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Modeling Surface Runoff Response to Soil and Water Conservation Measures using QSWAT+ in the Northeastern Highlands of Ethiopia

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Abstract Watershed management in the developing world rarely includes detailed hydrological components. However, the hydrological cycle has many interconnected components, such as precipitation, evapotranspiration, surface runoff, infiltration, and groundwater flow. A common challenge in hydrological studies is estimating runoff in watersheds where precipitation records exist, but runoff data is unavailable. Thus, there has been a lack of long-term quantitative assessment. The QSWAT+ model was used to analyze hydrologic phenomena and assess how watershed changes impact the hydrological cycle. 17 years of meteorological input data were used to run the QSWAT+ and model hydrological responses to soil and water conservation measures on paired micro-watersheds, called Amanuel and Degnu, in the northeastern highlands of Ethiopia. The results indicate that QSWAT+ successfully models surface runoff at a daily time step, achieving Nash-Sutcliffe Efficiency (NSE) values of 0.826 and 0.945, and Coefficient of Determination (R^2) values of 0.944 and 0.741 for Amanuel and Degnu, respectively. The model results can help policymakers, land-use planners, and water resource managers effectively allocate water resources and implement sustainable watershed management practices based on flow conditions.

Keywords Micro-watershed, Soil and Water Conservation, Surface Runoff, QSWAT+

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1. Introduction

Watershed management in the developing world rarely includes detailed hydrological components (Nyssen, et al., 2010). However, the hydrologic cycle has many interconnected components (Sitterson, et al., 2017) such as precipitation, evapotranspiration, surface runoff, infiltration, and groundwater flow. A common challenge in hydrological studies is estimating runoff in watersheds where precipitation records exist, but runoff data is unavailable (Majed, 2009). Historically, hydrologists estimated surface runoff using limited data and basic computational techniques (Sitterson, et al., 2017).

The Rational Method was the first widely used runoff estimation method published by Thomas Mulvaney in 1851, which uses rainfall intensity, drainage area, and runoff coefficient to determine the peak discharge in a drainage basin (Fathia, et al., 2023). However, it is essential to understand the hydrological response of the watershed to know water resource potential and suggest better land and water management practices. Several on-farm and on-watershed level studies were reported in the assessment of the impact of Soil and Water Conservation (SWC) measures, but most of them are at plot level (Fathia, et al., 2023). Although multiple studies have shown that SWC reduces land degradation by minimizing surface runoff and soil erosion in semi-arid environments, a long-term, quantitative assessment of its impacts at the watershed scale remains lacking.

Monitoring and modeling land degradation and hydrological processes can help implement proper soil and water conservation techniques. Currently, hydrological models have been applied extensively around the world for the last three decades at the watershed level to monitor the hydrologic responses to soil and water conservation (Fathia, et al., 2023). Modeling the hydrologic response to SWC measures is, therefore, essential for a reliable assessment of their impacts at the watershed level (Majed, 2009; Sitterson, et al., 2017). Determining the primary drivers of hydrological systems and modeling processes such as surface runoff, soil moisture enhancement, and groundwater recharge are crucial aspects of watershed management

Modeling helps gain a better understanding of hydrologic phenomena and how changes affect the hydrological cycle (Sitterson, et al., 2017) and is used to visualize what occurs in water systems due to changes in Watershed characteristics, and meteorological events. A watershed model provides a more comprehensive simulation of hydrologic processes compared to other models that focus primarily on individual processes (Engda, 2009). In recent years, watershed-scale modeling has become an important scientific research and management tool, particularly for understanding hydrologic processes at the watershed level.

Hence, this research was conducted to compare and model the hydrological responses to SWC measures on paired micro-watersheds at Mt. Yewel, Northeastern highlands of Ethiopia.

2. Methodology

2.1 Location

This study was conducted at two paired micro-watersheds called Degnu and Amanuel, in Wereillu Woreda of Amhara Regional State, Ethiopia (Figure 1). Degnu lies between 10^{0}50’00” and 10^{0}52’00” N and 39^{0}26'20" to 39^{0}27'23" E, with an altitude range of 2860 to 3160m.a.s.l., and the other pair, Amanuel micro-Watershed extends from10^{0}50’23" to 10^{0}52’07" N and 39^{0}25’37" to 39^{0}26’30" E with an altitude range of 2880 to 3260 m.a.s.l.

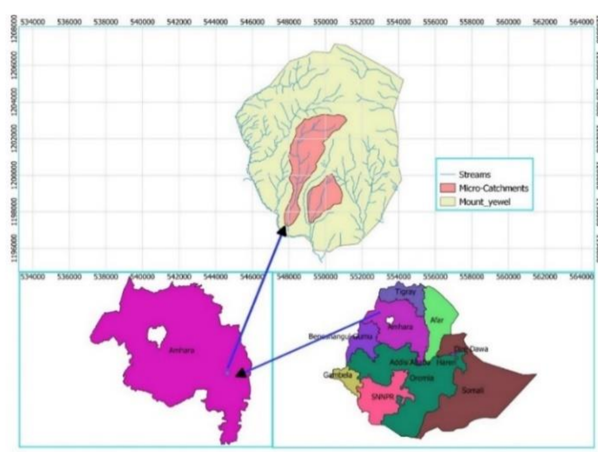

Fig 1. Location map of the study areas

2.2 Approaches

The approach to data collection and analysis was based on the conceptual model developed to understand the hydrologic cycle (Figure 2).

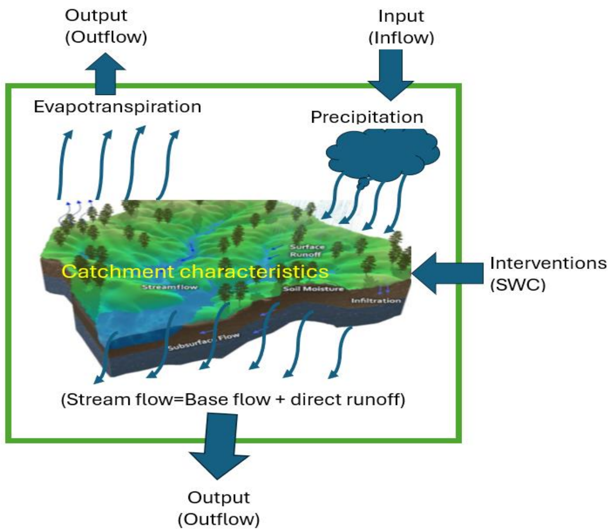

Figure 2. Schematic diagram of simplified water cycle

The water balance equation (Equation 1) governs the hydrological cycle by describing the flow of water into and out of a system for a specific period (Figure 2).

$Qs = P - ET - \Delta SM - \Delta GW$ ---(1)

Where P the is precipitation, Qs the is stream flow, ET is the evapotranspiration, ΔSM is the change in soil moisture, and ΔGW is the change in groundwater storage. From the schematic diagram (Figure 2), there are two outputs and one input component with reference to the watershed boundaries. The input component crossing the conceptual boundary is precipitation, while the output components are evapotranspiration and streamflow (surface runoff and base flow) exiting the watershed boundaries.

The precipitations were measured at/near the center of the micro-watersheds. The evapotranspiration for adjacent paired micro-watersheds is assumed to be the same or has no significant difference in comparing hydrologic responses to SWC measures. The components responsible for the micro-watersheds' stream flow variation are, therefore, watershed characteristics and watershed intervention (SWC).

Thus, watershed characterization and intervention inventories were made to easily compare the responses between the two micro-watersheds. Watershed characterization helps to identify the existence of similarities or differences in the watershed parameters such as watershed morphologies, land use, and slope classes between the two micro-watersheds in which hydrologic responses are dependent (Lakew, 2018). Hence, watershed characterization and comparisons were carried out for both micro-watersheds before comparing the hydrologic response to SWC measures. Watershed interventions (SWC) are human-induced activities purposely done aiming at modifying the stream flow of the micro-watersheds to create variation in wet and dry season stream flows. Hence, watershed treatment, which is the cause of variation in both dry and wet seasons, is the main concern of this study. Thus, detailed data collection and analyses were done based on the watershed intervention, particularly SWC measures.

2.3 Watershed Characterization

When comparing surface runoff responses, micro-watersheds located in the same or similar agrological zone have closely related landscape descriptors and, therefore, have comparable hydrologic responses. The major descriptors are listed here to look at how much the difference is between the two micro-watersheds in the study area. A list of the selected watershed parameters like drainage area and pattern, topography/slope, morphology, and other important parameters pertinent to hydrologic response is indicated in Table 1.

