrostatic soil water pressure profile in equilibrium with a water table depth of 23 m, to be deep enough from the surface to limit the impact on runoff and evapotranspiration processes.

To ensure that the simulated impacts of micro-dams on water fluxes are primarily driven by SLM practice conditions rather than changes in meteorology between the different periods, a forcing-free approach was adopted by applying the same atmospheric forcing across all simulations. This choice is made because antecedent rainfall has no impact on runoff production through soil moisture (Malam Abdou et al., 2016; Peugeot et al., 1997). The model was run for a five-year simulation period, from 01-January−2005–31-December−2009, with a 5-minute time step resolution and 30-year spin-up period. The spin-up was designed by repeating the five-year period six times to achieve an average interannual water storage change of less than 5% of the annual precipitation. This procedure was intended to reduce the influence of arbitrary initial subsurface moisture conditions on the scenario-based results, following standard model-initialization practice based on repeated forcing until internal states approach equilibrium (Rodell et al., 2005; Ajami et al., 2014).

2.2.3. Model parameters setup and calibration strategy

Model vertical discretization and hydrodynamic properties for all layers except the first two are based on numerous field and laboratory measurements reported by Velluet (2014) on another site nearby (Table 4) and was chosen to allow for vertical non-homogeneity.

The calibration process was carried out in four main steps (Fig. 4) to adjust the hydraulic properties for the different land use zones

Table 2
Domain configuration and discretization used in ParFlow-CLM simulations for the Tondi Kiboro hillslope.

Domain Configuration		
Plateau Slope	**Plateau Edge Slope**	**Domain Dimensions**
0.2%	6.3%	800 m (Y-direction), 100 m (X-direction), 30 m (Z-direction)
Model Discretization		
Horizontal Grid (Y-direction)	**Horizontal Grid (X-direction)**	**Vertical Grid (Z-direction)**
32 cells of 25 m	1 cell of 100 m	30 layers for 30 m total depth
Soil Depth Layers		
H1: 0–0.01 m (crust) H2: 0.01–0.20 m H3: 0.20–0.70 m H4: 0.70–1.20 m H5: 1.20–30 m		

Table 3
Parameter ranges used in the calibration process.

Parameter	Unit	Land use / Surface type	Range	Source
α	m^{-1}	Bare soil	[0.41; 3.22]	Braud et al. (1997);
		Vegetated strip		Šimůnek et al. (1998)
		Plateau breakaway		
n	-	Bare soil	[1.6; 5]	Manyame et al. (2007);
		Vegetated strip		Rockström et al. (1998)
		Plateau breakaway		
Saturated hydraulic conductivity (Ks)	m/s	Vegetated strip	[8.33E−6; 5.33E−3]	
Manning’s roughness coefficient	$s/m^{1/3}$	Bare soil	[0.015; 0.048]	McCuen (2005);
		Vegetated strip	[0.3; 0.6]	Mounirou et al. (2020);
		Plateau breakaway	[0.015; 0.048]	Mounirou et al. (2021)
		Micro-dam treated area	[0.1; 10]	

Table 4
Calibrated and literature-based soil hydraulic parameters used in ParFlow-CLM for different land use types. [a]Vandervaere et al.(1997); [b]Velluet et al. (2014); Asterisked values were calibrated.

Land use type	Layers	Ks (m/s)	Porosity	α	n	θres	θsat
Bare soil	H1	2.7E−7[a]	0,358	2,5*	1,5*	0,028	0,9
	H2	2.7E−6[a]	0,358	10*	2*	0,033	
Vegetated strip	H1	3.83E−5*	0,358	2,5*	1,5*	0,28	
	H2	3.83E−5*	0,358	10*	2*	0,033	
Plateau breakaway	H1	5.55E−7[a]	0,358	2,5*	1,5*	0,28	
	H2	2.7E−6[a]	0,358	10*	2*	0,033	
All	H3	5[b]	0,321	3,33	2	0,087	
	H4	7[b]	0,358	3,33	2	0,075	
	H5	7[b]	0,34	5	2,3	0,1	

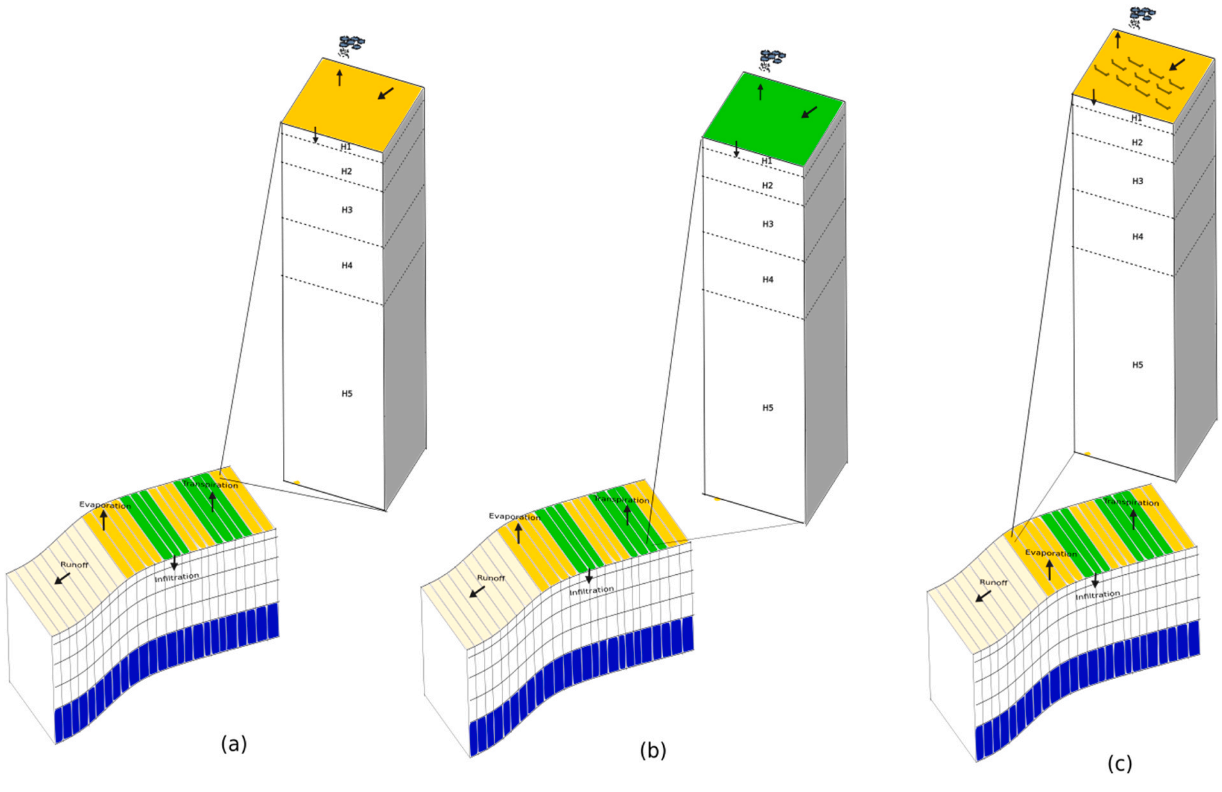

Fig. 4. Calibration process steps: (a) bare soil parameters fitting at plot scale, (b) vegetated strips parameters fitting on the hillslope and (c) SLM integration on the hillslope.

within the hillslope.

