Vol. 6 (Iss. 1) 2025, pp. 99-112 African Journal of Empirical Research https://ajernet.net ISSN 2709-2607

Simulating the Influence of Rainfall Variability on Discharge in the Upper River Yala Basin, Kenya

Miima Winstone Atamba[1]
Veronica Kiluva Mwikali[2]
Wekulo Saidi Fwamba[3]

[1]atambam@yahoo.com
[2]vkiluva@mmust.ac.ke
[3]fwamba05@gmail.com

[1]https://orcid.org/0009-0009-5814-8191
[2]https://orcid.org/0000-0002-2369-8654
[3]https://orcid.org/0009-0007-0931-4347

[1,2,3]Masinde Muliro University of Science and Technology, Kenya

https://doi.org/10.51867/ajernet.6.1.10

……

ABSTRACT

Climate variability is significantly altering river flows globally, increasing the risk of floods and droughts. Projections indicate both rising and declining flows across various regions, influenced by the impacts of climate variability and land use changes. Research has shown that climate change, land use, and pollution exacerbate water scarcity for half the global population, impacting ecosystems, especially in vulnerable regions. This study focuses on the Upper Yala River in Kenya, exploring climate variability's influence on discharge in various Land Use contexts using the SWAT model. Existing research highlights the significance of land use, hydrological indicators, and climate data, establishing a framework to analyze stream flow trends. The study analyzed climate and stream flow data from 1990-2020 using the SWAT model for hydrological assessment and predictions for the years 2024 to 2040 was done. The research was guided by Water Balance Theory and employed a descriptive and analytical design. Data collection included meteorological data from weather stations, hydrological data from gauging stations, and land use and land cover (LULC) data from remote sensing and satellite imagery. The Soil and Water Assessment Tool (SWAT) was used to simulate river discharge and assess the impacts of climate variability, integrating climate, land use, soil type, and topographic data. Data analysis involved descriptive statistics to summarize discharge data, correlation analysis to link rainfall variability and discharge patterns, and performance metrics like the Nash-Sutcliffe Efficiency (NSE) and Coefficient of Determination (R^2) to validate the model. Statistical techniques identified long-term trends in climate and streamflow, focusing on inter-seasonal and inter-annual variations. The Upper Yala River Basin experiences significant inter-seasonal and inter-annual streamflow variations, primarily influenced by rainfall fluctuations. A strong correlation between simulated and observed discharge data for the Upper Yala River Basin was demonstrated. The mean observed discharge was 48.69 m^3/s, with maximum and minimum values of 163.09 m^3/s and 0.328 m^3/s, and a standard deviation of 34.28 m^3/s. In contrast, the simulated discharge had a mean of 53.56 m^3/s, with maximum and minimum values of 174.41 m^3/s and 0.360 m^3/s, and a standard deviation of 37.87 m^3/s. The minimal differences between the observed and simulated values underscore the model's effectiveness in accurately reflecting the impacts of rainfall variability on river flow dynamics. The study concluded that in the Upper River Yala watershed, rainfall variability accounted for 94.2% of the variations in river discharge quantity. The study recommends enhancing climate monitoring by adding weather stations and stream gauges in the basin and utilizing remote sensing for tracking land use and vegetation changes. Improved data availability from these measures will enable better discharge predictions and inform water management decisions to mitigate climate impacts on the river basin and surrounding communities.

Keywords: Annual Low Flow, Climate Variability, SWAT Model, Watershed

……

I. INTRODUCTION

Global warming is increasing the risk of significant ecological changes in river flows worldwide. For every 1.0°C rise, about 21.4% of model simulations show medium-high risk of change in high flows, and 22.4% in low flows (Intergovernmental Panel on Climate Change [IPCC] (2014). These risks rise substantially with 3.0°C warming, particularly affecting low flows in regions like South America, southern Africa, Australia, southern Europe, and parts of the USA (Thompson *et.al*,. 2021). Climate change introduces new water management challenges globally, impacting water availability, allocation, and adaptation needs. Global climate models (GCMs) predict changes in stream flow and hydrology that align with observed global warming trends. Climate change is anticipated to impact future river flows globally, raising concerns not only due to potential increases in flood and drought events but also because of the effects on water quality, erosion, river morphology, and ecosystems (IPCC, 2014). In the Vakhsh River basin of Central Asia, projections for 2099 indicate a rise in median and high flows, though low flows may decrease.