***Drainage pattern**:* Drainage patterns and streamlines were generated from DEM_30 using QGIS 3.28 with ground truthing. The drainage pattern of the study area (Mount Yewel) is radial and dendritic, with a 3rd stream order. Mount Yewel is south-facing, with a convex slope, conical in shape draining towards Selgi River which is the main tributary of the upper Blue Nile River. Amanuel and Degnu micro-watersheds are part of the Mount Yewel draining again to SelgiRiver. Both study micro-watersheds have similar dendritic drainage patterns with 2nd-level stream order in Strahler's system (Mohan, et al., 2012).

Topography: Like the drainage pattern, the landforms were also generated from DEM_30. The landform in both cases includes a rolling plain at the bottom and a hilly slope near the upper part. In the case of the Degnu micro-watershed, the upper part is a V-shaped valley steeper on the right side.

***Watershed Morphology**:* The rate and volume of stream flows as well as associated sediment yield from the watersheds do have strong relations with shape, size, slope, and other parameter indices of the landscape (Yuguo, et al., 2018; Mohamoud, 2004). The study in Lakew (2018) indicates that there are some important relations between basin morphology and hydrologic responses. If the watershed and hydrologic characteristics are related, quantitative indices must also represent the watershed form. These indices for the study sites are generated from measured parameters. Some of the parameters were calculated from measured data in both micro-watersheds using QGIS 3.28 computer software and some of them were found by simply measuring or counting from the maps.

Table 1Morphologic characteristics of micro-watersheds.

S/N	parameters	symbol	Unit	Formula	Result/Indices	
					Amanuel	Degnu
1	Area	A	km2	Measured	7.16	2.73
2	Perimeter	Pb	km	Measured	16.34	7.33
3	Axial length	Lb	km	Measured	6.73	2.92
4	Basin width	W	km	Measured	2.26	1.85
5	Total no. streams	N	no	Counted	9	3
6	Total stream length	L	km	Measured	12.96	4.47
7	Mainstream length	Lm	km	Measured	6.77	2.73
8	Mainstream slope	S	%	Measured	14.49	18.92
9	Stream order	Os	no	Counted	2	2
10	Stream density	Sf	no/km2	N/A	1.26	1.10
11	Drainage density	D	km/km2	D=L/A	1.81	1.63
12	Overland flow length	Lo	m	Lo=1/2D	276.28	305.85
13	Shape factor	B	unit less	B=Lb2/A	6.32	3.12
14	Form factor	Rf	unit less	Rf=A/Lb2	0.16	0.32
15	Elongation ratio	E	unit less	E= Dc/ Lb	0.46	0.64
16	Circularity ratio	Rc	unit less	Rc=4A/Pc2	0.49	1.46

Land use/land cover: The two micro-watersheds have similar patterns in their land cover. The land uses of both research sites are dominantly cultivated areas. The cultivated areas cover about 66 % at Amanuel and 70% at Degnu (Table 2) with a slightly higher cropland proportion at Degnu but there is no significant difference (p=0.48) between them. Cultivated areas are on the upper steeper parts in both cases while grazing lands are in the lower flatter parts. Scattered trees, villages, and gullies also existed in both micro-watersheds. Mixed agriculture (crop and animal husbandry) is the dominant economic base of the study area.

Table 2. Land use/cover and Slope class distribution of the micro-watersheds.

Land use (ha)	**Amanuel**		**Degnu**	
	ha	**%**	**ha**	**%**
Cropland	473.59	***66%***	190.8	***70%***
Forest	63.85	9%	36.46	13%
Grassland	15.98	2%	12.65	5%
Shrub land	87.86	12%	0	0
Degraded land	45.03	6%	13.79	5%
Road	0	0	5.55	2%
Settlement	29.82	4%	14.18	5%
Total	716.13	100%	273.43	100%
Slope class (%)				

0	3.72	0.52	1.42	0.57
0-3	18.19	2.54	6.95	3.93
3-8	63.66	8.89	24.31	11.11
8-15	140.79	19.66	53.76	21.5
15-30	312.30	***43.61***	119.24	***44.7***
30-50	156.47	21.85	59.74	16.37
>50	21.05	2.94	8.04	1.81
Total	716.13	100	273.43	100

Slope class: The dominant slope class falls in the range of 15 to 30 % (**Table 2**) in both micro-watersheds (43.61% at Amanuel and 44.70% at Degnu micro-watersheds). However, the difference is not significant (p=0.21) at 95% confidence interval.

Soil: The soil types in both Watersheds are extracted from the national grid soil map of the Amhara region with a resolution of 250 m by 250m using the zonal statistics method in the QGIS 3.28 interface. This was done by overlaying the micro-watershed shape files as input over the regional raster soil map on which zonal statistics were made. ***Soil textural classes***, mainly concerned with the size and shape of mineral particles, were extracted from the same map using the same method as soil types. The dominant particles (Clay, sand, and Silt) were identified, and textural classes were determined using the soil textural triangle. The soils identified in both watersheds are Sandy loam on the upper and clay and Clay loam clay on the lower parts. ***Soil depth*** in both the micro-watersheds ranges from deep to very deep (>150cm) in the lower part, and medium to shallow (<25 cm) soil in the upper part of both micro-watersheds. ***The soil color,*** which is a useful indicator of drainage, is brown with a few black soils on the upper part and black soil on the lower end in both micro-watersheds. ***Soil Bulk Density*** (BD), ***Soil carbon*** content (SOC), and ***Soil PH*** (PH) were also extracted from the nation soil map of the Amhara region in the zonal statistic method. ***Available water*** content was taken from Hailu et al., (2015). ***Hydrologic soil groups*** (HSG) were taken from the standard table.

Climate: Climate data recorded at Kabe meteorological station (just a few kilometers downstream of the research sites) for the last 30 years (1992-2022) was obtained from the Ethiopian National Meteorology Authority. Excluding rainfall data in 1993and data from 2017 to 2019 due to many missed/unrecorded data, the mean annual rainfall of the area is about 844.67mm. The maximum annual rainfall recorded at Kabe station was 1,172.80mm in 2010 and the minimum was 436.60 mm in 2015. The maximum monthly rainfall was observed in July, followed by August. During this research period (22/11/2020 to 8/11/2022), daily rainfall data were recorded on both study sites for the whole research period using manual rain gauges installed at/near the center of both micro-watersheds. Long-term average data (1992-2021) shows that the area's mean monthly minimum and maximum air temperatures (Kabe Met. station) are 8.73 and 18.38^0 C, respectively.

Area Coverage of SWC measures: Different physical soil and water interventions have been implemented in the Degnu micro-watershed since 2011. These include soil bunds, stone-faced soil bunds, and loose stone check dams.

Terrace Density: Terrace densities over both the micro-watersheds were determined from the Google Earth Image of 2021 "***on screen digitizing"*** method. Digitized lines were saved in the KML file format and converted into layers to make them shape files and be compatible with the QGIS interface. Physical soil and water conservation measures at Degnu cover about 47.21% of the total area and 53% of the total cultivated lands with few biological interventions on the bunds. Physical measures area coverage at Amanuel is about 6.91% of the total area which is about 9.23% of the total cultivated lands.

2.4 Precipitation Data Collection

Manual rain gauges were installed near the center of both micro-watersheds to collect precipitation data for this research period and compare it with the long-term data of the Kabe station. The data collected at these sites are almost similar to the Kabe Met. Station. Rainfall data was collected every morning at 8:00 A.M except at the times of rainstorms. During the rainstorms, the data collection records were delayed until the rain stopped. The data collectors recorded the depth of water in the rain gauge using graduation on the manual rain gauge itself and emptied the content after each record. The time interval between rainfall events was defined as being more than 6 hours, otherwise, it was considered as the same rainfall event (LeRoy Poff, 2006). Rainfall data were collected from 22/11/2020 to 8/11/2022 with some interruption from 26/10/2021 to 02/01/2022 due to the prevailing civil war in the study area.

2.5 Surface Runoff Measurement

Stream gauging stations were established at the outlet of both micro-watersheds to measure stream discharges (surface runoff and base flow). Stream flow data were collected on the same date as the rainfall data collection period. A broad crest weir made from masonry wall, as wide as the stream outlet, was constructed across the outlet of both streams in such a way that all the stream flow was guided to pass through it. The impermeable bedrock, close to the land surface at the Watershed outlet, is assumed to prevent groundwater outflow below the weir. Thus, all the surface flow from the micro-watersheds leaves the micro-watershed (basin) as the stream flows over the weir. Wooden staff, on which a steel meter was fixed, were used to measure the depth of water over the weir vertically. The water depth of steam flow (surface runoff) over the weir was measured every 20 minutes during the flood flows and at 8:00 A.M. every morning when there was no rainfall.