1 - First, a tilted 1D column model was built and used to calibrate the soil retention parameters following the van Genuchten (VG) model used in ParFlow for the bare soil on the plateau using runoff data from Peugeot (1995), and hydraulic conductivity measurements from Vandervaere et al. (1997) for the first two soil layers (H1 and H2, Fig. 4.a.).

2- In the second step with a 2D configuration, the hydraulic conductivity of (H1 and H2) in the vegetated strips was adjusted by increasing the calibrated value for the bare soil until no surface runoff left the strips in line with field observations. The other VG parameters have been kept identical to the bare soil's one (Fig. 4.b) (personal communication).

3- The parameters of H1 and H2 for the plateau breakaway were defined through additional calibration at the hillslope scale against observed runoff data measured at the catchment outlet.

4- Finally, micro-dams are implemented, using the Manning roughness coefficient as an equivalent parameter of micro-dams density, due to its effect on the surface runoff / infiltration partition at event scale (Fig. 4.c).

For each step, 100 parameter sets were sampled within ranges defined from the literature (Table 3) using the Latin Hypercube Sampling (LHS) method (McKay et al., 1979). Deeper layers (H3 to H5) are common across land use types and exhibit a range of Ks values from 5 to 7 m/s, with porosity and α values increasing with depth. These values were taken from Velluet et al. (2014) to reflect vertical heterogeneity observed on field. The residual water content (θres) ranges from 0.033 to 0.1, while the saturated water content (θsat) is fixed at 0.9 for all layers (Table 3).

In this framework, Manning's roughness coefficient was used as an effective parameter assigned to the treated cells which does not explicitly resolve the geometry of individual structures, but which aims at reproducing the hydrological functioning such as temporary ponding and storage, delayed emptying. The treated zone was located on the last three cells (BSS3), immediately upstream of the plateau breakaway and remained spatially fixed in the model. The 3% and 8% scenarios therefore do not represent two explicitly different treated footprints, but two levels of effective hydraulic impact represented by two different equivalent Manning values applied to the same treated cells.

The baseline Manning value was first calibrated against the pre-restoration rainfall–runoff relationship and represents the effective roughness of the untreated hillslope. The Manning values retained for the 3% and 8% scenarios were then calibrated against event-based runoff observations after treatment. The baseline calibrated value ($0.012\ s\cdot m^{-1/3}$) lies slightly below the literature-informed range initially considered for bare-soil areas. This small deviation is interpreted as a scale effect, since the calibrated value represents an effective hillslope-scale roughness reproducing the integrated runoff response of the untreated system rather than a direct local field measurement.

The uncertainty associated with Manning roughness coefficient assigned to the treated cells was also performed through a local sensitivity analysis with values sampled within the range defined for the micro-dam treated area (Table 3). For each implementation stage, the retained Manning value was defined as the arithmetic mean of the 10 best-performing Manning values identified using the event-based runoff diagnostics defined in 2.2.4. Simulations were then rerun with the retained values and used in the final scenario analysis.

2.2.4. Model evaluation

The model simulations were assessed against observed runoff and soil water storage changes. Specifically, model performance was evaluated by analyzing the event-based relationships between rainfall depth (R, in mm) and simulated runoff depth (Q, in mm), as well as simulated changes in soil water storage (ΔS, in mm). Precipitation events were defined based on a minimum rainfall of 0.5 mm and a minimum inter-event time of 6 h (Desconnets, 1994). A linear relationship of the form $Q(R) = C_R \times (R - R_{th})$ was fitted to both observed and simulated data, where R_{th} is the minimum rain amount before the runoff appearance, and C_R is a runoff/rainfall for rainfalls larger than R_{th}. The performance of the model was quantified using three metrics: the differences in the rainfall threshold required to generate runoff (R_{th}), the differences in the runoff ratio, and its 95% confidence interval (CI). The coefficient of determination (R^2) was also computed to evaluate the dispersion of the data around the fitted model in each dataset (observed and modeled series). In addition, the root mean square error (RMSE) was computed between simulated and observed event-based runoff depths derived from the fitted rainfall–runoff relationships over the common set of rainfall events and used as a complementary global mismatch indicator together with C_R and $R_{th.}$

Drainage is computed as the residual term of the water balance across the catchment. It is also computed for each model column, after running again the 5 year series with no lateral transfers, to compute the lateral variations of the water budget, cell by cell along the y dimension, and after checking for consistency the catchment water budget in both simulations. As there is no lateral subsurface outflow under the simulation setup, this vertical drainage can effectively be used as a proxy for groundwater recharge at the local scale. Consequently, the model is evaluated against event-based runoff and soil water storage changes, whereas simulated drainage is an output interpreted as a local hillslope-scale proxy for diffuse groundwater recharge under the tested scenarios for which the model water conservation give confidence.

3. Results

3.1. Model calibration

The calibrated and literature-based soil hydraulic parameters used in the ParFlow-CLM simulations are summarized in Table 4 within the ranges proposed in Table 3.

Calibrated Ks values for the vegetated strips (3.83E−5 m/s for both H1 and H2) are significantly higher than those of the bare soil

(2.4E−7 m/s and 2.7E−6 m/s) as expected. The VG parameters (α and n) for vegetated zones are consistent with increased water retention and reduced runoff. In contrast, the plateau breakaway presents lower Ks and similar VG parameters to bare soils, indicating limited infiltration capacity.

In addition to soil hydraulic properties, Manning's roughness coefficient was calibrated to account for the effects of micro-dams according to SLM implementation levels. The calibrated Manning's values (Table 5) show a strong rise from 0.012 (bare soil) to 1.02 as coverage increased, in line with the major impact of these micro-dams on runoff.

