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Effects of Forest Harvesting Operations on Hydrology: Experiences From the Palatinate Forest Biosphere Reserve

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ABSTRACT

The use of timber harvesting and skidding machines significantly alters a catchment's hydrological processes due to soil compaction effects. Although it is obvious that the use of heavy forest machines increases surface runoff and water yield, quantifying these effects remains challenging. This research aimed at exploring how physically based hydrological models are suited for investigating the effects of soil compaction on hydrologic responses at the catchment scale. We employed a process-based SWAT+ hydrological model to assess the impact of temporary (e.g., skid trails) and more permanent timber harvest infrastructure on the hydrologic response of the Palatinate Forest Biosphere Reserve in Germany. We specifically analysed the role of soil compaction in hydrological processes by simulating water fluxes under three scenarios: uncompacted soil (baseline), compacted soil during harvest and skidding operations (Scenario-1) and due to permanently constructed infrastructures (Scenario-2). Results demonstrated substantial alterations in water fluxes under Scenarios-1 and -2 compared to the baseline, with annual average surface runoff increasing by 74% and 125%, respectively, and lateral flow decreasing by 14% and 26%. These changes varied notably between steep and low slope areas. Steep slope regions exhibited significantly larger increases in surface runoff, while low slope areas experienced greater reductions in lateral flow and percolation. This differentiation underlines the combined influence of management scenarios and slope, highlighting the critical need for forest harvesting strategies that account for spatial variability and the types of machinery employed.

1 | Introduction

Forest harvesting and skidding operations significantly alter soil properties due to the use of heavy machinery for timber extraction, tree removal, and log transport. These activities exert substantial pressure on forest soils, often leading to compaction (Solgi et al. 2023). Skid trails (e.g., temporary pathways for logging equipment) are particularly prone to soil compaction

caused by machinery such as tractors and trucks (Cambi et al. 2017). Compaction disrupts soil structure, reducing biological activity, porosity, and permeability, which are critical to maintaining soil health and hydrological balance (Solgi et al. 2023).

Soil compaction is commonly assessed using indicators such as bulk density (BD), available water capacity (AWC),

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hydraulic conductivity (K), soil texture, and organic matter content (Cambi et al. 2017). On skid trails and machine pathways, infiltration is often severely impaired, leading to increased surface runoff during heavy rains. This combination of higher soil BD and reduced macroporosity, infiltration capacity, and hydraulic conductivity has profound implications for forest hydrology (Van den Akker et al. 2023; Jourgholami and Labelle 2020).

The consequences of soil compaction extend beyond hydrology, negatively impacting plant growth, water quality, and nutrient cycling. Compacted soils shrink pore spaces, reduce infiltration, and accelerate surface runoff and erosion, creating challenges for forest and agricultural land management as well as soil and water conservation efforts. Globally, the growing extent of soil compaction is an increasing concern. For example, 23% of agricultural land in Europe is affected by soil compaction, with Germany facing similar challenges (Arias-Navarro et al. 2024). Addressing these impacts is crucial for sustaining soil health and maintaining ecological balance in managed landscapes.

Forest harvest operations also disrupt the hydrological cycle by altering water partitioning, movement, and storage. However, directly quantifying the impacts of soil compaction on watershed processes remains challenging. This underscores the importance of physically based hydrological models, which can simulate and quantify the effects of soil compaction on watershed hydrological responses, including those associated with skid trails and permanent infrastructure used for timber harvesting.

This study focuses on evaluating the capacity of the SWAT+ model to simulate hydrological processes in the Palatinate Forest Biosphere Reserve, with particular attention to the impacts of forest harvest operations on hydrological responses. The Palatinate Forest Biosphere Reserve, a managed forest ecosystem used for timber production, experiences widespread soil disturbances due to the formation of skid trails and pathways during harvest operations. These disturbances alter soil pore size distribution and other biophysical properties, which in turn affect hydrological processes such as percolation, surface runoff, lateral flow, and water yield (Picchio et al. 2021; Rachels et al. 2020).

To address these challenges, this study introduces a novel approach that leverages the semi-distributed, physically based SWAT+ model to examine the effects of soil compaction on catchment-scale hydrology. Unlike conventional methods relying on paired experimental sites, this research incorporates spatially distributed changes in soil properties resulting from forest harvesting operations at the catchment scale. The key research questions for this study are:

- How accurate can SWAT+ simulate the hydrological impacts of forest soil disturbances, particularly soil compaction from forest harvesting, across different catchment areas and slope classes?
- How do changes in key soil properties, such as BD, hydraulic conductivity, and AWC, influence hydrological processes, including surface runoff, water yield, lateral flow,

percolation, and evapotranspiration, in catchment-scale applications?

- How do forest management practices affect water fluxes in a forested catchment?

By addressing these questions, the study aims to provide insights into the interplay between soil compaction and hydrological responses in managed forest ecosystems.

2 | Materials and Methods

2.1 | Study Area

The Palatinate Forest Biosphere Reserve, situated in the German federal state of Rhineland-Palatinate (Figure 1), is designated as a UNESCO biosphere reserve and shares a border with France (DUK 2021). There are seven major catchments within the biosphere reserve: Hardenburg to the north, Neustadt to the northeast, Siebeldingen to the east, Moosalbal and Thaleischweiler to the west, and Bobenthal and Hirschtal to the south. All the catchments within the biosphere reserve are designated as sub-catchments of the overall basin. The Palatinate Forest Biosphere Reserve has a diverse topography of rocky red sandstone landscape with a high percentage of forest land cover (StatLa RLP 2016). Based on our topographic analysis using digital elevation data, the landscape of the Palatinate Forest Biosphere Reserve is dominated by low mountains and hills, with elevations typically ranging from 92 to 662 m. Its highest peak is at Kalmit with 673 m (UNESCO 2024: <https://www.pfaelzerwald.de/biosphareaerenreservat/>). It is also characterised by numerous deep, narrow valleys and gorges dissecting the forest, with often seasonal and perennial streams flowing through them. These valleys enhance the biodiversity of the region by creating varied microhabitats. The Palatinate Forest is characterised by dense, deciduous, low mountain range forests of the temperate zone and extensively managed cash-crop stands (UNESCO 2005). According to StatLa RLP (2016), about 76% of the total area is covered by forest, predominantly beech and pine tree communities. Encompassing a total area of approximately 1809.7 km², this forest-dominated biosphere reserve plays a crucial role in providing various ecosystem services. Notably, it serves as a natural filter, contributes to water storage, aids in replenishing the groundwater system, and offers decentralised flood protection and climate regulation (Hausler and Scherer-Lorenzen 2001).

Forest harvesting for timber production in the Palatinate Forest Biosphere Reserve has a history spanning the middle ages due to charcoal and iron production. Harvesting intensified during the 19th and early 20th centuries due to industrialisation and local economic demands. The use of heavy machinery for timber extraction placed significant strain on the forest floor, leading to changes in soil physical properties.

Due to these environmental concerns, the Palatinate Forest was designated as a biosphere reserve in 1992. Since then, sustainable forest management and the protection of ecological systems have become priorities. This shift includes the establishment of core zones where forest management is minimised to allow for natural growth and conservation (UNESCO, 2005).

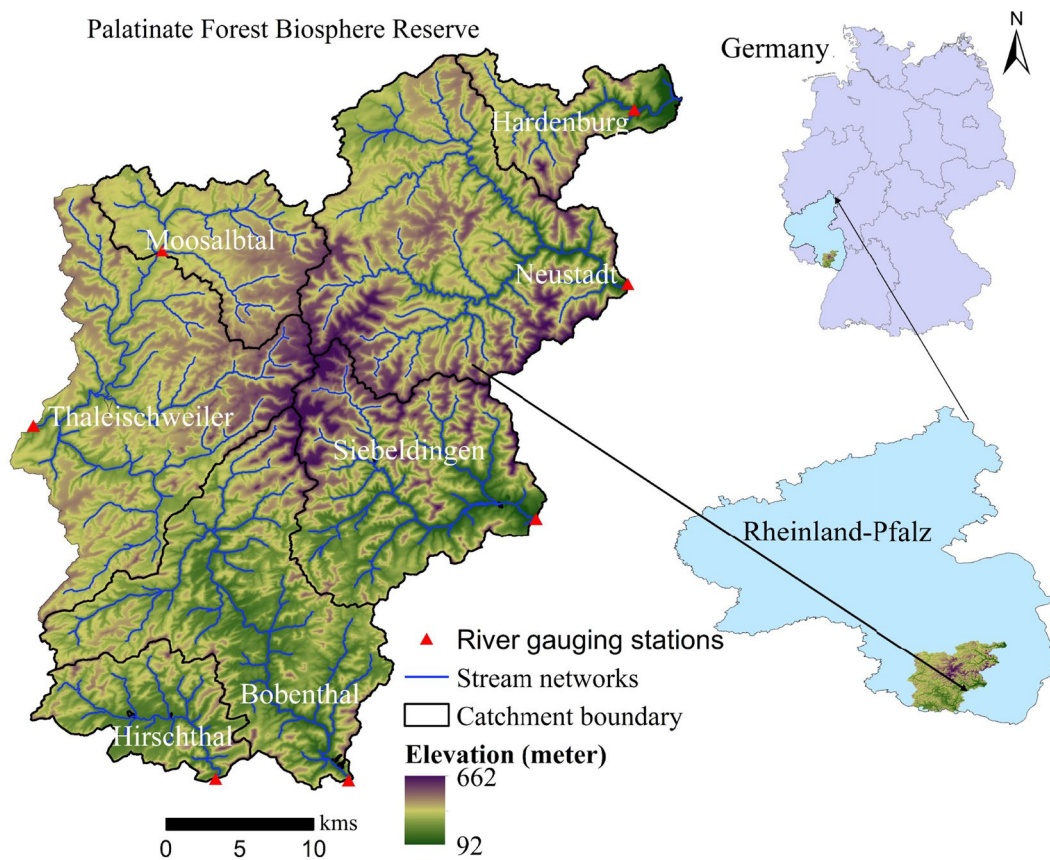


FIGURE 1 | Location of the palatinate forest biosphere reserve, subbasins, stream networks, and stream gauging stations.