The depth of water over the weir was also converted to discharge based on the known weir formula (Richard, 2005) given by: $Q=CBd^{3/2}$---(2)

Where Q is stream flow discharge (m^3/s), B is the width of the weir crest, length equal to the bottom width(m), d is the upstream head (water depth) measured from the bottom(m), and C is the discharge coefficient(unitless). Some literatures recommended C to be 1.71 for broad-crested weirs. However, most researchers recommended that the calculated values are better than taking fixed literature values (1.71).In this study, a broad-crested weir calculator developed by Rahul Dhar and modified by Steven Wooding in 2023, given by: $C = 1.0929* \left[\frac{1-0.2222}{1+(\frac{H_1-\Delta Z}{Lcrest})}\right]$ --(3) was used.

where C is the Coefficient of discharge(unitless), H_1 is the water height at the approach channel, ΔZ is the weir height, and L_{crest} is the Length of the weir along the flow, all in SI unit.

3. Modeling the Watershed Response

3.1 Model Classification

Based on the modeling approaches used and the nature of the employed algorithms, watershed models can be grouped into ***Empirica***l, ***conceptual***, or ***physically*** based models (Engda, 2009). ***Empirical models*** consist of functions used to approximate or fit available data. Such models are simple, non-linear relationships with input and output, and are classed as a black box concept (Sitterson, et al., 2017). ***Conceptual models*** interpret runoff processes by connecting simplified components in the overall hydrological process which provides a conceptual idea of the behaviors in a watershed (Sitterson, et al., 2017). Conceptual models represent the water balance equation with the conversion of rainfall to runoff, evapotranspiration, and groundwater. Each component in the water balance equation is estimated by mathematical equations that distribute the precipitation input data (Sitterson, et al., 2017). ***Physical models***, also called process-based or mechanistic models, are based on the understanding of physics related to hydrological processes. Physically based equations govern the model to represent multiple parts of real hydrologic responses in the watershed (Sitterson, et al., 2017). Spatial and temporal variations within the watershed are incorporated into physical models (Hadadin, 2006; Sitterson, et al., 2017). A physical model has a logical structure similar to a real-world system. The greatest strength of a physical model is the connection between model parameters and physical watershed characteristics which makes it more realistic (Sitterson, et al., 2017). However, a large number of physical and process parameters are needed to calibrate the model. Physical parameters are physical properties of the watershed and can be measured as process parameters (Loukas & Vasiliades, 2014). Hence identifying the model that is suitable for the hydrologic spatial process in a given watershed is a crucial issue in modeling.

3.2 Spatial Process

Watershed-scale models can further be categorized on a spatial basis as Lumped, Semi-Distributed, or Distributed Models (Engda, 2009).

1. Lumped model: The lumped modeling approach considers a watershed as a single unit for computations where the watershed parameters and variables are averaged over this unit. Lumped models do not consider spatial variability within the Watershed (Sitterson, et al., 2017) however, lumped models adequately simulate average runoff conditions with fast computational times. Lumped models include a lot of assumptions about hydrological processes. Land use changes may alter the runoff process in specified areas, but a lumped model averages these over the entire watershed. This implies that the lumped model doesn't capture the spatial variability of rainfall across a watershed (Ana, et al., 2020).

2. Semi-distributed model: Compared to lumped models, semi-distributed and distributed models account for the spatial variability of hydrologic processes, input, boundary conditions, and watershed characteristics (Sitterson, et al., 2017). Semi-distributed models reflect some spatial variability, but fully distributed models process spatial variability by grid cells. Semi-distributed models consider spatial variability at smaller scales than lumped models but do not calculate runoff at every grid cell.

In semi-distributed, the model process divides the watershed into smaller areas, with different parameters for each Sub-area representing important features in a watershed and combining the advantages of lumped and distributed models. Most models are semi-distributed because of data availability, spatial flexibility, and range in the spectrum between lumped and distributed models.

The benefits of a semi-distributed model are fast computational time and the ability to use less data and fewer parameters than a distributed model (Sitterson, et al., 2017). Conceptual and physical models can be run in a semi-distributed manner depending on input data. Spatial interpretation in a lumped model, a semi-distributed model, and a distributed model are shown in Figure 3.

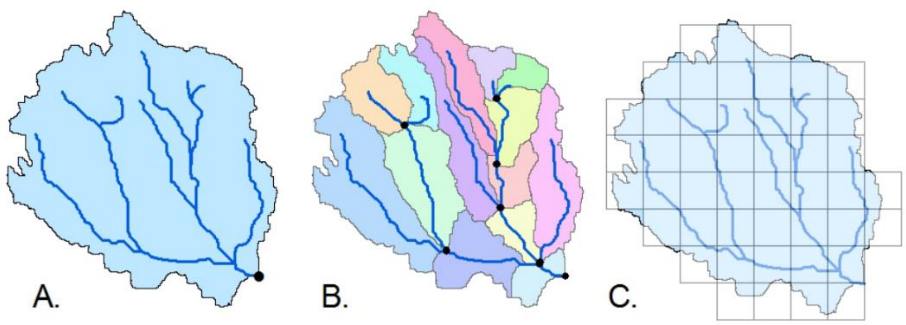

Fig3. Visualization of the spatial structure in runoff models*. A: Lumped model, B: Semi-Distributed model by sub-watershed, C: Distributed model by grid cell. After* Sisterson, et al. 2017

3. Distributed Models: Distributed models are the most complex because they account for spatial heterogeneity in inputs and parameters (Jinkang, et al., 2007). Fully distributed models separate the model process by small elements or grid cells. They are also structured like a physically based model which makes them more relatable to the actual hydrologic process. Distributed models route the calculated runoff from each cell to the nearest cell or stream, based on physical equations used to determine flow path and natural time lags. Distributed models are data-intensive, with all input data distributed spatially and temporally. Distributed models are also limited spatially by model resolution or by input grid size. Another weakness of distributed models is the computational time needed to run one simulation which can vary from one minute to several hours, depending on input data, watershed size, and computational constraints (Ana, et al., 2020). Such difficulties, when compared to lumped models, determine that distributed models are not widely used.

3.3 Model Selection

There are many different types of models, with some working better in certain situations than others (Sitterson, et al., 2017). Comparing models for runoff simulations to real-world runoff is a challenge (Smith, 2008). The challenging aspect is that observed discharge data cannot be directly compared to modeled runoff values because modeled runoff does consider subsurface interactions and discharge data (Sitterson, et al., 2017). A key question that has to be addressed is to select the most suitable model that gives results closest to reality for an intended purpose (Kikoyo & Oker, 2023). However, models differ in terms of complexity, data requirements, underlying equations, assumptions, and their performance in simulating hydrological processes.

Reviewing data requirements, physical meaning, user-friendliness, and spatial resolution are all necessary to determine which model type should be selected. For this study, the QSWAT+ model, an extension of QSWAT, was selected because of its simplicity, minimal parameter requirement, user-friendliness, spatial flexibility, applicability to small micro-watersheds, and consideration of different components of the outputs, such as surface runoff, soil moisture content, groundwater recharge, sediment yield, nutrients, and some more outputs.

QSWAT plus model is a semi-distributed watershed-scale continuous-time model that operates on a daily time step at a smaller micro-watershed (Fathia, et al., 2023; Sowmiya & Carolin, 2017; Patricia, et al., 2021). QSWAT Plus is a QGIS plug-in to create, run, and visualize the SWAT result. QGIS is an open-source public-domain software capable of executing hydrologic processes at the watershed level (Chris, 2023). QSWAT Plus can simulate streamflow, water balance, and other hydrological phenomena in a watershed by analyzing the relationship between land use, soil, slope, and weather parameters (Joseph, et al., 2019; Patricia, et al., 2021).

The Soil Water Assessment Tool (SWAT) and Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) models are widely recognized in the literature for their robustness and applicability in hydrological simulations (Imiya, et al., 2022). SWAT and HEC-HMS are commonly used for surface runoff predictions and environmental risk assessment developed as a river basin scale model suited for large complex watersheds (Miguel, et al., 2024; Imiya, et al., 2022). These two hydrologic models have been frequently used in tropical regions by many researchers (Imiya, et al., 2022). In these models, high flows were captured well by the SWAT model while medium flows were captured well by the HEC-HMS model. According to Imiya et al., (2022) dry and wet seasonal flows were simulated reasonably well by the SWAT model with slight under-predictions, but the HEC-HMS model under-predicted the dry and wet seasonal flows when compared to the observed values. These models are used in modeling soil erosion in a small watershed up to 1.62 km^2 (0.162ha). However, the QSWAT+ model has a performance of modeling hydrologic processes at even a smaller spatial scale as small as 0.066 km^2 (6.6 ha) which realistically represents the size of farmlands in the agricultural sector (Kikoyo & Oker, 2023). Thus. QSWAT+ model has a comparative advantage over the SWAT and HEC-HMS models in modeling small micro-watersheds at daily timesteps.