Fig. 5-*a* illustrates the sensitivity of the simulated event-based runoff response to the equivalent Manning roughness coefficient used to represent micro-dams in the treated cells. As Manning roughness increases, the simulated runoff coefficient $\mathbf{C_R}$ decreases, while the rainfall threshold $\mathbf{R_{th}}$ increases, consistently with the expected effect of stronger flow retardation and longer infiltration opportunity time. The retained Manning values for the 3% and 8% managed-area scenarios (0.384 and 1.02 $s/m^{1/3}$, respectively) are located in a plausible part of the tested parameter space and are associated with runoff responses that are consistent with the observed event-based behavior. For the 3% scenario, the retained run reproduces the observed runoff coefficient ($\mathbf{C_R}$=0.19) and yields a simulated rainfall threshold of 6.84 mm, close to the observed value of 7.37 mm. For the 8% scenario, the retained run reproduces the expected decrease in runoff efficiency ($\mathbf{C_R}$=0.17 compared with an observed value of 0.13) and yields a simulated threshold of 7.06 mm for an observed value of 6.15 mm. Fig. 5-*b* further shows that the overall model response varies markedly with Manning roughness, confirming that this equivalent parameter is a major control on the simulated rainfall–runoff relationship.

3.2. Rainfall-runoff relationship before and after SLM practices

Fig. 6 shows the comparison between simulated and observed runoff for the baseline scenario without SLM practices, and under the 3% and 8% managed-area SLM scenarios. The results indicate a reduction in **event-based runoff** for a given rainfall due to SLM practices which is consistent with field observations. The model captures the trend in rainfall-runoff dynamics, with the slope of the relationship decreasing as the proportion of SLM practices increases.

Table 6 presents the fitting results for observed and simulated event-based runoff for the baseline scenario and after SLM practices. The analysis includes the fitted runoff equation, precipitation threshold ($\mathbf{R_{th}}$), coefficient of determination ($\mathbf{R^2}$), confidence interval (**CI**), and the number of events used for the fitting. For the **baseline scenario**, both observed and simulated runoff exhibit a strong correlation ($\mathbf{R^2}$ **= 0.85 and 0.84, respectively**), with $\mathbf{R_{th}}$ of **5 mm (observed) and 6.40 mm (simulated)**.

Under the 3% managed-area scenario, the event-based runoff response decreases, as shown by lower fitted runoff coefficients and a slight reduction in R^2 values (0.79 for both observed and simulated data). In observations, R_{th} increases to 7.37 mm, while it reaches 6.84 mm in simulations. This difference could be partly attributed to the fact that the precipitation events used for the simulations were kept identical across the three scenarios, meaning that SLM practices only affect runoff once the rainfall threshold is exceeded. In contrast, the observational fits rely on different sets of rainfall events characterized by varying dynamics and intensities.

Under the 8% managed-area scenario, a more pronounced decrease in event-based runoff is observed, with a lower runoff coefficient in the fitted equation (C_R = 0.13 **for observed and 0.17 for simulated data**) and a decrease in $\mathbf{R^2}$ **(0.63 for observed and 0.59 for simulated data)**.

However, the variations observed in the precipitation thresholds remain relatively small and depend on the average characteristics of the sampled rainfall events. They also integrate measurement uncertainties and differences in event selection. Consequently, these changes should be interpreted primarily as **statistical variability associated with the sampled events rather than a direct effect of the SLM practices themselves**.

3.3. Impacts of SLM practices on soil water storage changes

SLM practices impacts on soil water storage dynamics were evaluated for each rainfall event by comparing model simulations with observed event-based changes in soil water storage as a function of rainfall (Fig. 7).

At the control site (Fig. 7-a), the model shows a similar pattern of water storage change increase as a function of precipitation amount as observed. The introduction of micro-dams (Figs. 7-b and 7-c) shows a noticeable increase in water storage in observations, which the model is able to reproduce. Some points above the 1:1 line correspond to the water harvesting capacity of micro-dams and the ratio between the harvested upstream area and the ponding micro-dams area.

These findings indicate that the model captures well the contrasting hydrological responses between bare soils and SLM-treated areas. In particular, it reproduces both the magnitude of runoff coefficients and their decrease after SLM implementation, as well as the overall infiltration-runoff dynamics at the event scale. The results also highlight that micro-dams help retain water in the soil and make it available for vegetation which will be more resilient to longer dry spells.

Table 5
Manning's roughness coefficients calibrated for each scenario.

Scenario	treated area (%)	Manning's value ($s/m^{1/3}$)
Baseline	0	0.012
Partial implementation	3	0.384
High implementation	8	1.02