Hydrological model simulations suggest average annual stream flow could increase by 17.5% to 52.3% under different climate scenarios (Tessema *et.al.*, 2021).

Climate change is expected to significantly alter river flows in multiple regions. In Thailand, changes in Mun River flows could impact agricultural water needs, increasing uncertainty and complicating local water management (Li & Fang, 2021). In the Upper Indus Basin, an overall rise in future stream flows is projected, while Lebanon's El Kalb River may see a 28–29% reduction in annual discharge by 2040 (Khan *et.al.*, 2020). In Britain, river flow simulations predict sharp summer decreases (up to 45% by 2080) but potential winter increases, particularly in the north and west. High-flow projections vary due to regional factors, with some catchments in Britain experiencing increased heavy precipitation without necessarily leading to higher flood flows (Kay, 2021). New Zealand's river hydrology shows rising mean annual floods in the south and variable low flows, which have significant implications for societal and environmental well-being (Collins, 2020). In the USA-Mexico Santa Cruz River Basin, projections indicate a drier future with reduced precipitation and sharp streamflow declines (87.6% in winter and 63% in summer). Near-term projections in the U.S. suggest an increase in major flood events (2.9%–8.1% in Connecticut, 9.9%–13.7% in the Merrimack River), guiding floodplain management strategies (Shamir *et.al.*, 2021). Canada has seen increased average precipitation since the 1950s, with regional variations in flow stability and distribution changes, indicating a need for substantial water management investment to sustain agriculture (Bhatti *et.al.*, 2021).

The Upper Yala River Basin in Western Kenya is vital for agriculture, water supply, and biodiversity. However, rainfall variability, influenced by both natural and human factors, significantly affects the basin's hydrology. Changes in climate, urbanization, and land use have led to unpredictable rainfall patterns, impacting river discharge and water availability for domestic, agricultural, and industrial use. The increasing occurrence of extreme weather events, such as droughts and heavy rainfall, raises concerns about water security. This study aims to simulate the impact of rainfall variability on river discharge patterns in the basin using hydrological models, with a focus on identifying trends and potential future scenarios to inform water management strategies and support local communities.

1.1 Statement of the Problem

River Yala is one of the key tributaries of Lake Victoria, exhibiting high fluctuation rates during wet and dry periods. It experiences relatively fast runoff due to intense and prolonged rainfall. The increasing frequency of extreme weather events has significantly influenced stream flow variations, affirming the strong correlations between Lake Victoria tributary inflows and precipitation (Paul & Oppelstrup, 2020). Discharge projections for River Yala over the coming decades show no apparent systematic trends. Instead, the projected discharge trajectories suggest marked inter-annual variations, regardless of the Representative Concentration Pathway (RCP) scenarios. These variations are primarily observed in the timing and magnitude of discharge peaks and lows (Olaka *et al.*, 2019). A simulation of rainfall-runoff interactions in the mid-block of the River Yala catchment revealed a strong correlation with rainfall trends. However, the effect of these interactions on the river's hydrological characteristics remains insufficiently explored (Odiero, 2019). The upper River Yala catchment is characterized by medium-gradient hills, wetlands, and floodplains. The soil texture predominantly consists of silty clay to clay, which influences its hydrological response (Olale *et al.*, 2019). The Kenyan government has proposed constructing the Keben Dam at the confluence of the Kimondi and Mokong' tributaries within the upper River Yala catchment. This project aims to supply treated water to nearby towns and establish a small-scale hydropower system. However, there is a need to simulate the catchment's hydrological aspects under varying climate conditions to assess potential impacts effectively (Jared, 2018). Despite the importance of River Yala, limited information exists on the impact of climate variability on the discharge of the upper River Yala Basin, Kenya. Addressing this knowledge gap is crucial for effective water resource management and adaptation to climate change.

1.2 Research Objective

The objective of this study was to model the influence of rainfall variability on discharge in the Upper River Yala Basin, Kenya.