Currently, QSWAT+ is the latest model applied for watershed-based hydrologic analysis because of its capability to accommodate various outputs (Yihun, et al., 2023; Patricia, et al., 2021). Moreover, SWAT+ adopts most of the theoretical and empirical equations and assumptions in SWAT with a few significant changes incorporated in it to address the limitations of the older version of SWAT (Kikoyo & Oker, 2023).

QSWAT+ has been developed to quantify the impact of land management practices on large, complex watersheds on a daily time step and allows a basin to be divided into subbasins based on topography to incorporate spatial details in small micro-watersheds (Johnson, 1962). Each subbasin is further divided into hydrological response units (HRUs), which are unique combinations of slope, soil, and land cover (Yihun, et al., 2023; Sitterson, et al., 2017). In QSWAT +, individual HRUs are simulated independently, area-weighted, and added for each subbasin, and then routed through a stream network to the basin outlet (Anirudh & Giridhar, 2015).

3.4 Model Application.

3.4.1 Input Data and Model Structure

The inputs for the QSWAT+ are Digital Elevation Model (DEM), Land use map, Soil Map, and meteorological data. DEM_30 is freely available from the ASTER satellite digital data. Land use maps of the micro-watersheds for QSWAT+ input were prepared by the "***on-screen digitizing***" method from Google Earth in 2021 saved as a KML file and converted to layers for compatibility with the QGIS interface. All maps were converted into a similar projection system (UTM projection). Land use and Soil maps were generated as shape files, all larger than the actual watershed boundary, to avoid short of the DEM-30 layers during the watershed delineation process in running the QSWAT+ model. Finally, the shape files of land use and soil maps were rasterized using the QGIS analysis tool. Soil Parameters and climate data, as discussed in section 2.3, were used as input for QSWAT+. Figure 4 indicates the structure of SWAT plus Model.

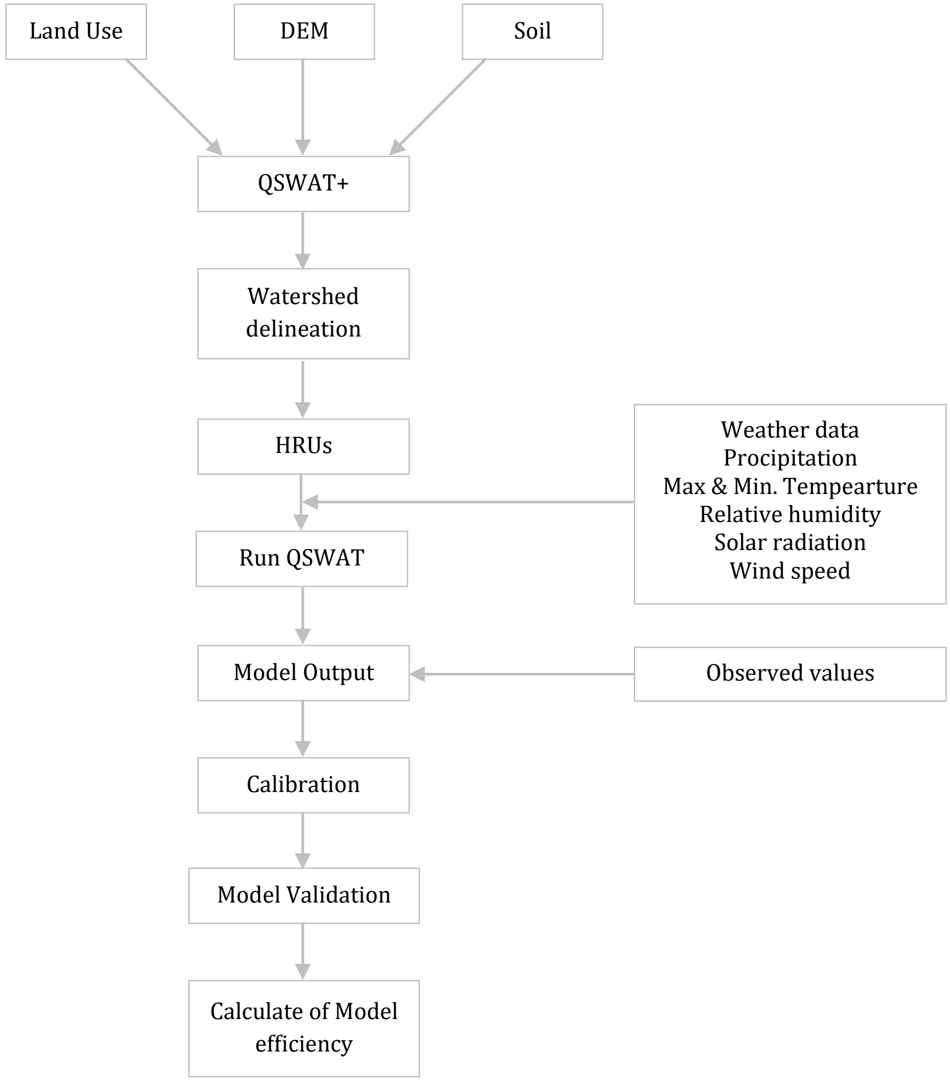

Fig.4 Model structure for SWAT plus

After selecting a semi-distributed watershed model, QSWATPlus was provided with input files (Met. data) in the form of a table in CSV format and raster maps of land use and soil with its look-up table to generate the output from both micro-watersheds. Two years of warmup periods were selected for running this model. After the first run, adaptation (input modification) was made for the best fit of the output and rerun the model.

3.4.2 Model Calibration

Before the calibration of parameters, sensitivity analysis was performed (Table 3) with selected parameters (cn2, alb, alpha, esco, epco) chosen based on a review of the existing literature (Ana, et al., 2020) in the "**Latin hyper-cubic one factor at a time**" method with the objective function of ***Nash-Sutcliffe Efficiency*** *(*NSE).However, the relative sensitivity of parameters is dependent on the variables included in the objective function and the time step considered (Ana, et al., 2020). After running the sensitivity analysis, the most sensitive parameter was the Curve number (nc2) which was used for parametric calibration.

Table 3. Sensitivity analysis result of the micro-watersheds

watershed	group	Change type	Name	Sensitivity
Amanuel	hru	percent	cn2	0.792
	hru	replace	epco	0.003
	hru	replace	esco	0.17
	sol	replace	alb	0.0002
	aqu	replace	alpha	0.04
Degnu	hru	percent	cn2	0.974
	hru	replace	epco	0.013
	hru	replace	esco	-0.001
	sol	replace	alb	0.00001
	aqu	replace	alpha	-0.002

Following the sensitivity analysis, model calibration was carried out and Re-run for new values to find a "**best range**" for the calibrated parameter and ensure high-quality simulations with the specified objective functions.

Calibration and validation periods were established in SWAT+ Toolbox V.2.3 following the split-sample approach, by dividing the period into two, (22/11/2020 – 25/10/2021) for calibration and (03/01/2022 – 08/11/2022) for validation. Stream flow Calibration was conducted at a daily-time step in the **Latin-hypercubic Sampling Iteration** (CALSI) algorithm. Both the calibration and validation periods comprise dry and wet seasons to assess parameter timescale transferability. Table 4 indicates the values of the specified objective functions in the model calibration.

Table 4. The value of objective functions after calibration

watershed	group	Name	Abs. Min	Abs. Max	Best Value	NSE	KGE	MSE	RMSE	P Bias
Amanuel	HRU	CN2	35	95	2.987	0.909	0.774	0.006	0.078	21.725
Degnu	HRU	CN2	35	95	1.676	0.952	0.865	0.000	0.013	12.539

3.4.3 Model Testing/Validation

The final calibrated parameter ranges must be assessed for the validation periods with the same number of simulations as the calibration iterations. Therefore, parameter sets sampled from the final calibrated ranges were assessed in terms of model goodness-of-fit statistics (NSE, PBIAS, $R^{2,}$ and KGE). The "**best simulation**" is the simulation with one single set of parameters that yielded the best objective function value. Most Researchers used NSE and P Bias for the evaluation of model performance.

NSE values above 0.50 are **acceptable,** values from 0.65 to 0.75 are classified as "**good**", and values above 0.75 are "**very good**". Similarly, PBIAS < + 25% are acceptable, and PBIAS ≤ +10% are "very good". These ratings, however, are not strict but depend on the objective of the study site conditions and the modeling area size when model performance is evaluated (Ana, et al., 2020).