2.2 | Data

Model input data (Table 1), encompassing daily precipitation, maximum and minimum temperature, relative humidity, sunshine duration, and wind speed, was obtained from the German Meteorological Service (DWD (The Deutscher Wetterdienst) 2021) with a spatial resolution of 1000m by 1000m. The entire Palatinate Forest Biosphere Reserve was delineated by 86 grid cells, and the climate competence centre of Rhineland-Palatinate applied error corrections and interpolation techniques to enhance data quality (Dobler et al. 2004).

In addition to the climate data, spatial information such as a 10m resolution digital elevation model (DEM), land use/land cover maps, and tree species data was sourced from the State Forest Rhineland Palatinate of Rhineland-Palatinate Federal State (RLP 2020). To calibrate and evaluate the performance of the SWAT+ model, long-term streamflow records (1955–2020) were obtained from the State Office for the Environment Rhineland Palatinate (LfU (State Office for the Environment Rhineland Palatinate) 2021).

2.3 | The Hydrologic Model, SWAT+

This study includes setting up a SWAT+ model (Bieger et al. 2017, Rev. 2020.60.5), which is a comprehensive revision of the original Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1998; Arnold and Fohrer 2005) for the

Palatinate Forest Biosphere Reserve. The SWAT+ model offers increased flexibility in depicting spatial interactions and processes within a catchment (Bieger et al. 2019). SWAT+ has been widely applied to several catchments worldwide (Wagner et al. 2022). Our SWAT+ model configuration includes two shallow aquifer layers of similar spatial extent and one deep aquifer layer following (Wagner et al. 2022) and (Pfannerstill et al. 2014) to capture processes in groundwater-dominated catchments accurately and improve the stream–groundwater interaction. This approach, involving a second slow shallow aquifer layer and corresponding file adjustments, enhanced the model's ability to reasonably simulate groundwater discharge to streamflow, surface runoff, and actual evapotranspiration. We also discretised the watershed into upland areas and floodplains using the DEM inversion method incorporated into the landscape unit module of SWAT+ (Bieger et al. 2019). From the DEM, the boundary between upland and floodplain was identified. No thresholds for land use/soil/slope values were applied during HRU generation to explicitly include all land use/cover classes, soil types, and slopes in the model and resulting full HRUs without missing any land use, soil, and slope information (Lin et al. 2022). To obtain detailed information on the impacts of forest operations across different topographies, we used a 20% slope inclination as the threshold value. In the study area, areas with slopes of 20% or more are classified as steep terrain, and harvesters typically operate on slopes of up to 25% (Müller 2023). Therefore, we analyse impacts on areas below and above 20% slope inclination. In addition to slope, we also considered the landscape unit as the

TABLE 1 | Spatial and hydrometeorological data sources and availability used in this study.

Data type	Variable	Temporal/spatial resolution	Availability	Data source
Spatial data	Land use and land cover	10×10 m	Accessed Jan 2020	State Forest Rhineland Palatinate of Rhineland-Palatinate Federal State (RLP 2020)
	Soil	1:50000	Accessed Jan 2020	The State Office for Geology and Mining (LGB) of Rhineland Palatinate (LGB 2021)
	Digital elevation model (DEM)	10×10 m	Accessed Jan 2020	State Forest Rhineland Palatinate of Rhineland-Palatinate Federal State (RLP 2020)
Climate data	Precipitation, temperature (max/min), relative humidity, wind speed and sunshine duration	Daily, 1000×1000 m	1961–2020	German Meteorological Service (DWD 2021)
Hydrology	Streamflow	At the multiple gauging stations	1955–2019	He State Office for the Environment Rhineland Palatinate (LfU, 2020)
Compacted area	georeferenced GIS layers of permanent infrastructure and Skid Trail System		Accessed Jan 2021	The department for Strategic Planning and Service of the Landesforsten (RLP 2020)

spatial unit of analysis to get a general picture of the impacts of soil compaction on floodplains and upslope areas.

The spatial objects created included 99 subbasins, 405 channels, 795 routing units, 49,705 HRUs, and 197 aquifers for the baseline model. The Hargreaves method (Hargreaves et al. 1985) was used to compute potential evapotranspiration using the temperature data available for the region. This method was chosen over the Penman–Monteith method based on preliminary test runs, as it demonstrated superior performance in reproducing the observed hydrograph, flow duration curves, and statistical indices for the study area. For channel routing, the variable storage method was employed, and the curve number (CN) was used as the infiltration method. Furthermore, observed plant-related parameter values such as initial leaf area index and time to reach maturity were used in the plant database component for the main tree species to accurately represent seasonal transpiration patterns of the region.

2.4 | Calibration and Parametrization

We implemented a systematic calibration and validation approach for the baseline SWAT+ model involving the following steps:

- I. Initial Examination of Aquifer Parameters: Before automatic calibration, manual adjustments were made to groundwater parameters, and their impact on streamflow and water balance components was assessed.

Additionally, sensitive model parameters were identified through manual sensitivity analysis and a preliminary manual calibration. Finally, we established reasonable value ranges for subsequent automatic calibration, leading to the identification of 16 sensitive model parameters (Table 2).

- II. Automatic Calibration: Following manual calibration, an automatic calibration was performed using a multiple flow segment approach. The process was guided by performance and signature metrics (Pfannerstill et al. 2014; Haas et al. 2016). We used daily streamflow records from the Bobenthal gauging station for model calibration (Figure 1). The period from 1989 to 2020 was used for calibration and validation, with five-year warm-up period (1989–1993). The periods (2010–2020) and (1994–2009) were used for calibration and validation, respectively. R packages, including FME (Soetaert and Petzoldt 2010) for Latin hypercube sampling and hydroGOF (Zambrano-Bigiarini 2014) for model performance evaluation, were employed. Initial testing involved sampling 250 parameter sets and evaluation of model performance using streamflow data from gauge Bobenthal. Subsequently, the model was run for 3000 additional model parameter sets. The best parameter set was selected based on the highest KGE value for gauge Bobenthal. Statistical indices, including Kling–Gupta efficiency (KGE), Nash–Sutcliffe efficiency (NSE), Percent bias (PBIAS), and standardised root mean square error

TABLE 2 | SWAT+ model parameters and their values fitted during the manual and automatic calibration procedures.

Parameter	Default value	Tested value ranges	Change method	Fitted value	
Alpha factor for groundwater recession curve-1 (alpha_bf1)	0.05	[0.1, 1]	Absval	0.8884	Fast shallow aquifer
Recharge to slow shallow aquifer-1 (rchg_dp1)	0.05	[0, 0.5]	Absval	0.3	
Threshold depth of water in the fast shallow aquifer required to allow revap to occur-1 (revap1)	0.02	[0.02, 0.2]	Absval	0.2	Aquifer parameters calibrated manually by considering the effect of each parameter on the baseflow
Water table depth for revap to occur-1 (revap_min1)	5.0	[0, 20]	Absval	2.13	
Water table depth for return flow to occur-1 (flo_min1)	3.00	[0, 50]	Absval	3.35	
Depth-mid-slope surface to water table (initial)-1 (dep_wt1)	10	[0,10]	Absval	1.23	
Depth-mid-slope surface to bottom of fast shallow aquifer-1 (dep_bot1)	10	[1, 8]	Absval	4	
Alpha factor for groundwater recession curve-2 (alpha_bf2)	0.05	[0.05, 0.5]	Absval	0.45	Slow shallow aquifer
Recharge to deep aquifer-2 rchg-dp2	0.05	[0, 0.3]	Absval	0.01	
Threshold depth of water in slow shallow aquifer required to allow revap to occur-2 (revap2)	0.02	[0.02, 0.2]	Absval	0.09	
Water table depth for revap to occur-2 (revap_min2)	3.00	[0, 10]	Absval	9.42	
Water table depth for return flow to occur-2 (flo_min2)	5.0	[0, 10]	Absval	7.97	
Depth-mid-slope surface to water table (initial)-2 (dep_wt2)	10	[0, 20]	Absval	10.61	
Depth-mid-slope surface to bottom of slow shallow aquifer-2 (dep_bot2)	10	[0,10]	Absval	10	