1.3 Research Question

How does simulated rainfall variability influence river discharge in the Upper River Yala Basin, Kenya?

II. LITERATURE REVIEW

2.1 Theoretical Review

2.1.1 Water Balance Theory

The Soil and Water Assessment Tool (SWAT) model is primarily based on the water balance theory which was first formally advanced by C.W. Thornthwaite in 1948 as part of his work on climate classification and hydrology and applies hydrological, soil, and agricultural theories to simulate water, nutrient, and sediment dynamics in watersheds. It integrates several scientific principles to model the complex interactions within a watershed, focusing on predicting the impact of land management practices on water, sediment, and agricultural chemical yields. This theory enables SWAT to model hydrological processes by tracking the movement of water through different phases in the watershed (Arnold *et al.,* 1998).

2.2 Empirical Review

In a study by Pörtner *et al.* (2022), they highlighted that around half the world's population faces severe water scarcity for at least one month annually, largely due to climate change, land use changes, and water pollution. These factors drive ecosystem degradation, particularly affecting culturally significant species and ecosystems in the Arctic, mountainous areas, and biodiversity hotspots. Building on these general observations, the current study narrows its focus to assess climate variability impacts on tropical river catchments, specifically the Upper Yala River in Kenya. Abbas *et al.* (2022) found that climate variability adversely impacts water resources more than any other factor, especially by altering surface runoff in watershed hydrology, which is projected to worsen in future scenarios. This study aims to address a regional knowledge gap by exploring and modeling the influence of climate variability on the Upper Yala catchment's discharge, providing local insights into watershed impacts.

The World Water Program (2019) noted that water is a medium for many climate-related societal impacts, affecting sectors like energy, agriculture, health, and transportation. Climate change poses risks to freshwater ecosystems by disrupting stream flow and water quality, complicating drinking water treatment. However, knowledge gaps in understanding the temporal and spatial effects of climate change on hydrological cycles persist, particularly at decision-making levels—a gap this study seeks to fill for the Upper Yala catchment. Pokhrel *et al.* (2021) projected a global decline in Terrestrial Water Storage (TWS) by the mid- and late-twenty-first century, especially in the Southern Hemisphere, the U.S., Europe, and the Mediterranean, while Eastern Africa may experience TWS increases driven primarily by climate factors. While broader in scope, this study narrows in on climate variability's effect on river discharge in an East African tropical river basin, contributing focused data for the Upper Yala.

According to Peters-Lidard *et al.* (2021) seventeen indicators of the water cycle and management to assess climate change impacts on stream flow were identified. These indicators, including annual flow volume, high and low flows, and flow timing, capture different climate-sensitive aspects of the water cycle. Key metrics like maximum 3-day high flows can signal flood risks, while 7-day low flows reflect dry spells that affect water supply and environmental health. This study builds on these indicators to assess climate variability impacts on discharge in Kenya's Upper Yala River catchment. Bai *et al.* (2019) studied land use and climate change impacts on water-related ecosystem services in Kentucky, USA. The finding showed that climate change had more influence on water retention, while land use changes impacted soil retention and nutrient export. Recognizing the importance of land use, the current study will incorporate land use, soil maps, and digital elevation models in the SWAT model to evaluate their effects on river Yala's discharge.

In a study conducted by Pujiono *et al.* (2021) who investigated climate variability in Indonesia's Noelmina watershed, revealing increased temperatures and reduced precipitation, using these indicators to measure climate variability—a method similarly applied in this study with climate data from the Upper Yala catchment. Bismark *et al.* (2021) combined meteorological and remote sensing data with surveys to capture farmer perceptions of climate variability in Ghana's Lower Offin River Basin, which aligned with observed trends of rising temperatures, prolonged droughts, and changes in rainfall timing. This study adopts similar approaches by analyzing gauging station data to understand climate variability's impact on Upper Yala discharge.