Table 5. Model performance

Watershed	NSE	KGE	MSE	RMSE	P Bias	R^2
Amanuel	0.826	0.865	0.012	0.111	-0.222	0.944
Degnu	0.945	0.931	0.000	0.017	6.298	0.741

Table 5 indicates that the model is performing well with NSE values of 0.945 and 0.826 for Degnu and Amanuel watersheds respectively, and P Bias also shows good model performance (value <+25) which falls under the acceptable range in both watersheds.

4. Results and Discussion

4.1 Model Output

Normalization: In many data-driven comparison applications, the hydrological variable to be analyzed and compared needs to be in proper input structures (Gerald & Dimitri, 2007). In comparing the hydrological response of paired micro-watersheds, variables should be in a similar context. Here hydrological variables to be compared are surface runoff generated from the model output on both micro-watersheds (Amanuel and Degnu). Micro-watersheds having different sizes affect the total volume of surface runoff discharges. However, comparing small watersheds is better than large watersheds. This is because the comparison of large watersheds creates more variability due to the differences in watershed parameters including size. Thus, unlike large watersheds, small watersheds show a high degree of homogeneity in landscape descriptors (Mohamoud, 2004). As discussed in Machado, et al., (**2022**), large watersheds experience uneven rainfall distribution that often leads to an uneven surface runoff distribution. However, small watersheds tend to receive a more evenly distributed rainfall, and thus their hydrologic response reflects uniformity in the rainfall distribution (Mohamoud, 2004).

As the total surface runoff discharge is not a good indicator to evaluate the impact of watershed responses and see the significant difference in flood discharge rates, between the two micro-watersheds, normalization is needed.

Hence, Normalization/discharge per unit area (L^3 Km^{-2}) was calculated in both micro-watersheds for a fair comparison of hydrologic responses, as influenced by the watershed treatment, between the two micro-watersheds.

Surface Runoff: The hydrologic responses to soil and water conservation measures on both micro-watersheds are plotted in Figure 5 extracted from a CSV file of the model output. The result indicated that the total stream flow is higher at the untreated than the treated micro-watershed for all rainfall events that are attributed to size. To make the comparison of the response reasonable and avoid the effect of size, all the stream flows were converted to specific discharges and partitioned to dry and wet season conditions.

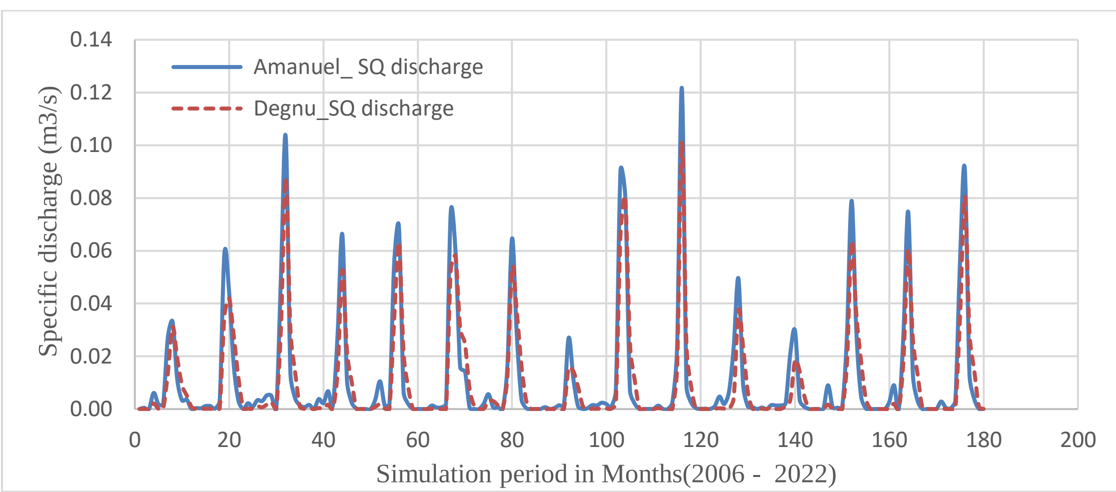

Fig 5. The stream flow pattern of the study micro-watersheds

The hydrologic responses, extracted from the model output, in specific discharge terms are plotted in Figures 6 and 7. The specific discharges were also partitioned into dry and wet seasons to look at the seasonal variation of stream flows. The result shows that as the wet season continued, the peak discharges at Degnu were attenuated because of the existence of physical soil and water conservation measures, supported by vegetation cover, to reduce surface runoff during the rainy season. However, the stream flow at Amanuel was higher in the wet season due to lack of watershed treatment that reduces peak flow whereas the dry period condition was reversed.

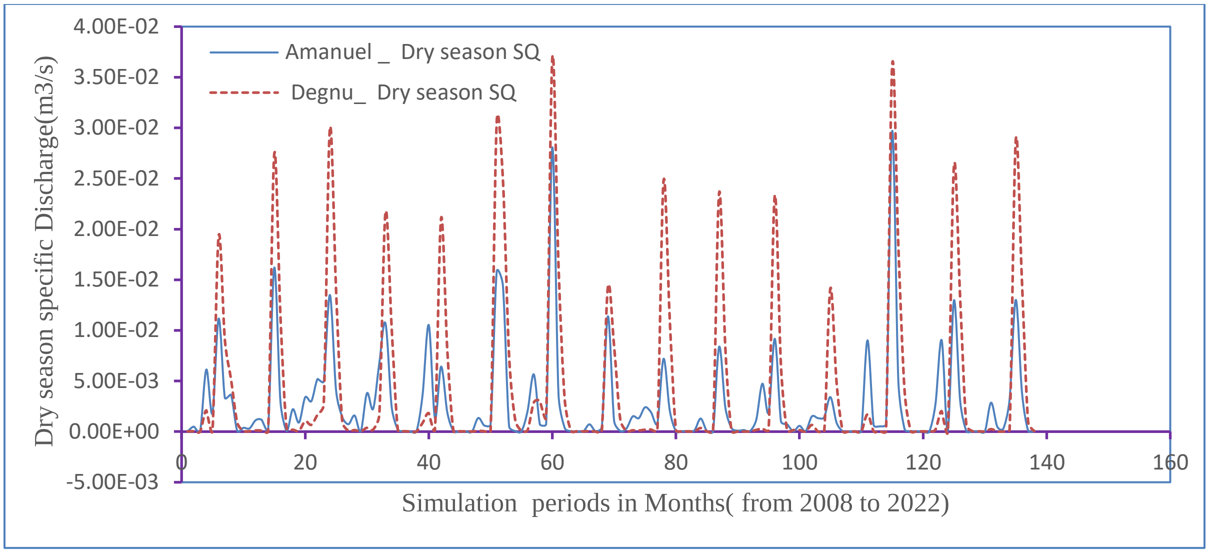

Figure 6 Specific discharge of the micro-watersheds in the dry seasons

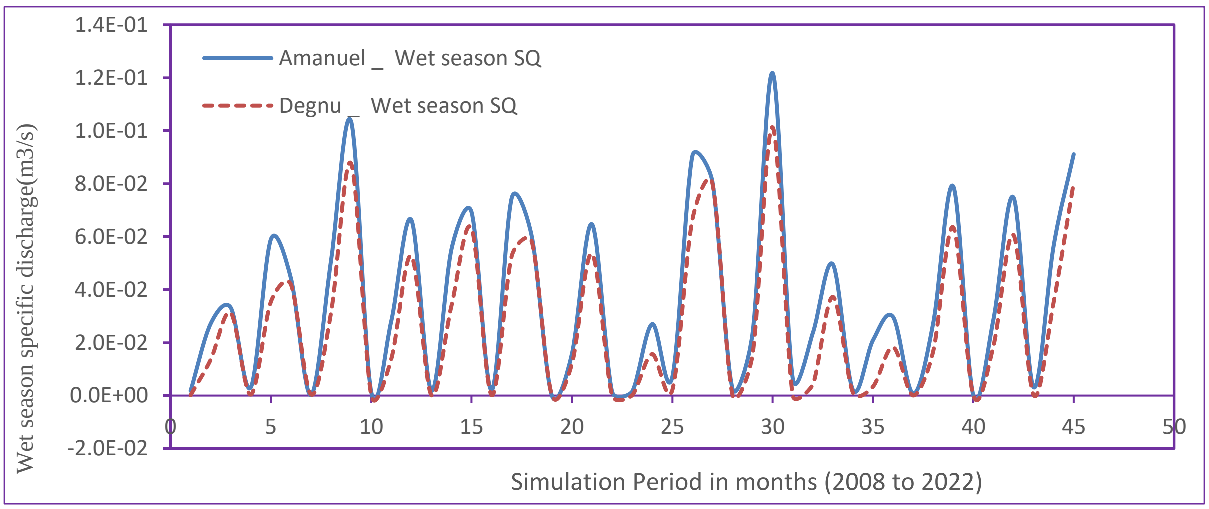

Figure 7 Specific discharge of the micro-watersheds in the wet season

Figures 8 and 9 represent the relation of observed and simulated stream flows of the study micro-watershed with R^2 0.9435 and 0.7411 for Amanuel and Degnu respectively. The flood hazard in the wet season and base flow in the dry season are well modeled in the QSWAT+ model.