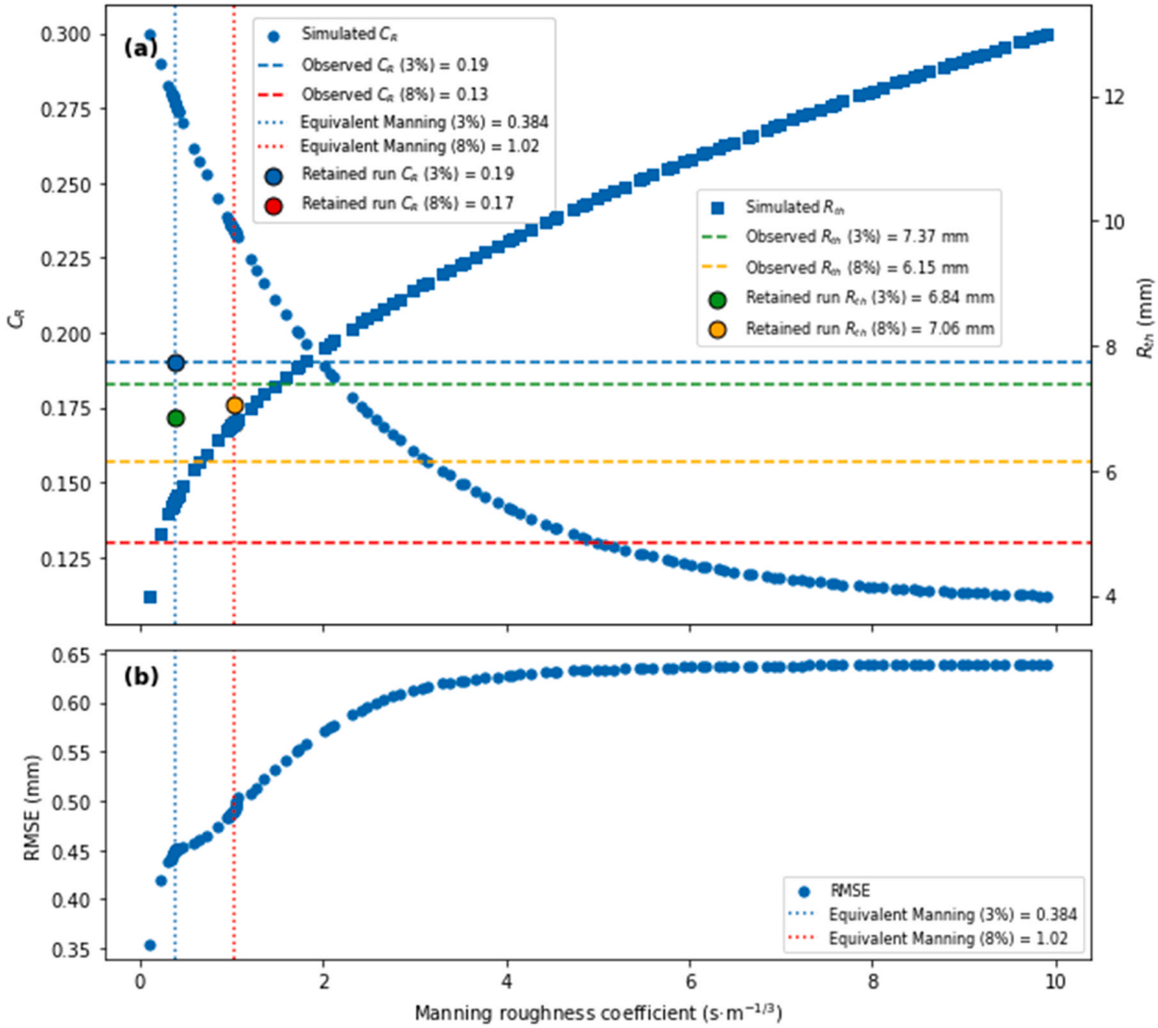

Fig. 5. Sensitivity of event-based runoff metrics and overall model fit to the equivalent Manning roughness coefficient used to represent the hydraulic effect of micro-dams: (a) simulated runoff coefficient $\mathbf{C_R}$ and rainfall threshold $\mathbf{R_{th}}$ as functions of Manning roughness, together with the observed values for the 3% and 8% managed-area scenarios. (b) evolution of the overall fit indicator (RMSE) across the tested Manning range, with the retained Manning values indicated for both scenarios.

3.4. Impacts on water budget

Fig. 8 presents the simulated water balance components using PF-CLM for the baseline scenario (without SLM practices) and under the **3% and 8% managed-area scenarios**. Storage corresponds to the annual variation of soil water storage. For the **baseline scenario**, approximately 71**% (320 mm)** of the annual rainfall was transferred to **evapotranspiration (ET)**, while around **13% (60 mm)** contributed to **groundwater recharge**, and **15% (68 mm)** was exported as **surface runoff**. **Under the 3% managed-area scenario**, **ET increased** to **324 mm**, **groundwater recharge rose** to 76 **mm (17%)**, and **runoff decreased** to **43 mm (less than 10% of rainfall)**. **Under the 8% managed-area scenario**, **ET remained stable** at **323 mm**, similar to the 3% managed-area scenario. However, **groundwater recharge further increased** to 80 **mm (18%)**, while **runoff decreased slightly** to **39 mm**. In our simulation setup, while reducing runoff, SLM practices substantially increased groundwater recharge (25%).

Introducing vertical-to-horizontal anisotropy in saturated hydraulic conductivity led to a decrease in evapotranspiration and an increase in deep drainage (~10.4 mm/year on average), while changes in runoff and storage variation remained negligible. These results suggest that anisotropy facilitates vertical percolation at the expense of surface water losses, emphasizing the importance of representing subsurface heterogeneity in Sahelian hydrological modeling. Therefore, it is relevant to inspect single-column contributions to the water budget to investigate the relative contribution of each land cover type.

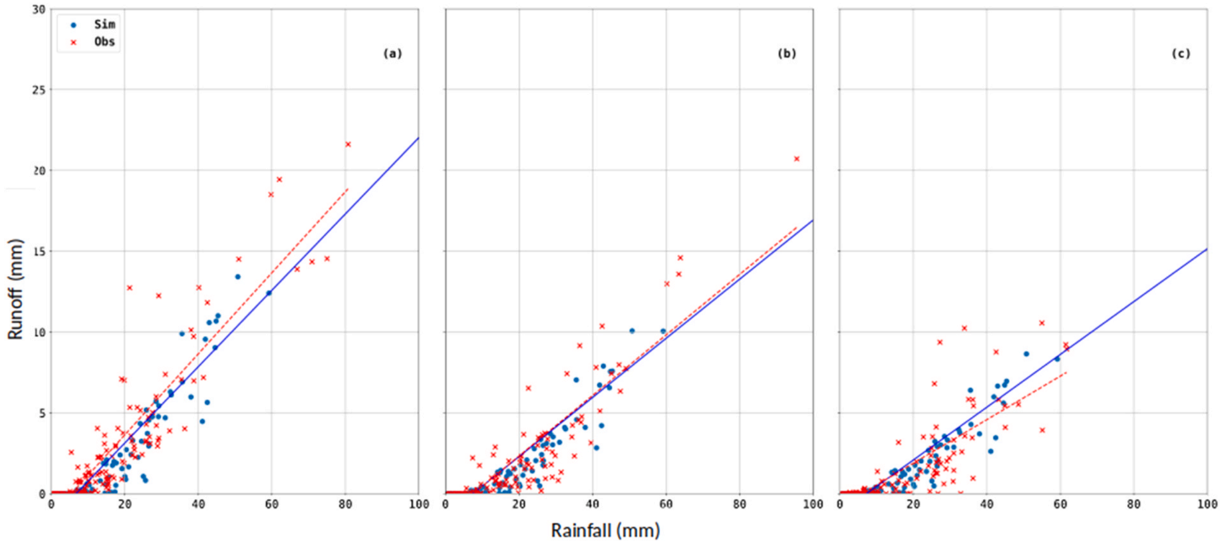

Fig. 6. Rainfall-runoff relationship under the baseline, 3% and 8% managed-area scenarios.

Table 6
Event-based rainfall-runoff fitting parameters for observed and simulated data under baseline, 3% treated-area, and 8% treated-area scenarios.