(Continues)

TABLE 2 | (Continued)

Parameter	Default value	Tested value ranges	Change method	Fitted value	
Curve number 2 CN2	Variable	[−20, 20]	Abschg	−5.55181	Parameter values fitted through automatic calibration
Soil water at CN3 (cn3_swf)	0.95	[0,1]	Absval	0.56684	
Soil evaporation compensation factor (esco)	0.95	[0,1]	Abschg	0.1000	
Plant water uptake compensation factor (epco)	0.5	[0,1]	Abschg	0.85191	
Soil depth (mm) (z)	200	[−30, 30]	Pctchg	2.82143	
Exponential of the lateral flow travel time (lat_ttime)	0	[0, 120]	Absval	90	
Snowmelt temperature (snomelt_tmp)	0.5	[−5.5]	Absval	4.89693	
Snowfall temperature (snofall_tmp)	1	[−5.5]	Absval	1.17065	
Slope length for lateral subsurface flow (lat_len)	50	[0, 150]	Absval	80	
Surface runoff lag coefficient (surlag)	4	[0.05, 16]	Absval	7.41828	
Maximum canopy storage (canmx)	1	[−20, 20]	Abschg	−4.04053	
Average slope length (slope_len)	50	[0, 100]	Absval	22.68735	
Percolation coefficient (Percolation)	0.9	[0, 1]	Absval	0.87406	
Saturated hydraulic conductivity of soil layer (k)	32.4	[−20, 20]	Pctchg	−13.85028	
Available water capacity of soil layer (AWC)	0	[0.01, 1]	Abschg	0.07107	
Lateral flow coefficient (lateral flow_co)	0.01	[0, 1]	Absval	0.63586	

Note: The aquifer parameters are fitted for the first and second aquifer layers. The suffix numbers 1 and 2 following the parameter names refer to the changes applied for the first and second aquifer layers, respectively.

(RSR), were calculated for all gauged streams with measured streamflow. Then, the best-performing parameter sets during calibration were validated by analysing model output for the validation period.

2.5 | Scenario Development

Three SWAT+ models, one base model with the recent soil conditions of the Palatinate Forest Biosphere Reserve beyond skid trails or pathways (here after called the baseline model) and two models considering compacted soil properties due to the forest skid trail system (here after called Scenario-1) and due to the impacts of forest infrastructures (here after called Scenario-2), were developed for the entire Palatinate Forest Biosphere Reserve.

We integrated the effects of compaction into the SWAT+ model, considering skid trail systems and the infrastructure (pathway system) as the two main mechanisms of compaction during forest harvest operations. The following step-by-step procedures describe how the effects of soil compaction were integrated into the SWAT+ model:

- a. Spatial overlay: The initial step in the compaction analysis involved defining the spatial coverage of compacted areas resulting from the skid trail system and infrastructure (pathway system). Additionally, areas of 30–50-year-old oak trees, which were driven on extensively in the course of afforestation activities from 1970 to 1990 (Lwf Aktuell 2003), were assumed to also show soil deterioration from driving with heavy machinery. For forest sites, the regeneration of BD is shown to take several years to decades, depending on soil characteristics,

severity of the impairment, climatic conditions, and biological activity (Bottinelli et al. 2014; Reichardt 2002; Zenner et al. 2007), as well as site-specific differences in water regime and clay content (Fründ and Averdiek 2016; Terzaghi 1943). The Research Institute for Forest Ecology and Forestry Rhineland-Palatinate provided spatial data, including the digitally tracked skid trail system and the preloaded area, as well as the pathway system (Figure 2). The ArcGIS raster overlay function was employed to integrate the influences of compaction on soil physical properties. This facilitated the generation of polyline and polygon intersected areas between the soil map and compacted regions, enabling the characterisation of soil properties accordingly. The generation of polyline and polygon areas helped us to include new compacted soil classes as identifiers for the compacted area and assign compaction-induced changes in the soil properties.

- b. Parameterization and scenarios: Following the spatial definition, we developed two scenarios for the compacted soil that included the skid trail system (Scenario-1) and the pathway system (Scenario-2) and applied changes to the soil BD, hydraulic conductivity, and available water content for soil classes intersecting with compacted areas. Soil parameter values, which were derived from driving tests by Reichardt (2002) and Schneider (2015) in the Palatinate Forest in the years 1989, 2002, and 2015, were used to adjust the soil parameters for the skid trail system and preloaded areas. For the pathway system, extreme compaction was assumed based on studies on ecologically damaging compaction, following Ampoorter et al. (2012) and Zemke et al. (2019). It should be noted that the soil classes and parameters for the uncompacted areas remained unchanged for both Scenario-1

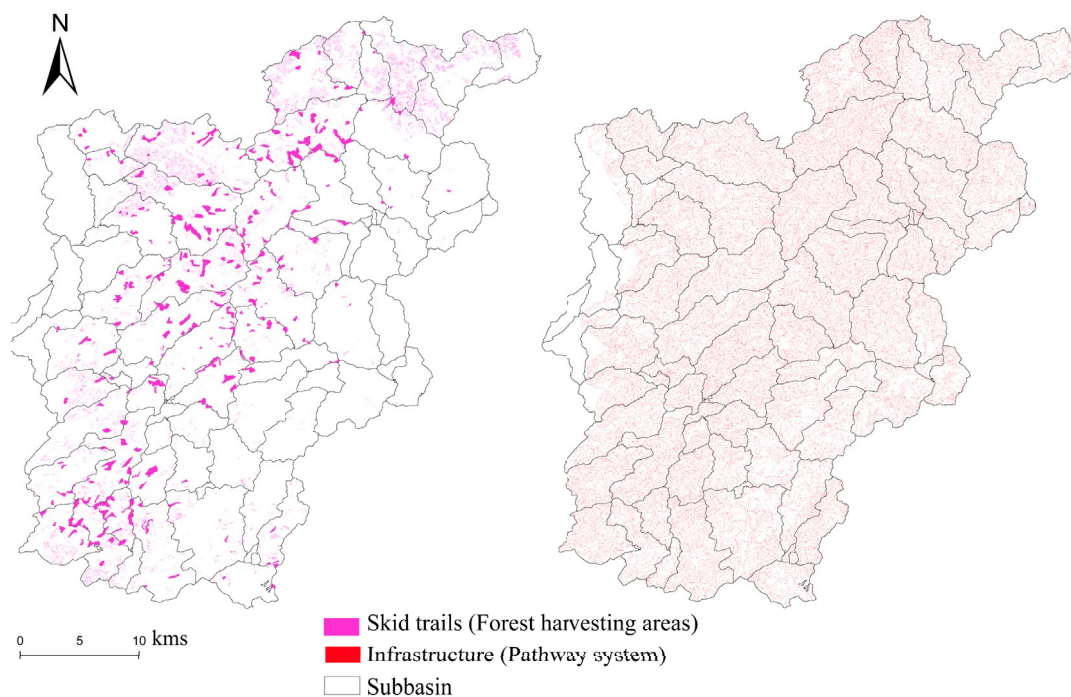


FIGURE 2 | Spatial distributions of compacted areas due to skid trail systems and preloaded areas (Scenario-1) and the pathway system (Scenario-2).