In a global analysis conducted by Gudmundsson *et al.* (2019) on stream flow trends using data from over 30,000 sites, examining low, average, and high flows. They found that stream flow trends had complex spatial patterns, making generalizations difficult, and that regional trends often obscured sub-regional variations. Recognizing these insights, the current study investigates stream flow changes in Kenya's Upper Yala catchment within the context of climate variability. Domínguez-Tuda & Gutiérrez-Jurado (2021) assessed hydrologic sensitivity to climate variability, emphasizing that topography—particularly high elevations and steep slopes—amplifies hydrologic responses. Building on this, the current study incorporates elevation to forecast climate variability impacts on the Yala River discharge.

A study by Zhang *et al.* (2020) on climate change and anthropogenic impacts on stream flow in a tropical basin in China, finding precipitation to be the most influential climate factor, with anthropogenic activities significantly affecting stream flow variation. Their study highlighted the greater variability of annual maximum (Amax) and minimum (Amin) stream flows over average flow. Addressing these findings and gaps, this study uses the SWAT model to evaluate land use impacts alongside climate variability on the Yala catchment's discharge. Chakilu *et al.* (2020) examined future climate impacts on the Upper Blue Nile Basin's stream flow under Representative Concentration Pathway (RCP) scenarios using the SWAT model, observing temperature and stream flow increases under RCP 2.6, RCP 4.5, and RCP 8.5 scenarios. Similarly, this study applies SWAT modeling to estimate the effects of climate variability on the Upper Yala catchment discharge, contributing a localized understanding of climate impacts on tropical river systems in Kenya.

In another study by Quansah *et al.* (2021) using the SWAT model to project mid- and late-21st-century climate impacts on stream flow in the Alabama River basin. Results showed fluctuations in mean monthly discharge and increased frequency and variability of peak flows, with spring and autumn seeing flow increases of 50%-250%, while summer flows decreased. Building on this, the current study models climate variability effects on the Yala River in Kenya. Mendez *et al.* (2022) examined climate change impacts on five tropical catchments in Costa Rica, using the Generalized Rational Model (GR2M) to highlight seasonal shifts in precipitation and temperature, which led to significant variation in future stream flow. Despite similarities with the tropical Yala catchment, this study uses the SWAT model to analyze current and future climate variability effects.

Similarly, Shrestha *et al*, (2021) studied 19 basins across South and Southeast Asia, showing projected increases in temperature (1.5–7.8 °C) and precipitation (−3.4 to 46.2%) by century's end, leading to an increase in river flow (−18.5 to 109%). This study processed geospatial and meteorological data in SWAT, a methodology applied here to simulate the discharge in the Yala catchment. Rickards *et al.* (2020) projected intensified monsoon flows in India's Upper Narmada Basin due to climate change, using the Groundwater and Surface Water Assessment (GWAVA) model, and noted increased dry season water stress due to rising demand. In comparison, the current study will use climate models and SWAT to assess climate impacts on Yala's discharge. Sok *et al.* (2022) evaluated future climate impacts on Cambodia's Sen River using SWAT with RCP2.6 and RCP8.5 scenarios, showing lower maximum and minimum flows than baseline levels, and reduced low-flow event frequency. The current study will adopt a similar SWAT-based approach but will focus on different time frames and geographical settings specific to the Yala River in Kenya.

III. METHODOLOGY

The Yala River basin spans 3,351 km² with elevations from 1,200 m in the lowlands to 2,200 m in the highlands. Originating from the Nandi Escarpment, the 219 km river flows through Kakamega and Siaya counties before emptying into Lake Victoria at Winam Gulf, contributing about 4.8% of its surface inflow with an average annual discharge of 37.6 m³/s (1950–2000 data). Predominant land uses in the upper basin include settlements, tea and coffee plantations, crop farming, and grazing. The area features well-drained, deep humic Nitisols in the uplands and midlands, with annual rainfall varying from 850 mm near Lake Victoria to 2,000 mm in the highlands. This study adopts a quantitative, modeling-based research design. The research employs a combination of hydrological modeling techniques and statistical analysis to simulate and assess the influence of rainfall variability on river discharge in the Upper Yala River Basin. The study analyzed climate and stream flow data from January 1990 to December 2020 for the upper Yala River catchment, focusing on temperature and precipitation due to data availability and reliability. Climate data was sourced from the Kenya Meteorological Department, and stream flow data from a gauging station at the basin's outlet was used to calibrate and validate the SWAT model. Spatial data, including a 30m resolution DEM, soil maps, and land use/land cover images, were obtained from United States Geological Survey (USGS) and Food and Agriculture Organization (FAO) resources. Trend analysis of climate variables from 2000 to 2019 was conducted using the Mann-Kendall test, chosen for its robustness with missing values and outliers, applying a 5% significance level. The study examined stream flow patterns under varying climate scenarios, utilizing SWAT for its efficiency and minimal input requirements in semi-distributed hydrologic modeling.