		Fitted model $Q(R) = C_R(R\text{-}R_{th})$	R_{th} (mm)	R^2	CI	Num of Evts
Baseline scenario	Obs	Q(R)= 0.24(R- 5)	5	0.85	[0.22;0.26]	89
	Sim	Q(R)= 0.25(R- 6.40)	6.40	0.84	[0.23;0.27]	79
After 3%	Obs	Q(R)= 0.19(R- 7.37)	7.37	0.79	[0.17;0.21]	116
	Sim	Q(R)= 0.19(R- 6.84)	6.84	0.79	[0.17;0.20]	144
After 8%	Obs	Q(R)= 0.13(R- 6.15)	6.15	0.63	[0.12;0.15]	114
	Sim	Q(R)= 0.17(R- 7.06)	7.06	0.59	[0.15;0.18]	144

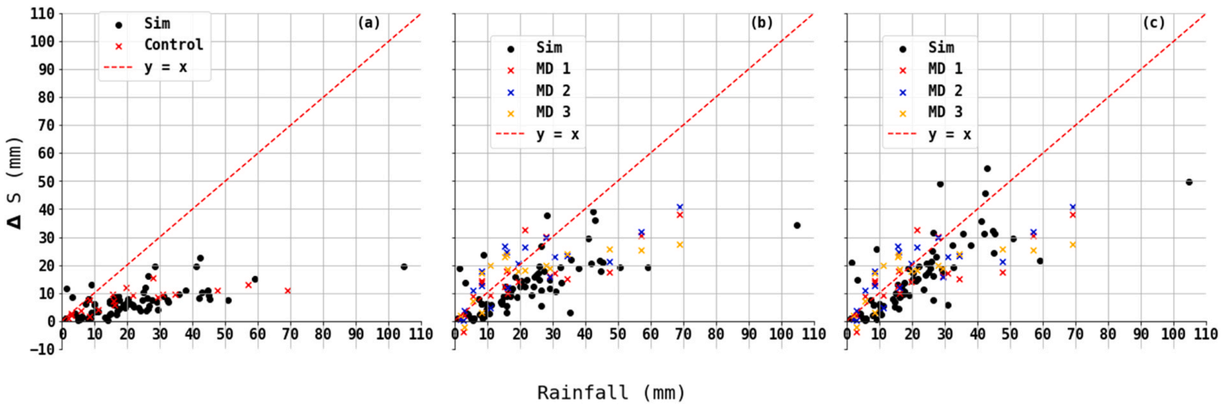

Fig. 7. Changes in soil water storage as a function of rainfall event amounts for both observations and simulations for control and three micro-dams (MD1,MD2, and MD3). Observed values were computed over 0–135 cm, while simulated values were extracted over 0–150 cm, the closest corresponding model depth interval.

3.5. *Impacts on diffuse recharge*

Fig. 9 presents the spatial distribution of mean annual water balance components, expressed as a percentage of annual rainfall, for the baseline, 3% treated-area, and 8% managed-area scenarios. In the baseline scenario, the vegetated strips (VGS1 and VGS2) behave as major drainage areas. They are characterized by high drainage values (>30% of annual rainfall), negative runoff values (that is, these cells have less runoff at their outlet than runon at their inlet), and evapotranspiration exceeding local rainfall, which indicates that these zones benefit from significant runon from upslope areas. In contrast, the bare-soil strips (BSS1, BSS2 and BSS3) generate

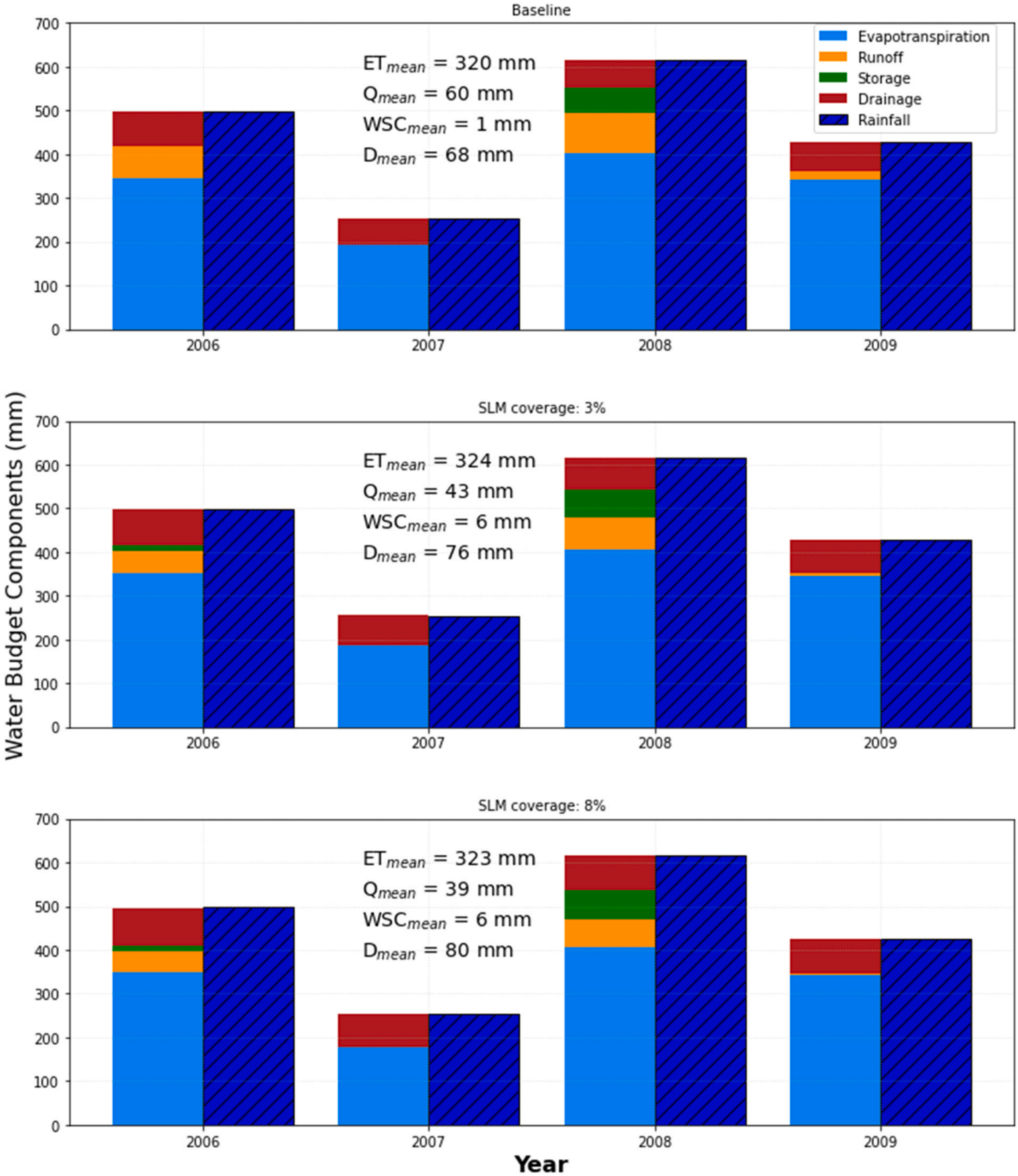

Fig. 8. Annual water balance components under baseline, **3% treated-area**, and **8% managed-area** scenarios compared to observed rainfall (2006–2009).