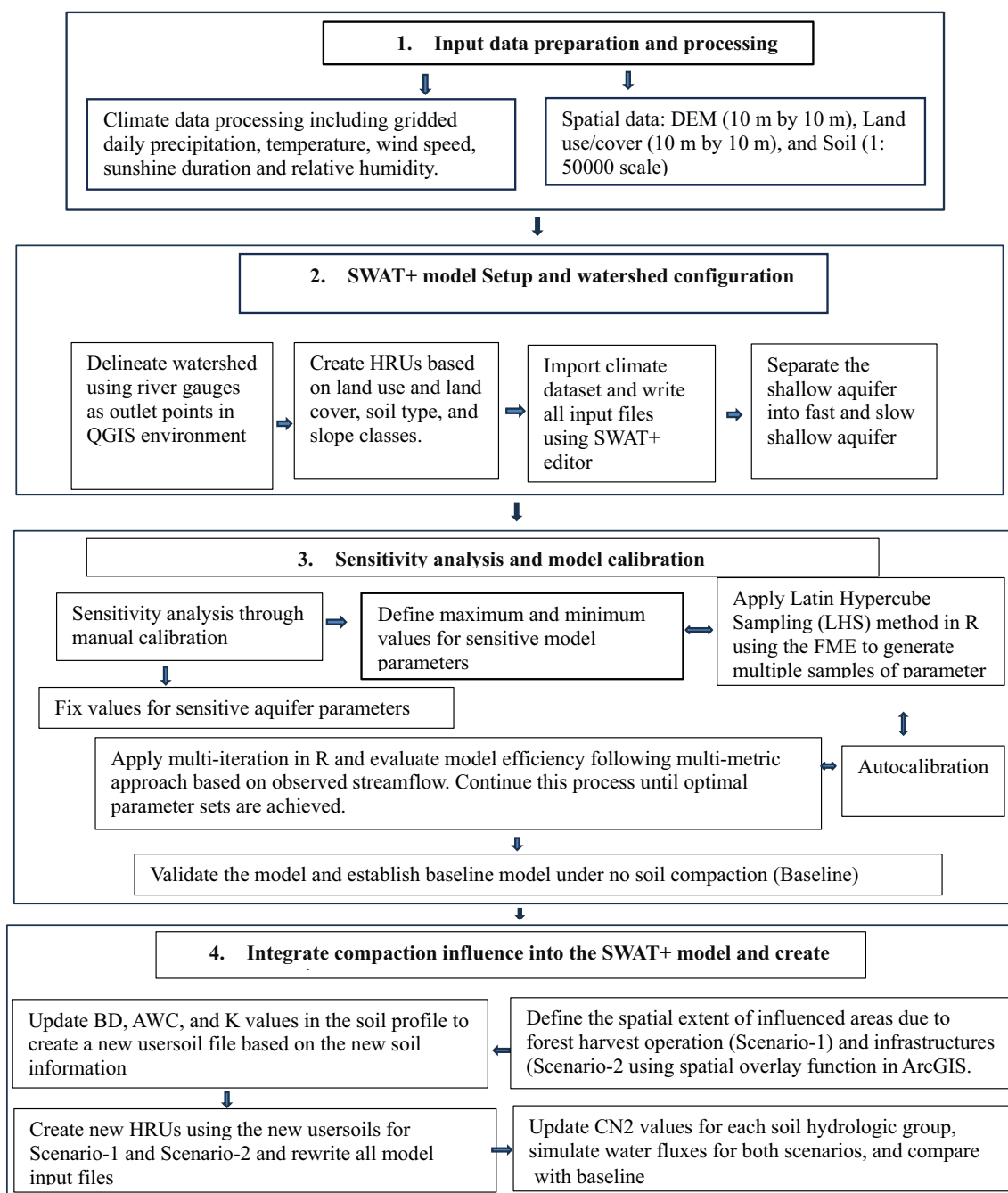


FIGURE 3 | Summary of workflow showing the successive steps implemented in the study.

and Scenario-2. Using the soil parameters for the scenarios, we updated the baseline SWAT+ model, resulting in two new models, which had 58,494 and 80,773 total number of Hydrological Response Units (HRUs) under Scenario-1 and Scenario-2, respectively. Other spatial objects, including sub-basins, channels, landscape units, routing units, and aquifers, remained the same as the baseline model. Results were analysed at the HRU level, as it provides the highest spatial detail and enables us to investigate the impacts in a spatially distributed way Figure 3.

Baseline model: The baseline SWAT+ model represents the recent soil conditions of the Palatinate Forest Biosphere Reserve beyond skid trails or pathways. It was calibrated and validated using climate, soil, and hydrological data from 1994 to 2020, a

period chosen to reflect the accepted sustainable forest management practices in the region. The baseline model includes accurate representations of the landscape's topography, soil properties, land use, and hydrological processes. Soil physical properties such as BD, hydraulic conductivity, and AWC remained at uncompacted levels, allowing for an undisturbed simulation of water fluxes.

Scenario-1- Skid Trail System: based on the spatial data we obtained from the department for strategic planning and service of the Landesforsten RLP (RLP (State Forest Rhineland Palatinate) 2020), about 13% of the Palatinate Biosphere Reserve watershed area experienced soil compaction during forest harvesting. Based on the driving tests, we assumed the compression pressure on the skid trails to vary vertically

within the layer depth. Likewise, the soil BD increased according to soil types and layers (ranging from +0.07 to +0.17 g/cm³). Accounting for these changes in the soil BD, we integrated the soil compaction into the SWAT+ model by modifying the soil parameter values in the soil database (Table 3). In response to changes in soil BD, hydraulic conductivity, and AWC across vertical soil layers at depths of 0–20 cm and 20–50 cm (layers 1, 2, and 3, Table 3), the default CN2 values for land cover types such as wood forest, wood pasture (wood_p), grain strow (sg_strow_g), and residue cover strow (rc_strow_g) in the model input database (“cntable.lum” file) were increased (Table 4). These adjustments altered the corresponding soil hydrologic groups. Furthermore, to reflect the updated CN2 values and hydrologic soil groups, modifications were made to the associated land use classes in the *hru-data.hru* file and the CN2 column of the *landuse.lum* file. These updates were applied to both scenarios.

Scenario-2- Infrastructure & Pathway System: The infrastructure & pathway system (Scenario-2) affected 11% of the Palatinate Forest Biosphere Reserve (Müller 2023). The compressional effect due to the infrastructure and road networks was assumed to be at its maximum level and distributed uniformly in the vertical soil profile. Following (Ampoorter et al. 2012; Zemke et al. 2019), the increase in the soil BD was 0.2 g/cm³ for all compacted soil types (Table 3).

Field and laboratory investigations conducted by the Research Institute for Forest Ecology and Forestry of Rhineland-Palatinate helped to estimate the changes in the soil parameter values (Klaes et al. 2016). Like Scenario-1, a new soil database was prepared which incorporated new soil classes for the compacted areas. Then, the CN2 values for wood forest, wood pasture (wood_p), grain strow (sg_strow_g), and residue cover strow (rc_strow_g) land covers were increased, as presented in

TABLE 4 | New curve number (CN) values for various hydrologic soil groups, determined based on the degree of compaction, soil physical properties, and different land-use classes.

Name	cn_a	cn_b	cn_c	cn_d
Baseline				
wood_f	36	60	73	79
rc_strow_g	67	78	85	89
urban	98	98	98	98
wood_p	45	66	77	83
sg_strow_g	63	75	83	87
Scenario-1				
wood_f_harv	57	76	95	95
rc_strow_g_harv	95	95	95	95
urban	98	98	98	98
wood_p_harv	71	83	95	95
sg_strow_g_harv	95	95	95	95
Scenario-2				
wood_f_pa	57	95	95	95
rc_strow_g	95	95	95	95
urban	98	98	98	98
wood_p_pa	71	95	95	95
sg_strow_pa	95	95	95	95

Note: Remark: wood_f refers to wood forest, wood_p refers to wood pasture, sg_strow_g refers to small grain strow, growing, and rc_strow_g refers to residue cover strow, growing. The suffixes harv and pa stand for skid trail system and pathway systems, respectively.

TABLE 3 | Values of soil bulk density (BD), available water capacity (AWC), and hydraulic conductivity before compaction (Baseline), and after compaction due to skid trail and preloaded areas (Scenario-1) and due to pathway system infrastructure (Scenario-2) in the vertical soil profile.

Soil class	Layer	Layer depth	Before compaction			After compaction			
			(Baseline)			Scenario-1		Scenario-2	
			BD	AWC	K	BD	AWC	K	BD
Sandy soil (Sand dominated regosol)	1	104	1.54	0.04	169.98	1.69	0.03	64.59	1.74
	2	270	1.59	0.06	101.52	1.75	0.05	38.58	1.79
	3	632	1.61	0.06	98.91	1.68	0.05	37.59	1.81
Loamy Sand (Loam dominated cambisol)	1	145	1.62	0.08	58.06	1.78	0.06	22.07	1.82
	2	320	1.62	0.08	57.48	1.69	0.06	22.99	1.82
Silty Sand (Silt dominated cambisol)	1	98	1.65	0.13	23.42	1.82	0.10	8.90	1.85
	2	250	1.65	0.12	29.19	1.82	0.09	11.10	1.85
	3	525	1.65	0.12	29.19	1.72	0.08	11.10	1.85
Sandy loam (Sand dominated loamy cambisol)	1	185	1.65	0.13	7.71	1.82	0.11	2.93	1.85
	2	557	1.6	0.14	6.82	1.67	0.11	2.59	1.80

Note: Numbers bold formatted refer altered values due to compaction.

Table 4. Consequently, the corresponding hydrologic soil group changed to another group (Table 4).

- c. Hydrologic processes simulations: The hydrologic processes were modelled for the baseline model, Scenario-1, and Scenario-2 based on the calibrated model parameters for the baseline. Finally, hydrological processes, including surface runoff, lateral flow, water yield, percolation, and actual evapotranspiration, were analysed considering annual average values for the entire basin and each HRU. Model results under compaction conditions were compared to the results from soils beyond skids trails or pathways, presenting absolute spatially distributed changes and percentage changes for major water balance components throughout the biosphere reserve.