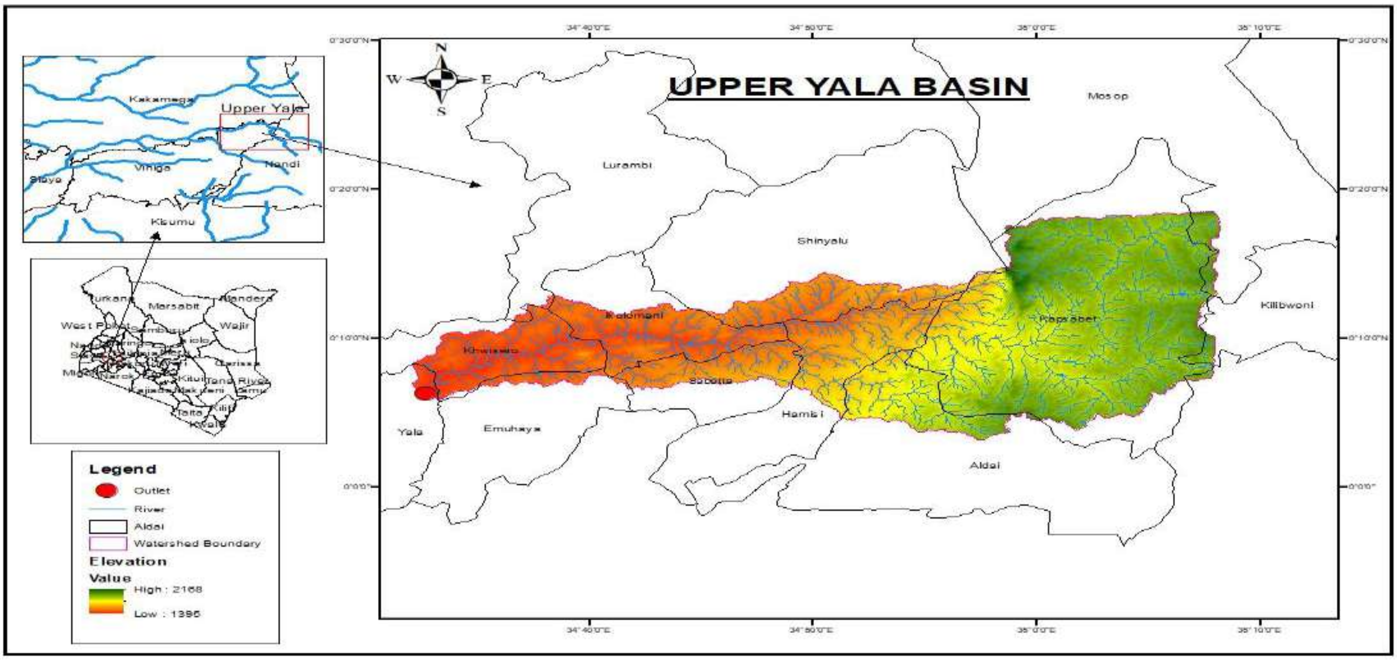

Figure 1

Map of the Study Area

IV. FINDINGS & DISCUSSION

4.1 SWAT Model Results

The study identified eighteen parameters for sensitivity analysis in modeling discharge in the Upper Yala River watershed, guided by findings from previous SWAT studies. Table 1 presents these parameters along with t-statistics, p-values, and rankings based on their sensitivity. The five most sensitive parameters, which greatly influence discharge, were further analyzed using the SUFI-2 procedure in SWATCUP, providing fitted, minimum, and maximum values for each. These parameters were ranked according to their sensitivity to refine the SWAT model calibration.