substantially more runoff (about 41% of annual rainfall), have lower evapotranspiration (~43%), and display only moderate drainage (~15%). The Plateau Breakaway (PLB) behaves more independently, with limited drainage and weaker exchanges than the plateau units. Under the 3% managed-area scenario, localized changes appear in the last three cells of BSS3, where the micro-dams are represented. In this treated zone, drainage increases from about 14–26% of annual rainfall, while storage also increases, indicating improved infiltration conditions. Under the 8% managed-area scenario, this local response becomes stronger, with drainage increasing to about 35% and storage remaining higher than in the baseline case. By contrast, the impact on the PLB remains limited, which

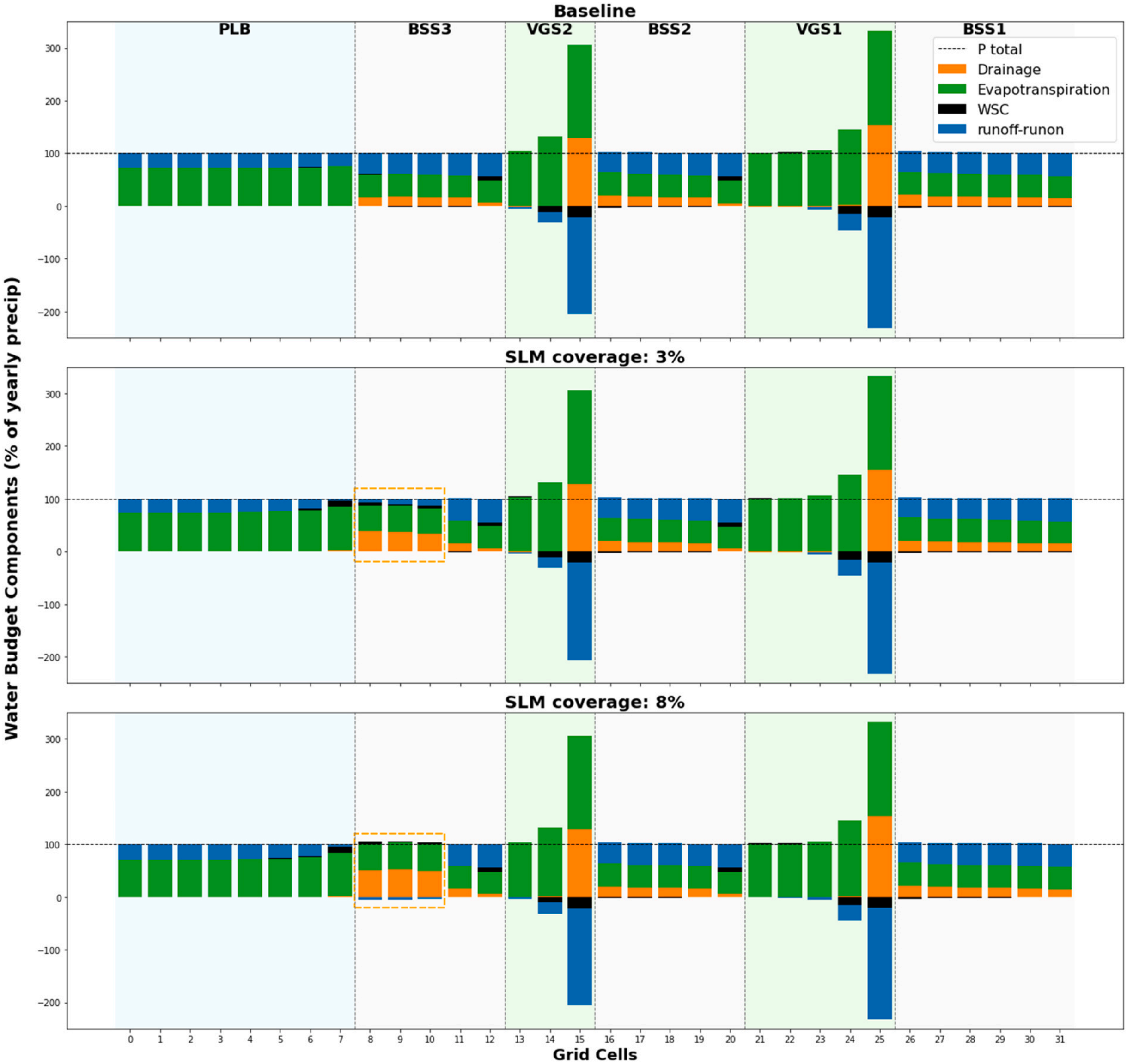

Fig. 9. Mean annual values of grid-scale water balance components under the baseline, **3% treated-area**, and **8% managed-area** scenarios. Zones are delimited by land surface types: BSS1–3 (Bare Soil strips 1–3), VGS1–2 (vegetated strips 1 and 2), and PLB (Plateau Breakaway). Cells 19–21 (in BSS3) correspond to the micro-dam structures and are highlighted with a dashed orange rectangle. The hillslope outlet is located at cell 0.

suggests that the benefits of the micro-dams remain largely localized within the treated bare-soil strip. Vegetated strips maintain high drainage and negative runoff (i.e. more runon than runoff) throughout all scenarios, confirming their role as persistent hydrological convergence zones. Overall, the simulations indicate that both natural vegetation patterns and SLM interventions are associated with enhanced infiltration and simulated diffuse recharge, but through different mechanisms. Vegetated strips act as long-term lateral redistribution and drainage hotspots, whereas micro-dams locally enhance infiltration within the treated cells by reducing runoff transfer and increasing infiltration opportunity time. In the treated BSS3 cells, the simulated increase in drainage approaches values observed in natural vegetated recharge hotspots, suggesting that micro-dams can locally enhance diffuse recharge under the tested configuration. However, these results should be interpreted at the hillslope scale only: they describe changes in local diffuse recharge and runoff partitioning within the modeled system, and do not provide a direct estimate of total catchment-scale recharge, particularly where focused recharge may occur in downstream convergence zones.