3 | Results

3.1 | Parameter Sensitivity Analysis and Model Calibration

Results from manual calibration indicated that aquifer parameters significantly influenced the low flow of streamflow. Key parameters affecting streamflow fitting included alpha base-flow factor (α_{bf} 1 & 2), deep aquifer percolation fraction

($rchg_{dp}$), fraction of water moving into overlying unsaturated layers from the shallow aquifer ($reavp_{co}$), minimum aquifer storage for return flow (flo_{min}), threshold depth of water in the shallow aquifer ($revap_{min}$), and depth –mid-slope surface to water table (dep_{wt}). Different parameter values were fitted for the first and second aquifer layers (Table 2). Improving model performance involved increasing α_{bf} (1 & 2), $rchg_{dp}$, and $reavp_{co}$ while decreasing flo_{min} , $revap_{min}$, and dep_{wt} .

During automatic calibration, CN2, lat_time, soil depth, lat_len, slope_len, soil hydraulic conductivity (k), AWC, lateral flow_co, and surlag were effective parameters in improving the model efficiency (Figure 4). Additionally, adapting measured plant parameter values including maximum and minimum leaf area index (LAI), initial biomass, and years to maturity based on plant species and ground data slightly enhanced model performance. KGE improved from 0.70 to 0.74 when using modified plant parameters, similarly enhancing NSE, PBIAS, and RSR values. Further adjustments to the aquifer parameters and other effective model parameter values resulted in the final parameter sets (Table 2) and reasonably fitted hydrograph curves (Figure 5) and statistical indices for the Bobenthal catchment (Table 5). Due to the presence of river networks that are not hydrologically connected (Figure 1), the optimal model parameter sets for the Bobenthal catchment were transferred to the other catchments (Neustadt, Thaleischweiler, Moosalbtal, Haderburg, and Siebeldingen) for the

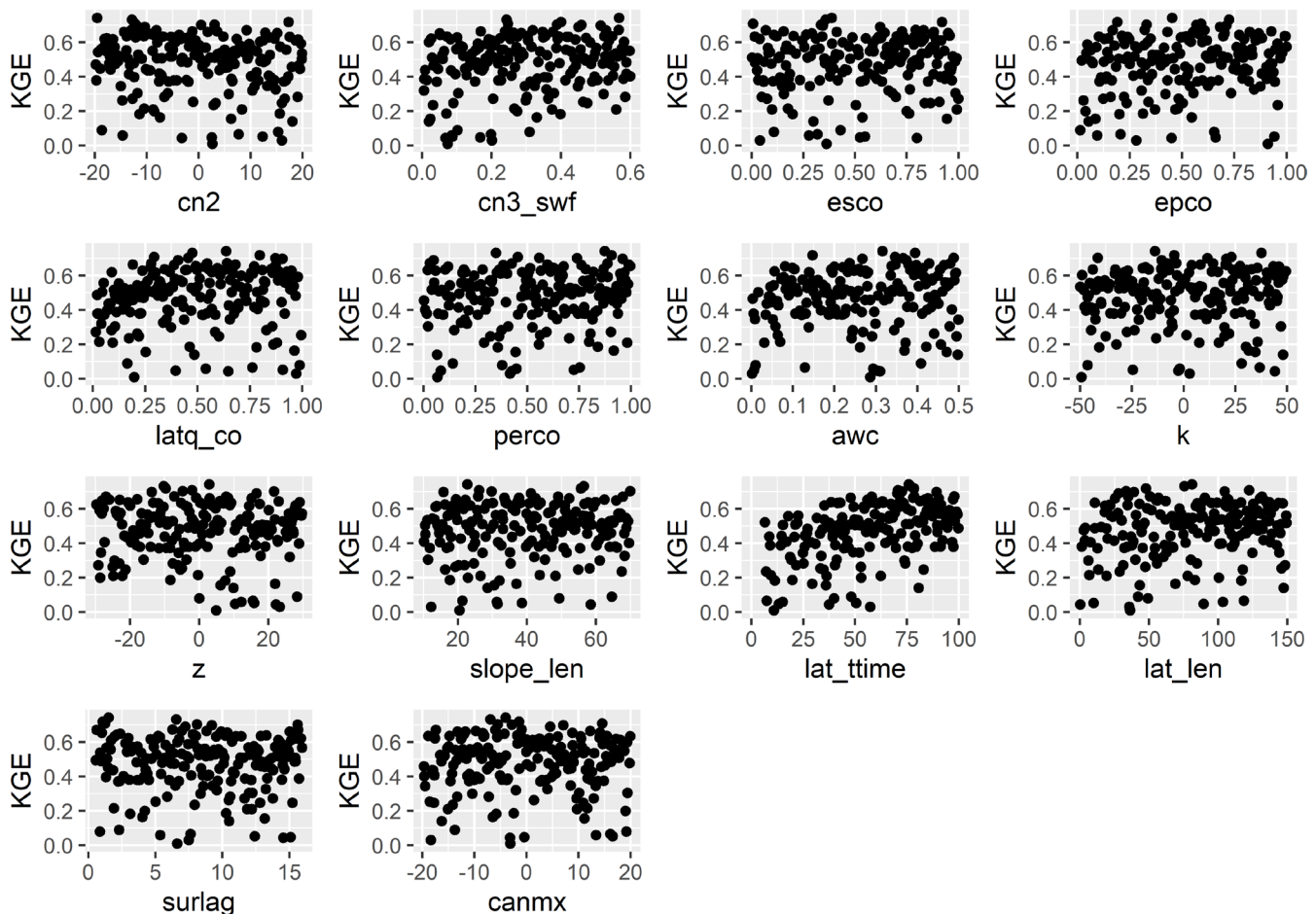


FIGURE 4 | Effective model parameters that influence the efficiency of the model performance under increasing/decreasing values (Bobenthal catchment). Horizontal and vertical axes represent parameters and model efficiency, respectively.

compaction scenario analysis. Utilising the optimal parameter sets from the Bobenthal catchment on the Neustadt, Thaleischweiler, and Siebeldingen catchments showed reasonable statistical indices, particularly in terms of KGE and PBIAS (Table 5). However, the model's performance for the Haderburg catchment was poor.

3.2 | Fast and Slow Shallow Aquifer Response

The targeted calibration to minimise underestimation of low-flow conditions in the hydrograph was achieved by applying the multi-storage groundwater concept proposed by Pfannerstill et al. (2014). Integrating fast and slow shallow aquifers into the SWAT+ model and adjusting critical parameters such as the alpha baseflow factor, deep aquifer percolation fraction, water transfer from the shallow aquifer to unsaturated layers, minimum aquifer storage for return flow, threshold depth of water in the shallow aquifer, and depth from mid-slope surface to the water table significantly improved the model's ability to capture

streamflow dynamics during low-flow periods, as shown in Figure 5 and Table 5.

Overall, the calibrated SWAT+ model simulated daily streamflow, with reasonable performance. The close alignment of observed and modelled streamflow in hydrographs and flow duration curves during calibration and validation confirmed the model's ability to replicate catchment hydrology. Performance metrics: NSE, PBIAS, and RSR consistently exceeded satisfactory thresholds in both phases (Table 5), as defined by Moriasi et al. (2007). Seasonal flow dynamics were well represented (Figure 5), although discrepancies during low-flow periods, particularly in the validation phase, highlighted areas for improvement. These differences likely stem from an inaccurate representation of heterogeneous rainfall patterns in low mountain ranges by the gridded precipitation input.

The mismatch between observed and modelled peak flows in certain years may stem from limitations of the curve number

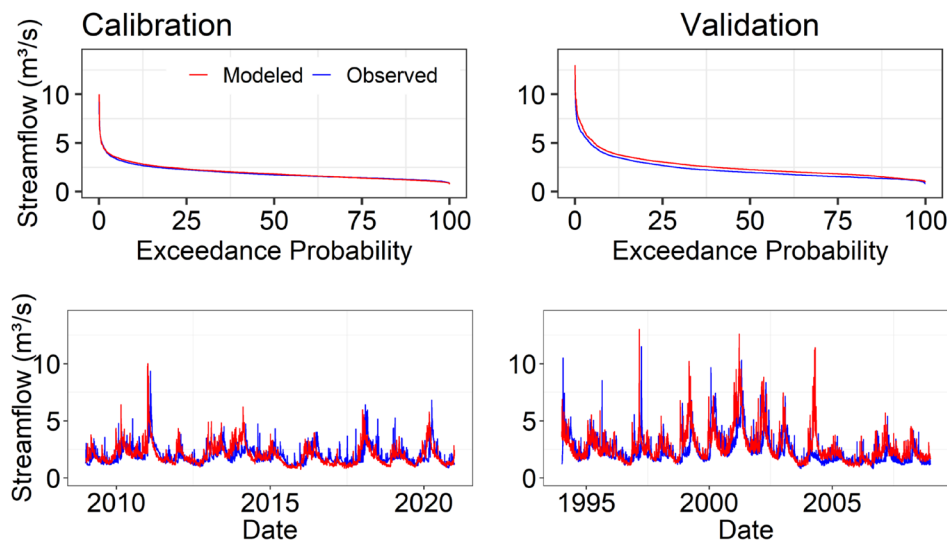


FIGURE 5 | Daily time series hydrographs and flow duration curves of modelled and observed streamflow of Bobenthal catchment for calibration and validation periods. Results are achieved after configuring the fast and slow shallow aquifers and model parameters.