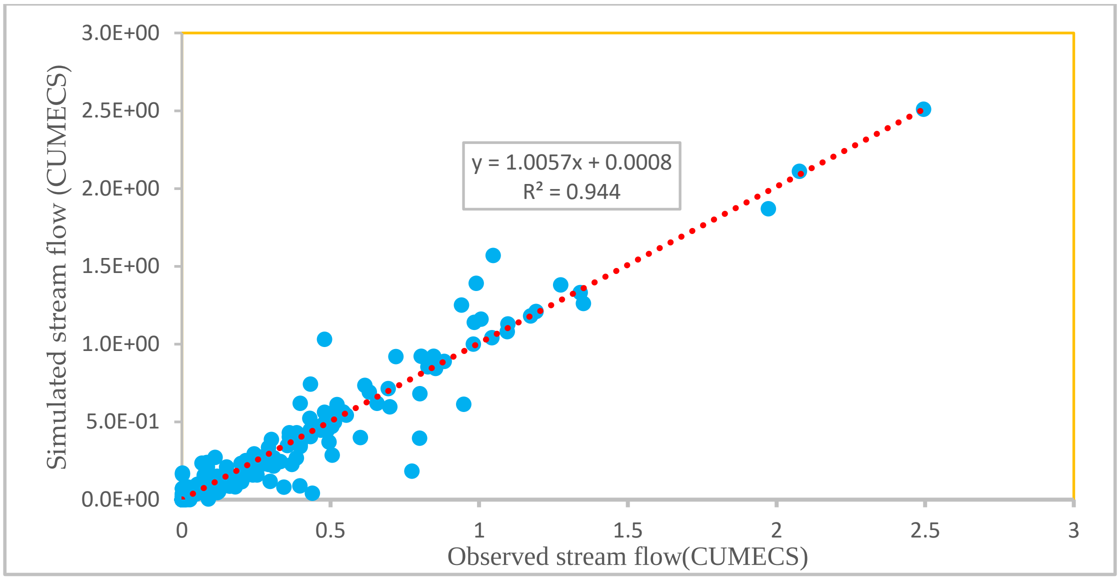

Figure 8 Observed Vs Simulated stream flow of Amanuel micro-watershed

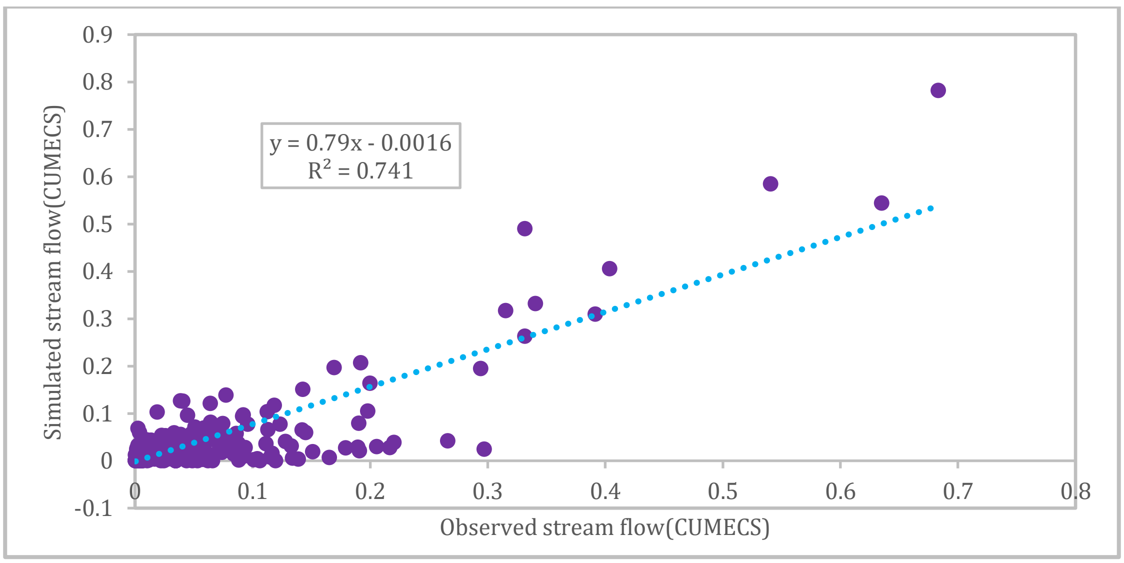

Figure 9 Observed vs. simulated stream flow of Degnu micro-watershed -

***Flow Duration Curve (FDC)*:**The flow duration curve(FDC), a plot of the percentage of exceedance against stream flow, is a useful tool in appraising the catchment characteristics of drainage basins (Ridolfi, et al., 2018; Engda, 2009; Luan, et al., 2021) and is used to describe the flow variability at two paired micro-catchments of the study area (Berihun, et al., 2020). In this study, the total duration method is used to derive the area-normalized flow duration curves.

Flow duration indices (Q1, Q50, and Q95) which are most widely used in comparing hydrologic response at the watershed level (Mohamoud, 2004) were used to represent the hydrologic responses of the study micro-catchments (Figure 10). It is used to Compare the hydrologic responses between the treated and untreated micro-catchments at high flow conditions, represented by the Q_1 index, medium flow condition represented by the Q_{50} index, and low flow condition represented by the Q_{95} index (Mohamoud, 2004).

Figure 10 revealed that the specific discharge of FDC for untreated (Amanuel) micro-watershed has the highest Q1 indicating high flood hazards while Degnu has a higher Q95 index which shows sustained base flow in the dry season.

From the model output analysis, the percentage of exceedance that daily flow exceeded the mean flow at treated micro-watershed is about 28.18 % whereas it is only 21.55% at untreated micro-watershed. This shows that treated micro-watershed has 6.63% more mean base flow than untreated micro-watershed.

Generally, FDC is applicable in water resource management at the basin scale for proper allocation of water for different uses such as domestic water supply, irrigation, flood risk management, industry, and other ecosystem services. The allocation of water, however, depends on the flow conditions. It is recommended that the low flow condition(Q95) is used to allocate water for ecosystem service, the medium flow condition(Q50) for irrigation, and the high flow condition(Q1) for flood risk management (Mohamoud, 2004).