Table 1

Parameter Sensitivity Analysis

Parameter	Description	Range	t-stat	p-value	Rank	Fitted value
CN2.mgt	runoff curve number for moisture condition II	35-98	15.829	0.0001	1	61
SHALLST.gw	Initial depth of water in the shallow aquifer [mm]	0-5000	5.001	0.0001	2	102
GW_SPYLD.gw	Specific yield of the shallow aquifer [m3/m3]	0-0.5	4.475	0.0001	3	0.135
RCHRG_DP.gw	Deep aquifer percolation fraction [fraction]	0-1	4.345	0.0005	4	0.008
GWQMN.gw	Threshold depth in the shallow aquifer required for return flow (mm)	0-5000	4.167	0.00012	5	47.45
CH_N2.rte	Manning's n value for main channel	0.01-0.3	4.125	0.0017	6	0.099
SOL_AWC.sol	Soil available water storage capacity [mm H2O/mm soil	0-1	4.121	0.0019	7	0.192
GW_DELAY.gw	Groundwater delay time [days]	0-500	3.95	0.0021	8	31
SURLAG.bsn	Surface runoff lag time [days]	0-25	3.857	0.0032	9	1.67
ESCO.bsn	Soil evaporation compensation factor	0-1	3.501	0.0045	10	0.35
CH_K2.rte	Effective hydraulic conductivity in the main channel [mm/h]	0.01-500	3.369	0.0125	11	0.082
EPCO.hru	Plant uptake compensation factor	0-1	3.091	0.0183	12	0.921
ALPHA_BF.gw	Base flow alpha factor [days]	0-1	3.065	0.0395	13	0.46
SOL_K.sol	Saturated hydraulic conductivity [mm/h]	0-2000	2.941	0.0592	14	25.79
GW_REVAP.gw	Groundwater revap. coefficient	0.01-0.2	1.902	0.1269	15	0.08
DEEPST.gw	Initial depth of water in the deep aquifer [mm]	0-10000	-1.762	0.1324	16	2273
REVAPMN.gw	Threshold depth of water in the shallow aquifer for 'revap' to occur (mm)	0-1000	1.532	0.2941	17	1.79
CANMX.hru	Maximum canopy storage [mm]	0-100	0.941	0.691	18	29

To improve alignment between actual and predicted discharge levels, the SWAT model calibration process involved adjusting sensitive parameters within permissible limits. In the sensitivity analysis using SWAT_CUP's SUFI-2 method, the SCS runoff curve number (CN2) was the most sensitive parameter, while maximum canopy storage (CANMX.hru) was the least sensitive. Uncertainty analysis showed satisfactory p-factor (0.61) and r-factor (0.69) values. Calibration and validation yielded a Coefficient of Determination (R^2) of 0.86 and 0.79, and Nash-Sutcliffe Efficiency values of 0.83 and 0.76, respectively, indicating close spatiotemporal agreement between observed and simulated streamflow patterns.

4.2 Modelling of Stream Flow (Calibration Period)

The SWAT Model provided results in a statistical format, which were further analyzed using Excel to create graphs illustrating the simulations of river discharge and climate variability. A warm-up period of two years was implemented during the calibration and validation phases. Calibration utilized rainfall data from 1990 to 2006, while validation used data from 2007 to 2019. Following validation, the model was run to generate output for river discharge and climate variability in the upper Yala River catchment from 2024 to 2043, with the overall modeling period spanning from January 1, 1990, to December 31, 2043. The calibration process focused on stream flow data from 1990 to 2006, comparing observed versus simulated data for each parameter under examination as shown in Figure 2.