TABLE 5 | Model performances evaluated based on statistical index values computed using modelled and measured streamflow time series data.

Objective function	Bobenthal	Neustadt	Thaleischweiler	Haderburg	Siebeldingen
Calibration statistics for the period (2010–2020)					
KGE	0.86	0.74	0.64	0.33	0.72
NSE	0.73	0.49	0.25	0.03	0.61
PBIAS	−0.30	16.8	4.5	0.30	9.5
RSR	0.51	0.71	0.86	0.98	0.62
Validation statistics for the period (1994–2009)					
KGE	0.74	0.57	0.57	0.19	0.60
NSE	0.49	0.10	0.10	0.001	0.38
PBIAS	−3.60	15.4	−0.90	13.0	2.0
RSR	0.71	0.95	0.95	0.99	0.79

Note: The objective functions were computed based on simulation outputs under the best calibrated model parameters for Bobenthal catchments.

method. As Nie et al. (2011) highlighted, the Soil Conservation Service (SCS) curve number method used in SWAT does not account for rainfall intensity or duration. Additionally, optimising model parameters across the entire hydrograph yields a better performance of middle-flow components (Tigabu et al. 2024) and may consequently contribute to deviations in peak-flow simulations.

3.3 | Impacts of Pathway Systems and Forest Skid Trail Systems on Hydrological Processes

In this section, we present impacts on the hydrologic processes resulting from forest harvest with heavy machinery. The compaction-induced changes in the soil resulted in changes in the soil hydrologic groups and the corresponding curve number values that influence the hydrologic responses of the areas affected. These changes in turn affect the partitioning and values of water balance components. The major water balance components that are subject to compaction-induced changes include surface runoff, lateral flow, water yield, ET, and percolation. Table 6 indicates the mean percentage changes of major water balance components that are caused by Scenario-1 and Scenario-2 for slope inclinations above and below 20%. The surface runoff was found to be one of the most impacted water balance components for soil compaction processes. Our results show that the surface runoff increased remarkably in both Scenario-1 and Scenario-2 (Table 6, Figure 6). The basin average increases were 115% and 102% for Scenario-1 and Scenario-2, respectively. Likewise, the water yield showed an increase in the annual mean values, while lateral flow and percolation showed decreases. Those changes in the water balance components varied based on soil type (Figures 6 and 7). The differences in the changes may be related to the variation in the soil structure, soil texture, and the ease of the soil for compaction.

The clay-dominated soil group (U) exhibited the least impact from compaction on surface runoff under Scenario-2, likely due to its minimal coverage in areas with slopes below 20% (Figure 6). Similarly, the soil group L (sandy loam soil) showed the lowest percentage increase in surface runoff compared to the surface runoff values of the baseline model. Unlike the clay-dominated soil groups, the sandy soil group (RS) resulted in the highest percentage increase in surface runoff. The mean percentage changes in percolation, lateral flow, and ET were negative for compacted areas below a 20% slope. Nevertheless, the water yield slightly increased as the decrease in lateral flow was compensated by the changes in surface runoff and ET. For the soil groups RS, percolation to the soil zone increased under compaction conditions of Scenario-1, even though a decrease was expected. These findings are not surprising, as the decrease in ET likely contributed additional water for percolation (Table 6).

Our findings revealed distinct effects of compaction under Scenario-1 and Scenario-2 on hydrological processes. Scenario-2 caused a greater increase in surface runoff compared to Scenario-1, while both scenarios led to significant decreases in percolation (Figure 7). The increase in water yield was more pronounced under Scenario-2. Relative to the baseline model, average annual surface runoff increased by 167% on slopes below 20% and 197% on slopes above 20% under Scenario-2 (Table 6).

However, this increase in surface runoff did not translate into higher catchment water yield due to a concurrent reduction in lateral flow. Lateral flow, which accounted for approximately 80% of the catchment water yield in the study area, declined by 20.3% on slopes below 20% and by 0.2% on slopes above 20% under Scenario-2. Similarly, percolation decreased by 20.1% on slopes below 20% and by 0.21% on slopes above 20%. Remarkably, compaction impacts were less pronounced on slopes above 20%, emphasising the critical role of slope management in steep terrain, where surface runoff generation is inherently high.

The impacts of soil compaction on water fluxes also differed between floodplains and upslope areas across both scenarios. Surface runoff increased, and lateral flow decreased more substantially in upslope areas than in floodplains for both scenarios (Table 7). Scenario-2 caused more significant increases in water yield and reductions in percolation and soil moisture than Scenario-1. In contrast, Scenario-1 led to reduced water yield in floodplains and increased percolation in upslope areas, highlighting key differences in hydrological responses between the two scenarios and landscape units.

3.4 | Impacts of Soil Compaction on the Spatial Distribution of Hydrological Processes

Spatially distributed maps illustrate changes in hydrological processes resulting from compaction. Variations in topography, soil types, and compaction-affected areas contribute to the spatial variability of hydrological processes. High-slope and sandy soil regions exhibit more pronounced changes compared to areas with lower slopes and clay-dominated soils, the latter due to the small amount of clay-dominated soils in the catchment (Table 6). The entire area experienced increased surface runoff, while both decreases and increases were observed in lateral flow (Figure 8).

Notable differences were observed between Scenario-1 and Scenario-2. Changes in surface runoff were more pronounced in Scenario-2 than in Scenario-1 (Figure 8), attributed to higher increases in curve number values for different soil groups and the broader spatial coverage of compacted areas. Similarly, water yield values showed larger changes in compaction due to Scenario-2 than in compaction resulting from Scenario-1 (Figure 9). In contrast to surface runoff and water yield, absolute changes in actual evapotranspiration and lateral flow were less substantial, with most changes in actual evapotranspiration being negative (Figure 9). It is important to note that changes in one water balance component may influence others. Overall, the results of the current compaction analysis are deemed reasonable for both Scenario-1 and Scenario-2, demonstrating that the SWAT+ model effectively simulates hydrologic processes under baseline conditions.

4 | Discussion

4.1 | Model Calibration

In this study, we calibrated the SWAT+ model using observed daily streamflow at the outlet of the Bobenthal catchment and transferred the calibrated parameters to other catchments. We

TABLE 6 | Resulted changes in water balance components due to soil compaction during forest skid trail system and preloaded areas (Scenario-1) and the pathway system (Scenario-2).

Soil	Surface runoff	Lateral flow	Water yield	Percolation	ET	Average soil moisture
Water fluxes % change for areas of slope class > 20% (Scenario-1)						
L	168.80	−8.87	6.09	−4.22	−0.32	−5.48
RS	284.10	−4.37	−2.14	4.98	−0.19	−0.80
S1	238.29	−4.77	0.64	−1.14	−0.35	−2.59
S2	50.00*	−28.81	−16.62	15.47	4.12	55.64
Mean	230.39	−11.70	−3.01	3.77	0.81	11.69
Water fluxes % change for areas of slope class ≤ 20% (Scenario-1)						
L	46.84	−10.26	15.65	−5.77	−0.31	−5.79
RS	46.84	−10.26	15.65	−5.77	−0.31	−5.79
S1	125.37	−6.44	9.07	−2.88	−0.48	−3.32
S2	40.00*	−44.35	17.17	−6.57	3.97	48.37
Mean	73.02	−17.83	14.39	−5.24	0.72	8.37
Mean for all slope classes (Scenario-1)						
L	51.56	−9.64	12.30	−5.58	−0.31	−5.73
RS	107.29	−5.23	−0.47	0.42	−0.39	−2.09
S1	63.82	−5.67	5.08	−2.78	−0.46	−3.18
S2	42.29*	−35.57	−13.20	−2.83	4.00	49.85
Mean	74.23	−14.03	0.93	−2.69	0.71	9.71
Soil	Surface runoff	Lateral flow	Water yield	Percolation	ET	Average SM
Water fluxes % change for areas of slope classes > 20% (Scenario-2)						
L	74.54	−35.62	43.87	−34.81	−2.48	−13.81
RS	168.43	−19.32	67.35	−24.27	−2.90	−9.35
S1	311.33	−19.87	150.12	−25.23	−2.75	−8.59
S2	233.05	−25.73	138.13	−33.15	−2.55	−9.36
U	43.72*	−27.57	39.77	−27.31	−2.07	−11.96
Mean	196.84	−25.62	87.85	−28.95	−2.55	−10.61
Water fluxes % changes for areas of slope classes ≤ 20% (Scenario-2)						
L	50.36	−36.11	43.05	−32.78	−2.40	−13.66
RS	145.12	−19.38	113.62	−23.71	−2.89	−9.73
S1	179.90	−19.78	145.24	−24.81	−2.66	−8.32
S2	202.83	−26.29	170.06	−33.33	−2.57	−9.52
U	256.74	−10.70	28.63	−21.02	−1.17	−9.34
Mean	166.99	−22.45	100.12	−27.13	−2.34	−10.11
Mean for all slope class (Scenario-2)						
L	53.25	−35.87	43.10	−33.02	−2.42	−13.68
RS	147.60	−19.35	99.94	−23.80	−2.89	−9.66
S1	183.62	−19.86	144.14	−24.90	−2.68	−8.38

(Continues)

TABLE 6 | (Continued)

Soil	Surface runoff	Lateral flow	Water yield	Percolation	ET	Average SM
S2	203.07	−25.94	161.46	−33.29	−2.57	−9.49
U	38.96	−29.33	20.59	−27.88	−1.46	−11.03
Mean	125.30	−26.07	93.85	−28.58	−2.40	−10.45

Note: The changes refer to values computed with reference to baseline simulation based on soil type and slope classes $\leq 20\%$ and $> 20\%$ under Scenario-1 and Scenario-2. Remark: The soil abbreviations L, RS, S1, S2, and U stand for Sandy dominated loam (class 4), Sand dominated cambisol (class 1), loamy sand cambisol (class 2), Silty sand cambisol, and silt dominated clay cambisol, respectively. Bold formatted numbers refer mean values and values with * refer absolute changes.

also integrated the impact of soil compaction into the model. During calibration, we encountered challenges in minimising disparities between the modelled and observed streamflow, particularly in representing low flow. This limitation likely arose from the simplistic representation of groundwater processes in the SWAT+ model (Bailey et al. 2023) and the rapid response between precipitation and runoff influenced by aquifer storage effects (Cenobio-Cruz et al. 2023).