4. Discussion

4.1. Limits to the approach

4.1.1. Infiltration/evaporation partition

Modeling natural hydrological systems remains a challenging task due to their complex, heterogeneous, and nonlinear nature. While the model captures key physical processes, assumptions and parameterization choices introduce uncertainties in the infiltration/evaporation partitioning. Soil moisture retention and evapotranspiration are influenced by surface conditions and vegetation, yet their accurate representation in a physically based model like ParFlow-CLM depends on parameterization choices, initial conditions, and model structure. A key assumption of the event-based runoff analysis is that antecedent soil moisture has no impact on runoff generation at the studied site. This assumption is supported by the sparse distribution of rainfall events and by previous work in the region indicating weak event-to-event soil moisture memory in runoff production over crusted Sahelian surfaces. Under this assumption, using the same atmospheric forcing across scenarios allows us to isolate the effect of land surface changes induced by SLM. However, this hypothesis may be less valid under unusually clustered rainfall sequences or under wetter antecedent conditions, and therefore represents a limit of the present setup.

Additionally, **uncertainties in evapotranspiration estimates** can significantly impact the water balance, leading to **large biases in drainage calculations** and the lack of recharge observations prevents to better constrain this variable. However, we believe the simulation setup is constrained enough on the runoff calculation to be relevant on the infiltration/runoff partition. Micro-dams are therefore an efficient SLM practice to store more water, whether it is rapidly used by vegetation or infiltrates deeper to the water table.

It is important to note that the simulated micro-dams represent recently implemented structures with limited vegetation establishment, as reported by Ingatan Warzagan (2020). Over time, natural vegetation may grow on these structures and could significantly reduce groundwater recharge. This highlights the need to consider the temporal evolution of land cover when assessing the long-term hydrological impacts of SLM practices.

4.2. Site-specific limitations

The present study should be interpreted as a process-based analysis of a small degraded lateritic hillslope system typical of south-west Niger, rather than as a direct regional extrapolation to all Sahelian environments. TK North captures key landscape features commonly observed in this region, including crusted bare-soil areas on the plateau, remnant vegetated strips, and a plateau breakaway controlling runoff redistribution. More generally, this type of lateritic plateau–breakaway toposequence is a recurring hydrological unit in south-west Niger, and previous work has shown that point-scale surface measurements over crusted Sahelian soils can remain informative for runoff behavior at much larger scales (Vandervaere et al., 1998**). In that sense, the present setup should not be viewed only as a site-specific geometric replica, but rather as a process-based representation of a class of runoff-generating hillslopes typical of south-west Niger. It therefore provides a relevant experimental framework to investigate how micro-dams may modify runoff partitioning, infiltration, and diffuse recharge at the hillslope scale. Further downstream, depending on hydrogeological contrasts, including sedimentary basins or hard rock settings, runoff will flow in very dynamic river networks (hard-rock areas) or end in endorheic depressions and valley-bottom systems, where the relative importance of diffuse versus focused recharge may differ substantially (sedimentary areas). The present results should therefore be interpreted as representative of a class of degraded lateritic plateau hillslopes, not as a direct quantitative prediction for all Sahelian catchments.**

Soil hydraulic parameters play a crucial role in determining infiltration rates and surface runoff at event scale. While efforts were made to characterize hydraulic conductivity and Manning roughness coefficients based on field surface observations (Table 2) and calibration processes, uncertainties remain for sub-surface hydraulic characteristics for which very few data are available for the plateau geologic context in the region, specifically for retention properties. This calls for further field campaign to document these properties, not only with texture data now available globally, for example, through SoilGrids (Hengl et al., 2017), but also through more suction and moisture profiles. Hydraulic conductivity is known to be log-scaled, and slight variations in this parameter across catchments or across the landscape may limit the generalization of these results.

Furthermore, the representation of SLM structures, such as micro-dams, introduces additional limitations. Using Manning's roughness coefficient as an equivalent parameter to represent these structures does not explicitly differentiate the effects of individual structures on flow resistance and infiltration enhancement. This parameterization assumes a uniform effect over the modeled area, whereas observed changes in soil water storage are typically measured at the location of individual structures. As a result, the model includes the inter-structure spaces in the estimation of soil water storage variations, potentially diluting the localized effects captured in field measurements. The modeled water storage changes are indeed lower than observed ones, an indication that results may still be consistent. Additionally, the design, position, and density of micro-dams strongly influence their capacity to retain and infiltrate runoff, yet these spatial heterogeneities are not explicitly represented in the current model implementation. Although the equivalent Manning approach successfully reproduces the observed runoff response, it does not explicitly represent overflow processes or hydraulic interactions among multiple micro-dams distributed across complex hillslope configurations. This simplification prevents a fine-scale analysis of how each structure impacts runoff and groundwater recharge dynamics. To improve the accuracy of model simulations, **monitoring systems should be intensified in areas treated with SLM structures and plateau regions where subsurface properties remain poorly characterized**. Higher meter resolution modeling approach to represent explicitly the micro-dams in 2D like (Heinen et al., 2022) or in 3D, constrained with detailed soil moisture profile time series and electromagnetic survey

(Warzagan, 2020), could help to better understand the infiltration and drying processes around micro-dam structures, consolidate the presented results, and improve the reliability of impact assessments for land management interventions. Enhanced field data collection, particularly for key components such as **evapotranspiration, soil moisture, and localized runoff**, would provide valuable constraints for model calibration and validation.

The Manning sensitivity analysis confirms that simulated runoff response is strongly affected by the equivalent roughness assigned to the treated cells. For both the 3% and 8% managed-area scenarios, the selected Manning values fall within a low-misfit region of the tested parameter space rather than corresponding to an isolated optimum. This supports the robustness of the qualitative response simulated in this study, namely reduced runoff transfers and enhanced infiltration/drainage in the treated zone, while also confirming that the exact magnitude of the response remains sensitive to the chosen equivalent roughness. The Manning parameter should therefore be interpreted as an effective upscaled parameter controlling runoff routing and infiltration opportunity time, not as a direct measurable property of individual micro-dams. Finally, it should be noted that the $\mathbf{C_R}$ and $\mathbf{R_{th}}$ relationships as functions of the Manning roughness coefficient are monotonous and can be easily represented by an analytical power functions whose parameters may be expressed as a function of the managed-area percentage.