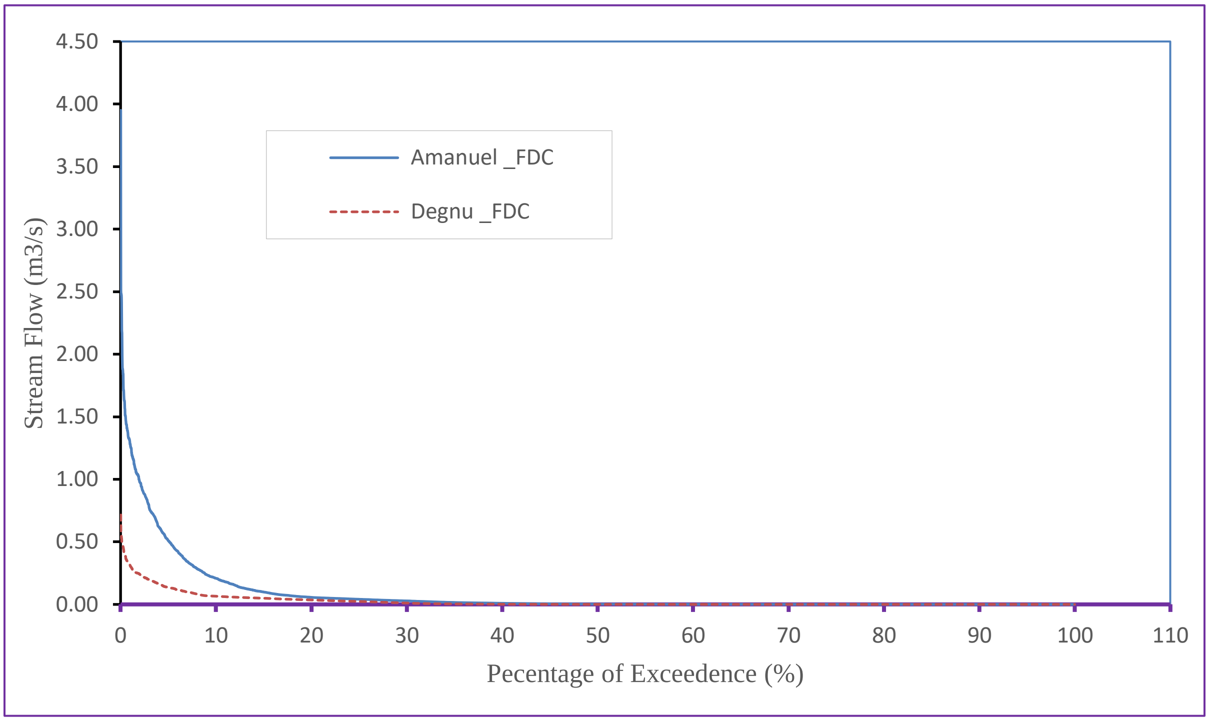

Figure 10 Flow duration curve of the stream flow

Runoff Coefficient (RC): The difference in specific discharges can also be expressed in the ratio of runoff to rainfall (RC). RC is governed by the amount of runoff generated in response to rainfall events in the watersheds. Rainfall is lost in the form of runoff, abstractions including interceptions by vegetation, direct evaporation from the land surface in rainy periods, and surface infiltrations. Surface infiltration is one of the major components in reducing surface runoff which is one of the main factors that highly influence RC in watersheds. Surface infiltration is affected by watershed treatment including physical soil and water conservation measures. Physical SWC improves surface infiltration because of the increased time of concentration.

The model output offers the annual surface runoff and precipitation information in CSV file format to calculate the RC for both watersheds. The calculated mean runoff coefficients (RC-values) for annual recorded rainfall were 0.47 at Amanuel and 0.34 at Degnu (Table 6). The rainfall and RC values in 2015 were excluded from the RC calculation because of its extremely low annual rainfall value (437.0 mm) or maybe unrecorded data.

Table 6. Runoff coefficient of the study micro-watersheds

Years	**Annual precipitation(mm)**	**Amanuel Surface runoff (mm)**	**Degnu _Surface runoff (mm)**	**Amanuel _RC**	**Degnu _RC**
2008	698	261	174	0.37	0.25
2009	846	401	277	0.47	0.33
2010	1,170.00	588	427	0.5	0.36
2011	815	373	244	0.46	0.3

2012	903	468	335	0.52	0.37
2013	955	521	407	0.55	0.43
2014	820	381	308	0.46	0.38
2016	1,060.00	598	460	0.56	0.43
2017	949	492	391	0.52	0.41
2018	860	302	192	0.35	0.22
2019	744	179	110	0.24	0.15
2020	915	454	327	0.5	0.36
2021	806	407	297	0.5	0.37
2022	930	522	388	0.56	0.42
Mean	**890.79**	**424.79**	**309.79**	**0.47**	**0.34**

Across all years, the runoff coefficient was consistently lower in the treated micro-watershed, whereas the untreated micro-watershed exhibited a 13% higher runoff coefficient which is in alignment with findings by (Mohamoud, 2004). This was due to the significant reduction of surface runoff as a result of watershed treatment which helped to increase the infiltration capacity of the soil profiles (Figure 11).

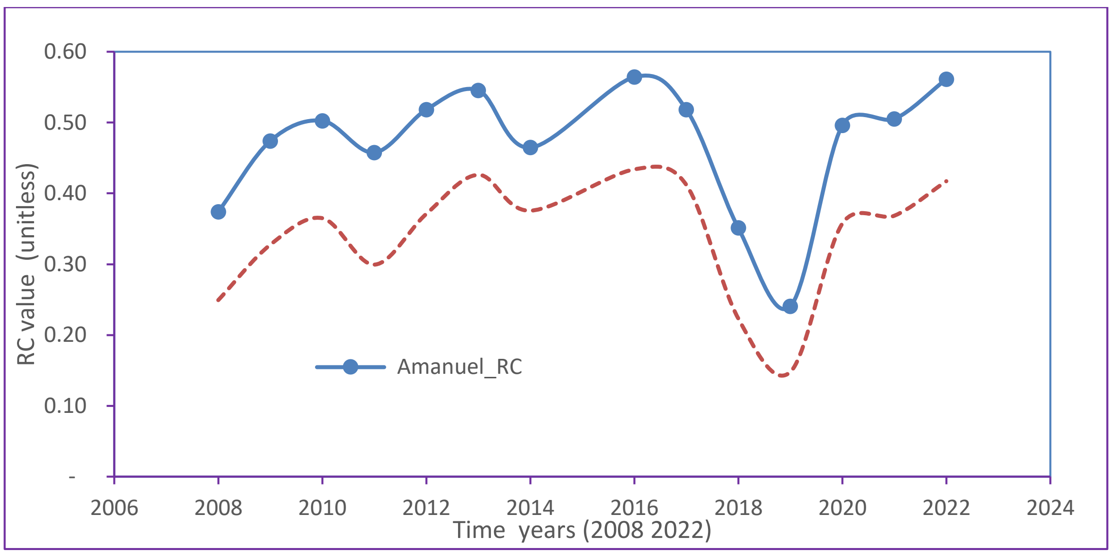

Figure 11. Aplot of the Annual Runoff Coefficient (RC) for the study of micro-watersheds

Commutative RC shows the almost constant slope which shows the consistency of the Runoff coefficients across the years (Figure 12) in both micro-watersheds. However, the slope is gentle at treated and steep at untreated micro-watershed. A steep slope is an indication of a quick response.

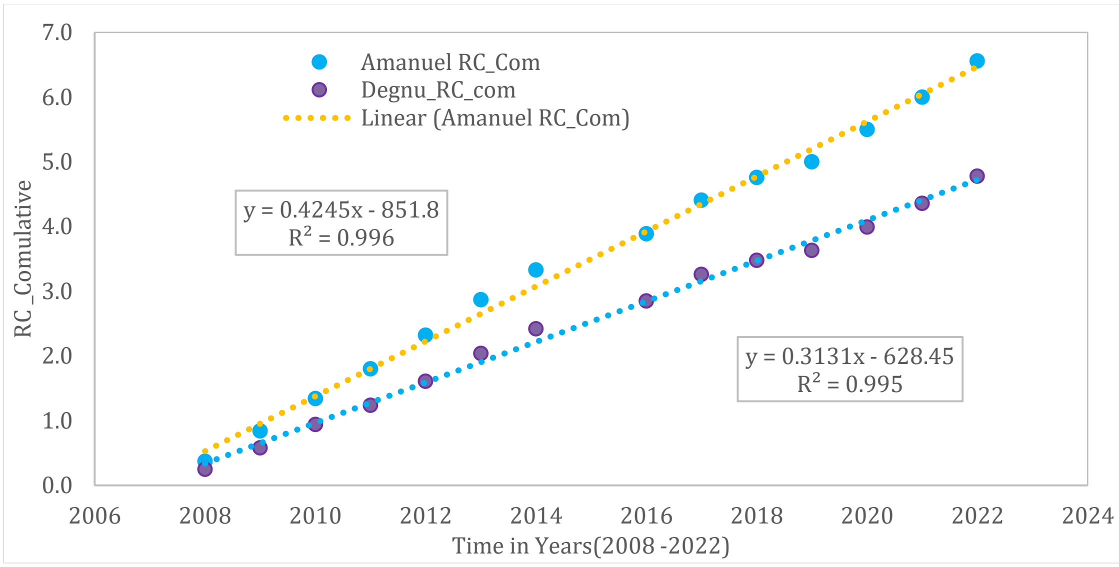

Figure 12 Cumulative Runoff coefficient values in the simulation periods (2008 -2022)

Reduction of surface runoff by 13% means the same amount of water was captured within the treated (Degnu) micro-watershed which helps to enhance groundwater recharge. Taking the mean annual rainfall (890. 79 mm = 0.89079m), the additional volume of water captured due to watershed treatment in each square kilometer can be calculated as, 0.13 *0.89079 m* 1 *10^6 m² = 11,5826.1 $m^3 km^{-2} yr^{-1}$ or so much water volume is lost every year because of lack of watershed treatment.

This shows that about11,5826.1 $m^3$of water could be captured annually per square kilometer at Amanuel which could have recharged the groundwater reserve if it had been treated at the level of Degnu and could have sustained the dry period flow discharge in the form of base flows.

The model result shows that the difference in runoff coefficient values between the treated and untreated micro-watersheds is highly significant ($p<0.001$) at a 95% confidence interval which agrees with the works of (Yuguo, et al., 2018; Adugnaw, et al., 2017).