To address these issues, we separated the shallow aquifer into fast and slow components and calibrated their parameters independently. Adjusting aquifer parameters such as flo_min (water table depth for return flow), revap_min (water table depth for revap), dep_wt (initial water table depth), and dep_bot (depth to aquifer bottom) significantly improved low flow simulation. Similarly, Wagner et al. (2022) and Pfannerstill et al. (2014) demonstrated improved low flow predictions for the Kielstau catchment in Germany by employing fast and slow shallow aquifer layers with independent parameter calibration.

4.2 | Impact of Soil Compaction on Water Fluxes

Forest ecosystems provide significant benefits to human well-being; however, forest skid trail systems and machine trafficking can disrupt the water cycle with negative consequences. Our results revealed notable changes in the spatio-temporal annual water balance components of the Palatinate Forest Biosphere Reserve due to soil compaction from forest harvesting techniques under Scenario 1 and Scenario 2. These scenarios showed increases in surface runoff and water yield, coupled with decreases in lateral flow and actual evapotranspiration.

Consistent with our findings, Picchio et al. (2021) reported increased water yield from forest skid trail systems in their review of 155 paired catchment studies globally.

In our study, we found decreased actual evaporation, lateral flow, water percolation, and soil moisture for both Scenario-1 and Scenario-2. Consequently, the reduced actual evapotranspiration and percolation under these scenarios explain the increases in surface runoff and water yield. These increases can be attributed to the rise in soil BD and a reduction in soil hydraulic conductivity. Heavy machinery, such as harvesters used during forest harvesting operations, increases soil BD and reduces total porosity, especially for water-leading macro- and mesopores, less for water-containing micropores (Jourgholami and Labelle 2020; Rachels et al. 2020), thereby hindering vertical and lateral water movement in the soil profile.

Soils with greater heterogeneity in grain size distribution are more vulnerable to compaction due to their higher number of grain contact points (Terzaghi 1943). Silt- and loam-dominated soils, with a higher proportion of meso- and micropores, experience a more significant reduction in conductive meso- and macropores than sand-dominated soils, leading to lower infiltration capacity, reduced seepage, and higher surface runoff (Müller 2023). This disrupts the soil's retention function more acutely. For example, soil class U already has the lowest hydraulic conductivity in undisturbed conditions due to its high percentage of micropores. Additionally, the limited spatial extent of soil classes L and U reduces their overall impact on catchment-scale annual averages (Müller 2023). Soil compaction effects were most pronounced in soil class S2, which exhibited distinct runoff peaks post-compaction, whereas undisturbed conditions had not previously induced overland flow on these HRUs (Table 6).

Comparing Scenario-1 and Scenario-2 with the baseline, the magnitude of changes was significantly higher in Scenario-2, owing to the greater degree of compaction from gravel-based road construction. The increase in soil BD under Scenario-2 was substantially larger than that in Scenario-1.

4.3 | Forest Management Implication

Our findings demonstrate that forest harvesting significantly impacts water fluxes within catchments, with notable effects on surface runoff, lateral flow, water yield, and percolation. These changes are largely driven by soil compaction caused by harvesting activities. In Scenarios 1 and 2, surface runoff increased markedly, particularly on slopes exceeding 20%, while lateral flow and percolation decreased more substantially on slopes below 20%. Scenario 2 demonstrated greater overall impacts on watershed responses compared to Scenario 1, highlighting the critical role of harvesting methodologies (e.g., lightweight machinery, harvesters, skidders) in mitigating soil compaction and its effects on water dynamics.

The increased surface runoff from forest harvesting raises the risk of flooding during heavy storms, adversely affecting forest ecosystems and human well-being. High-slope areas are particularly vulnerable, emphasising the need for site-specific forest management strategies. To address these challenges, measures should aim to enhance water retention and minimise compaction impacts. For instance, forest roads typically lack water retention capacity, as noted by Gupta et al. (2009), while modifications to path density and drainage systems (Bott 2002) can help manage surface runoff. Simulation results indicate that

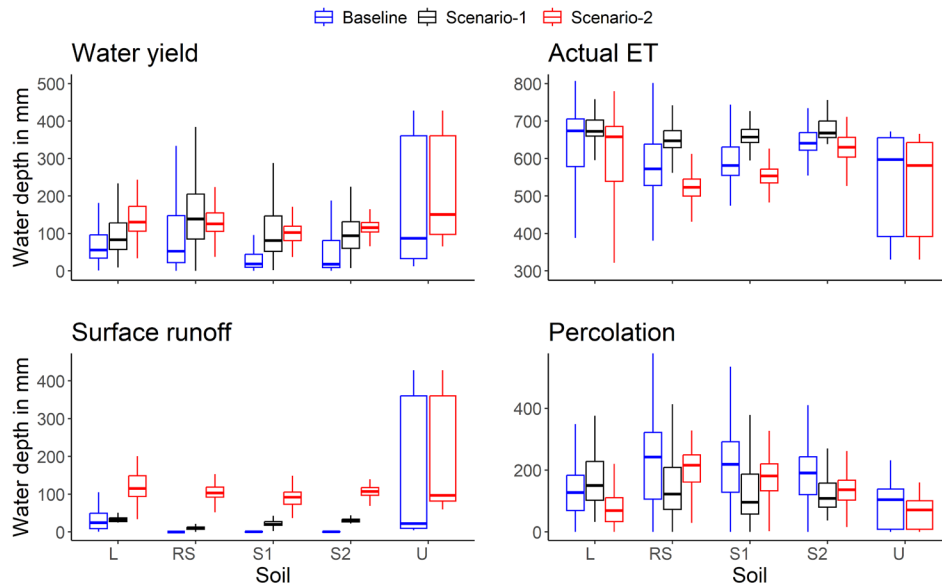


FIGURE 6 | HRU-based water yield, actual ET, surface runoff, and percolation modelled with SWAT+ Scenario-1 and Scenario-2 compared to the baseline model.

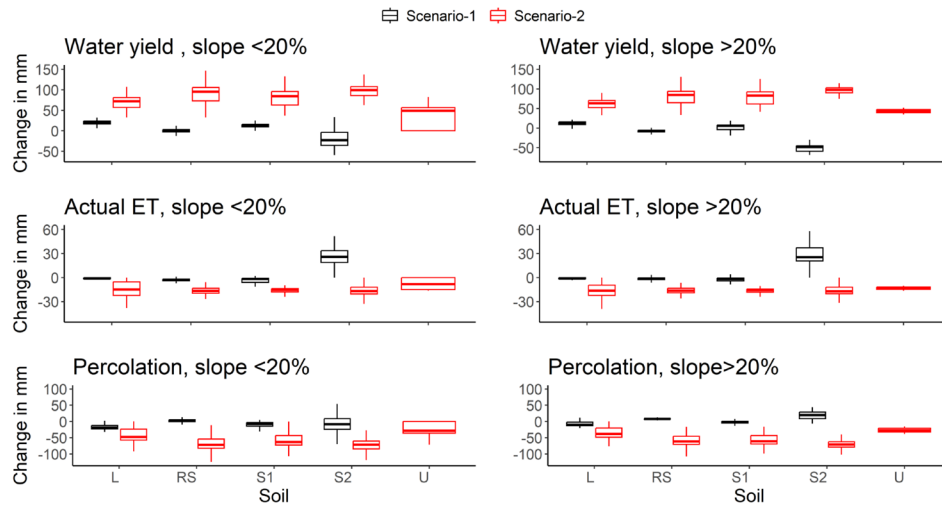


FIGURE 7 | Changes resulted from SWAT+ modelled water yield, actual evapotranspiration, and percolation due to soil compaction for HRUs distributed on slope inclination below and above 20% under forest Scenario-1 and Scenario-2.