4.3. *Impacts of SLM practices on water resources*

4.3.1. *Diffuse vs. focused recharge*

Drainage values simulated under baseline appear high in absolute terms compared to recharge estimates reported in the Sahelian literature. Cuthbert et al. (2019) estimated total recharge (focused and diffuse) at ~30 mm/year using the water table fluctuation method. **MacDonald et al. (2021) found 15–20 mm/year, highlighting low recharge in the region.** Kafando et al. (2025) **simulated mean annual recharge of 63 mm (R/P ≈ 9%) in the hard rock basin of Sanon, with yearly values ranging from 30 to 114 mm depending on climatic conditions. Recharge was highly variable spatially, reaching 27–28% in cultivated valley bottoms but dropping to nearly 0% on vegetated lateritic ridges. This suggests that our model may overestimate drainage, particularly in vegetated areas. While one hypothesis initially considered was the assumption of zero runoff at the outlet of the vegetated strips, a more likely explanation lies in the representation of vegetation itself (LAI values, rooting depth, oasis effects, and surface roughness, etc.) which may critically control water partitioning in these zones. This could result in artificially high recharge estimates beneath these zones, and suggests a need to refine vegetation parameterization and root zone representation.**

More generally, the present results must be interpreted in light of the scale of the numerical setup. The model is constrained by event-based observations at the plot and outlet scales, but recharge is analyzed from multi-year simulations over an idealized hillslope representation. The study therefore informs the response of diffuse recharge and runoff partitioning within the modeled hillslope system, but does not provide a direct estimate of total recharge at the full catchment scale, where flatter cultivated areas downstream, especially in the Dantiandou district will favor evapotranspiration reducing the total recharge despite observed focused recharge processes which also play a major role (Massuel et al., 2011**,** Boucher et al., 2012**).**

Drainage can also be evaluated in relative terms by normalizing values against the baseline scenario (i.e., 100 × D_SLM / D_baseline), which isolates the effect of SLM implementation independently of model structural uncertainties. SLM practices led to a relative increase of D of 11% and 19% under the 3% and 8% managed-area scenarios, respectively. These findings are consistent with those reported in similar semi-arid contexts. For instance, Garg et al. (2012) **documented an increase in groundwater recharge from 9% to 20% of annual rainfall (equivalent to ~70 to ~174 mm) following agricultural water management interventions in the Kothapally watershed in India, underscoring the effectiveness of small-scale structures like bunds and check dams in enhancing infiltration and then recharge if the water is not used by pioneer vegetation.**

A key limitation of this study is that it does not allow quantifying the impact of reduced surface runoff on focused groundwater recharge occurring at downslope convergence zones. Yet, such recharge has historically contributed to rising groundwater levels in sedimentary south-west Niger areas over the past decades, driven by increased runoff following land degradation. In our simulations, surface runoff (Q) decreases from 60 mm to 39 mm, i.e. a 35% reduction. Likewise, the effects of runoff reduction on surface water resources such as temporary ponds used for livestock and irrigation in endorheic systems are not captured by the current hillslope-scale setup. Addressing these questions would require larger-scale modelling approaches, which could build on the present framework.

Table 7 **summarizes the annual drainage values simulated under baseline, 3% and 8% managed-area scenarios, together with the relative change with respect to the baseline. These results highlight the consistent increase in modeled diffuse recharge proxy under both SLM scenarios. On average, drainage increased by 11% under the 3% scenario and by 19% under the 8% scenario, supporting the interpretation that SLM enhances local diffuse recharge within the modeled hillslope system.**

5. Conclusion

The hydrological impacts of sustainable land management (SLM) practices on a Sahelian hillslope were evaluated using the integrated physically-based model ParFlow-CLM. By simulating the water balance under baseline and managed conditions, we examined how land surface heterogeneity and targeted SLM interventions influence key hydrological processes, including evapotranspiration, surface runoff, and diffuse groundwater recharge.

A key outcome of this study is the use of Manning roughness coefficient as a proxy to represent the hydrodynamic effects of SLM

Table 7
Annual drainage and relative change under the 3% and 8% managed-area scenarios, with baseline drainage used as a proxy for diffuse recharge.

Year	Baseline drainage (mm/yr)	3% drainage (mm/yr)	Change vs. baseline (%)	8% drainage (mm/yr)	Change vs. baseline (%)
2006	81	85	+5	89	+10
2007	62	70	+13	75	+21
2008	65	72	+11	77	+18
2009	65	75	+15	82	+26
Mean	68.2	75.5	+11	80.7	+19

Note: Drainage is used here as a hillslope-scale proxy for diffuse recharge. Relative change was computed as $100 \times (D_{SLM}/D_{baseline} - 1)$.

structures. This approach allowed the model to reproduce observed reductions in runoff and increases in soil water storage under different implementation levels, demonstrating its relevance for simulating land management impacts at the hillslope scale.

The results demonstrate that representing two field-based SLM implementation stages through equivalent Manning roughness values applied to the treated zone can substantially modify water balance partitioning, by decreasing runoff and increasing soil water storage and diffuse recharge at the hillslope scale, according to the observations. The redistribution of surface water may also favor recharge in downstream areas, underscoring the broader hydrological influence of strategically placed interventions.

The recharge-related results presented here should nevertheless be interpreted as modeled scenario outcomes at the hillslope scale, derived from multi-year simulations after spin-up, rather than as direct estimates of total catchment-scale groundwater recharge. In particular, the present setup addresses changes in local diffuse recharge within the modeled hillslope system where runoff is generated. Downstream hydrological processes like focused recharge or enhanced evapotranspiration around ponds, dallols and crop areas are outside the scope of this study. In addition, the retained Manning roughness values should be interpreted as effective upscaled parameters used to represent the hydraulic influence of micro-dams. This implies that the present results are most relevant for understanding process reorganization at the hillslope scale and should not be extrapolated directly to larger Sahelian catchments without additional spatially explicit modeling.

This study opens perspectives for upscaling the modeling of SLM impacts, by showing that equivalent parameterizations such as Manning's roughness can capture aggregated hydrological responses. However, the simplified representation of micro-dams and vegetation structures raises questions about the sensitivity of recharge estimates to model assumptions, particularly regarding infiltration processes in treated areas. Future work should focus on uncertainty quantification through targeted sensitivity analyses, especially for parameters controlling recharge dynamics. This would help assess the robustness of the results under varying configurations of soil properties, land use, and SLM density. Extending the approach to larger catchments is possible, but requires improved understanding of process scaling and heterogeneity effects. In this context, strengthening hydrological monitoring on key fluxes such as evapotranspiration, soil moisture, and drainage would provide valuable support for model evaluation and calibration.

CRediT authorship contribution statement

Jean-Pierre Vandervaere: Validation, Resources, Data curation. **Aghali Ingatan Warzagan:** Validation, Resources, Data curation. **Christophe Peugeot:** Resources, Data curation. **Agnidé Emmanuel Lawin:** Validation, Supervision, Project administration. **Mahamadi Tabsoba:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Basile Hector:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization. **Jean-Martial Cohard:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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