5. Conclusion

In this research, 17 years (2006 to 2022) of Meteorological input data were used to run the QSWAT+ model in comparing the impact of SWC measures in two paired micro-watersheds. The results indicate that QSWAT+ successfully models surface runoff at a daily time step, achieving Nash-Sutcliffe Efficiency (NSE) values of 0.826 and 0.945, and Coefficient of Determination (R^2) values of 0.944 and 0.741 for Amanuel and Degnu, respectively

More Specific discharges were generated from treated (Degnu) micro-watershed in the dry season while it was low in untreated (Amanuel) micro-watershed. Despite its morphological parameters, the treated micro-watershed exhibited lower peak discharges during the wet season and maintained sustained flow in the dry season. Besides surface runoff discharge, the runoff coefficient at the treated micro-watershed was low.The model results demonstrate that watershed treatment has a significant influence on surface runoff discharge and runoff coefficient (RC) values ($p < 0.001$).Flow duration curves at treated micro-watershed were also smooth and gentle slope depicting reduced surface runoff in the wet season and sustained flow in the dry season. Thus, soil and water conservation activities in the treated micro-watershed effectively attenuated surface runoff peaks during the wet season.

Therefore, watershed treatment can mitigate flood hazards during the rainy season and support sustained dry-season flows.

The model results can be valuable for policymakers, land-use planners, and water resource managers in effectively allocating water resources for various uses based on flow conditions. Additionally, it can support the implementation of appropriate watershed management practices to promote the sustainable utilization of resources.

Ethical Approval: Not applicable.

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Conflicts of Interest: We declare that there is no conflict of interest among authors and other parties

Data Availability Statement: Data can be available via the first author upon request.

References

Adugnaw, T. A. et al., 2017. Impact of Soil Depth and Topography on the Effectiveness of Conservation Practices on Discharge and Soil Loss in the Ethiopian Highlands. *Research gate.,* pp. 1-17.

Ana, C. L. F., D. Y. & Nadia, B., 2020. Comparison of single-site, multi-site, and multivariable Variable SWAT calibration strategies. *Hydrological Sciences Journal,* 65(14), pp. 2376-2389.

Anirudh, R. & Giridhar, M., 2015. *QSWAT Model Application in Watershed Delineation - A Case Study, Tirupathi.* Hyderabad, India, Environment and Society.

Berihun, M. L. et al., 2020. Evaluating runoff and sediment responses to soil and water conservation practices by employing alternative modeling approaches. *Science of the Total Environment,* pp. 1-19.

Chris, G., 2023. *QGIS Interface for Soil and Water Assessment Tool (SWAT+).* [Online] Available at: https:// swat.tamu.edu

Engda, T., 2009. *Modeling Rainfall, Runoff and Soil Loss Relationships in the Northeastern Highlands of Ethiopia, Andit Tid Watershed. Thesis Presented to Cornell University in Partial Fulfillment of the Requirements for the Degree of Master.,* s.l.: s.n.

Fathia, J. et al., 2023. Long-Term Impact of Soil and Water Conservation Measures on Soil Erosion in a Tunisian Semi-Arid Watershed. *MDPI, LAND,* Volume 12, pp. 1-20.

Gerald, C. & Dimitri, S., 2007. Baseflow separation techniques for modular artificial neural network modeling inflow forecasting. *Hydrological Sciences Journal,* Volume 52, pp. 490-507.

Hadadin, A. N., 2006. Watershed models and their applicability to the simulation of the rainfall-runoff relationship. *WIT Transactions on Engineering Sciences,* Volume 52, pp. 193-202.

Hailu, A. H., Kibebew, K. & G/Kidan, H., 2015. Characterization and classification of soils of Kabe Subwatershed in South Wollo Zone, Northeastern Ethiopia. *African Journal of Soil Science,* Volume 3 (7), pp. 134-146.

Imiya, M. C. et al., 2022. Comparison of Two Hydrological Models, HEC-HMS and SWAT in Runoff Estimation: Application to Huai Bang Sai Tropical Watershed, Thailand. *Fluids, MDPI,* Volume 7, pp. 1-14.

Jinkang, D., Xie, S., Xu, Y. & Chong-yu, X. b., 2007. Development and testing of a simple physically-based distributed rainfall-runoff model for storm runoff simulation in humid forested basins. *Journal of Hydrology (2007) 336, 334–346,* 15(1), p. 334– 346.

Johnson, A. I., 1962. *Methods of Measuring soil moisture in the field.* Third printing 1992 ed. WASHINGTON: United States Government Printing Office.

Joseph, C., Paquit, Indie, C. D. & Angela, G. T.-B., 2019. *Training Manual for SWAT in QGIS 2.6.1 (Revised 2019).* [Online].

Kikoyo, D. & Oker, T., 2023. Comparative Evaluation of the Performance of SWAT, SWAT+, and APEX Models in Simulating Edge of Field Hydrological Processes. 11, 37-49. *Open Journal of Modelling and Simulation,* Volume 11, pp. 37-49.

Lakew, W. J., 2018. *Effect of soil and water conservation measures on hydrological processes and sediment yield in the highlands of North-Western Ethiopia,* Wageningen: Wageningen University.

LeRoy Poff, N. B. P. B. &. C. O. C., 2006. Hydrologic variation with land use across the contiguous. United States: Geomorphic and eco. Hydrology.

Loukas, A. & Vasiliades, L., 2014. Streamflow simulation methods for ungauged and poorly gauged watersheds. *Natural Hazard and Earth System Science,* Volume 14, pp. 1641-1661.

Luan, J., Liu, D., Lin, M. & Huang, Q., 2021. The construction of the flow duration curve and the regionalization parameters analysis in the northwest of China. *Journal of Water and Climate Change,* 12(6), pp. 2639-2653.

Majed, S. A. S., 2009. *Estimation of Runoff for small watershed using Watershed Mmodeling System (WMS) and GIS.* Hurghada, Egypt, s.n.

Miguel, O. d. P. .. et al., 2024. Comparative Analysis of SWAT and HEC-HMS Models for Efficient watershed managemnt. *RGSA – Revista de Gestão Social e Ambiental,* 8(11), pp. 1-16.

Mohamoud, Y., 2004. *Comparison of Hydrologic Responses at Different Watershed Scales,* Athens, Georgia: U.S. Environmental Protection Agency.

Mohan, P., Ghose, M. K. & Yash, R. K., 2012. Automatic Association of Strahler's Order and Attributes with the Drainage System. *International Journal of Advanced Computer Science and Applications.,* Volume 3(.8).

Nyssen, J. et al., 2010. Impact of soil and water conservation measures on catchment hydrological response: A case in north Ethiopia. *Hydrological Processes,* pp. 1-35.

Patricia, J.-S., Pablo, B.-G., Julio, P.-S. & José, M., 2021. Impact Assessment of Gridded Precipitation Products on Streamflow Simulations over a Poorly Gauged Basin in Streamflow Simulations over a Poorly Gauged Basin in. *MDPI Water,* Volume 13, pp. 1-21.

Richard, H. C., 2005. *Analysis and Design of Surface Irrigation Systems. UNESCO-IHE Land and Water Development Course.,* Delft: UNESCO_IHE.

Ridolfi, E., Kumar, H. & Bárdossy, A., 2018. A methodology to estimate flow duration curves at partially ungauged basins. *Hydrology and Earth system science,* Volume 4, pp. 1-30.

Sitterson, J. C. K., Kurt, P., Muluken, W. & Brian, M., 2017. An Overview of Rainfall-Runoff Model Types. *U.S. Environmental Protection Agency, Office of Research and Development, Oak Ridge Institute for Science and Education. Natural Research laboratory.*

Smith, T. J., 2008. *A Conceptual Precipitation - Runoff Modeling Suite: Model selction, Calibration and Predictive uncertaininty Assessment.* Bozeman, Montana: MONTANA STATE UNIVERSITY.

Sowmiya, S. & Carolin, A., 2017. Simulation of Runoff for an Agricultural Watershed Using SWAT Model. *International Journal of Innovative Research in Science, Engineering and Technology,* 6(6), pp. 11505-11512.

Yihun, D., Srinivasan, R. & Chris, G., 2023. *QGIS Interface for SWAT+: QSWAT+ Step-by-Step Setup for the Robit Watershed, Lake Tana basin.* Texas: University of Texas.

Yuguo, H., Gary, F. & Ying, O., 2018. 22. Yuguo, H., Gary, F., and Effects of Soil and Water Conservation Practices on Runoff, Sediment and Nutrient Losses. www.mdpi.com/journal/water. *www.mdpi.com/journal/water.*