TABLE 7 | Changes (%) on water balance components due to soil compaction during the forest skid trail system and preloaded areas (Scenario-1) and the pathway system (Scenario-2).

Water fluxes % changes as computed for floodplain and upslope landscape units						
	Surface runoff	Lateral flow	Water yield	Percolation	ET	Soil moisture
LSUs	Scenario-1					
Floodplain	46.33	-3.78	-0.75	-0.60	-0.06	-1.25
Upslope	445.26	-11.04	0.40	1.20	-0.25	-0.33
	Scenario-2					
Floodplain	80.12	-10.37	52.44	-10.74	-2.01	-6.82
Upslope	139.15	-21.07	97.14	-25.01	-2.77	-10.40

Note: The changes refer to values computed with reference to the baseline simulation based on floodplains and upslope landscape units (LSUs).

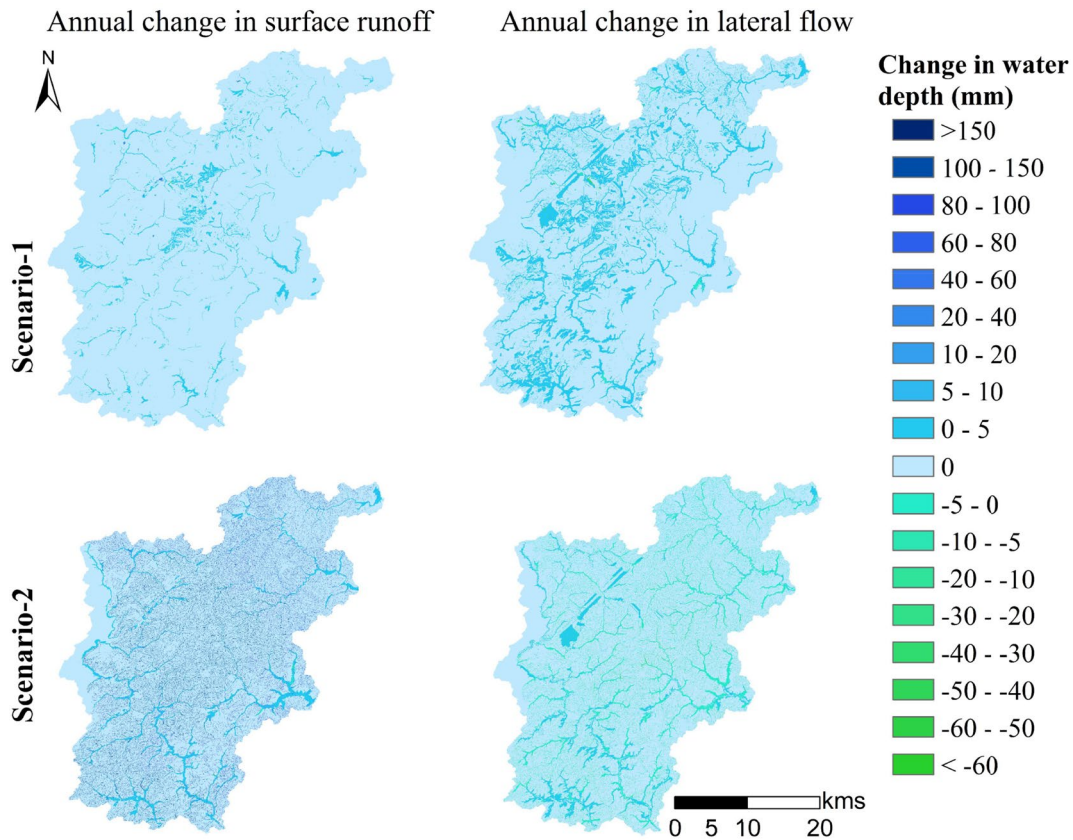


FIGURE 8 | Spatial variability of changes in surface runoff and lateral flow due to Scenario-1 and Scenario-2 systems.

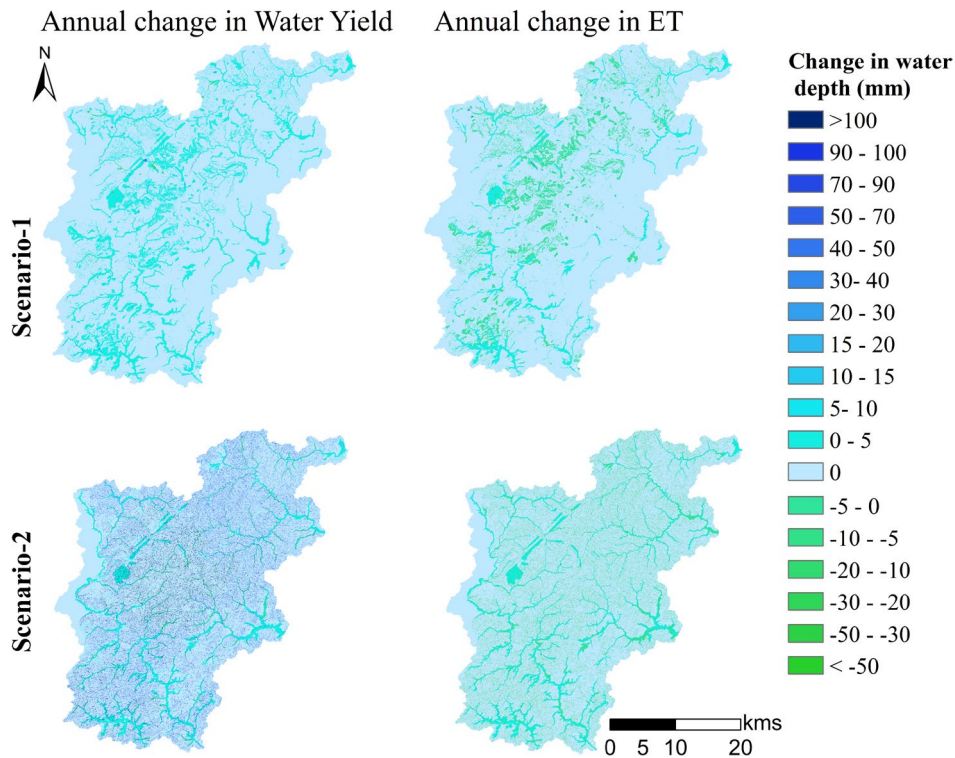


FIGURE 9 | Spatial variability of changes in water yield and actual evapotranspiration due to Scenario-1 and Scenario-2 system.

soil compaction effects vary by soil type, with clay- and silt-rich soils experiencing heightened infiltration issues, reduced aeration, and diminished percolation (Müller 2023). Developing

vulnerability maps that incorporate soil properties can guide soil-conserving harvesting practices and reduce traffic intensity, enhancing forest resilience.

To further mitigate compaction effects, strategies should redirect surface runoff into adjacent forest stands to improve infiltration and retention. Conventional wheel-driven vehicles cause inevitable soil damage, suggesting the need for alternatives such as soil protection mats (Siebert et al. 2023) or longer winching distances to reduce road density. Post-harvest operations should focus on decompacting skid lines and designing diagonal depressions to direct water back into forested areas.

Moreover, forest road networks should be redesigned to minimise water accumulation and maximise re-infiltration into neighbouring stands. Transverse road profiles can facilitate water flow directly into forests, replacing traditional ditches and culverts with infiltration stone packages that distribute water widely and channel it downhill into adjacent areas (Schüler 2024). These measures collectively enhance the forest's capacity for water regulation and contribute to sustainable forest management practices.

5 | Conclusion

This study used the SWAT+ model to simulate the effects of soil compaction caused by forest harvesting on hydrological processes in Germany's Palatinate Forest Biosphere Reserve. Two scenarios were evaluated: Compaction from skid trails and pre-loaded areas, as well as from pathway systems. The key findings of this study include:

1. The SWAT+ model demonstrated its use for assessing the hydrological impacts of forest harvesting under different management scenarios. Incorporating multi-layer groundwater storage and calibrating the fast and slow shallow aquifer parameters separately improved low-flow simulations in particular.
2. Forest harvesting under both scenarios increased surface runoff and water yield while reducing lateral flow and evapotranspiration due to soil compaction from heavy machinery. These results highlight the importance of considering impacts in space and machinery types in forest management to minimise adverse effects.
3. To reduce the impacts of soil compaction, slope-sensitive methods, lightweight machinery, and soil vulnerability mapping should be adopted. Improved road designs, such as using infiltration stones and reducing culverts—can enhance runoff retention, protect water regulation, and mitigate flood risks.
4. Forest management should focus on dismantling unnecessary infrastructure where feasible as well as on exploring alternative harvesting techniques to reduce environmental impacts. Future research should quantify the hydrological effects of these practices in the context of climate change, particularly concerning ecosystem services, to provide concrete insights for decision makers. Modelling approaches should also integrate channelized flow paths, especially on skid trails, to better assess surface runoff and erosion potential. Additionally, strategies to promote soil regeneration on abandoned skid trails are urgently needed to mitigate long-term adverse effects.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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