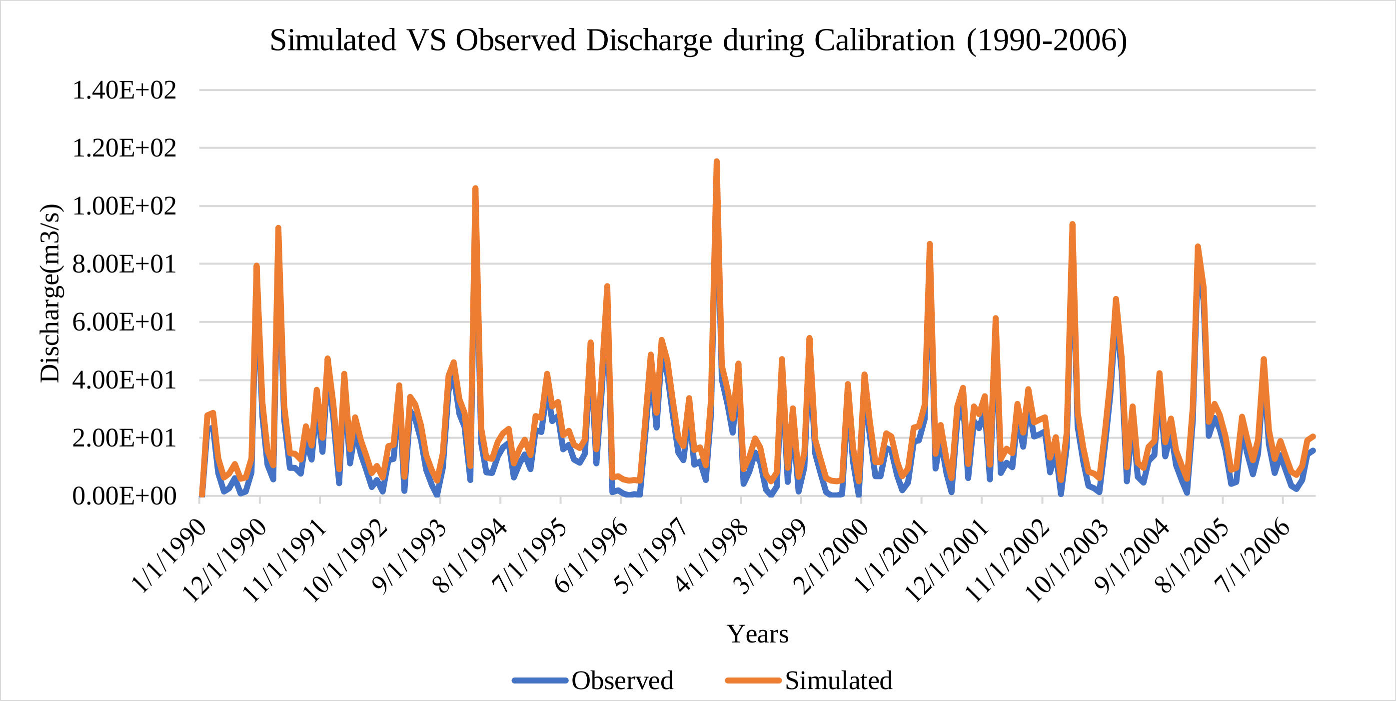

Figure 2

Comparison between Observed and Simulated River Discharge in the Period of 1990-2006 during the Calibration Process in the Upper Yala Catchment

During the calibration period from 1990 to 2006, there was a strong correlation between observed and simulated river discharge measurements in the upper Yala River catchment, with only minor variations between the datasets. The model demonstrated effective simulation of river discharge, achieving a Pearson's correlation coefficient (r) of 0.92, indicating it is a reliable predictor of river discharge in the area. Additionally, a coefficient of determination (R^2) of 0.87 further confirmed the strong relationship between the simulated and observed discharge data during this period.

4.3 Modelling of Stream Flow (Validation Period)

The model validation process utilized stream flow data to compare observed and simulated river discharge values for the period from 2007 to 2019. This comparison aimed to validate the accuracy of the results obtained for river discharge and climate variability, ensuring the model's reliability in predicting stream flow during this timeframe as shown in Figure 3. The validation process for the SWAT model in the Upper Yala catchment demonstrated strong performance, with a Pearson's correlation coefficient (r) of 0.99 and a coefficient of determination (R^2) of 0.98, indicating a very high relationship between observed and simulated river discharge values. While there were slight discrepancies in some years, the overall agreement was notable, with an R^2 of 0.94 reflecting minimal variation between datasets. Both the calibration and validation periods yielded strong correlation values above 0.7, confirming the accuracy of the model. Although groundwater percolation contributed to some flow loss, the findings indicate that the SWAT model is an effective tool for estimating streamflow in the Yala River.

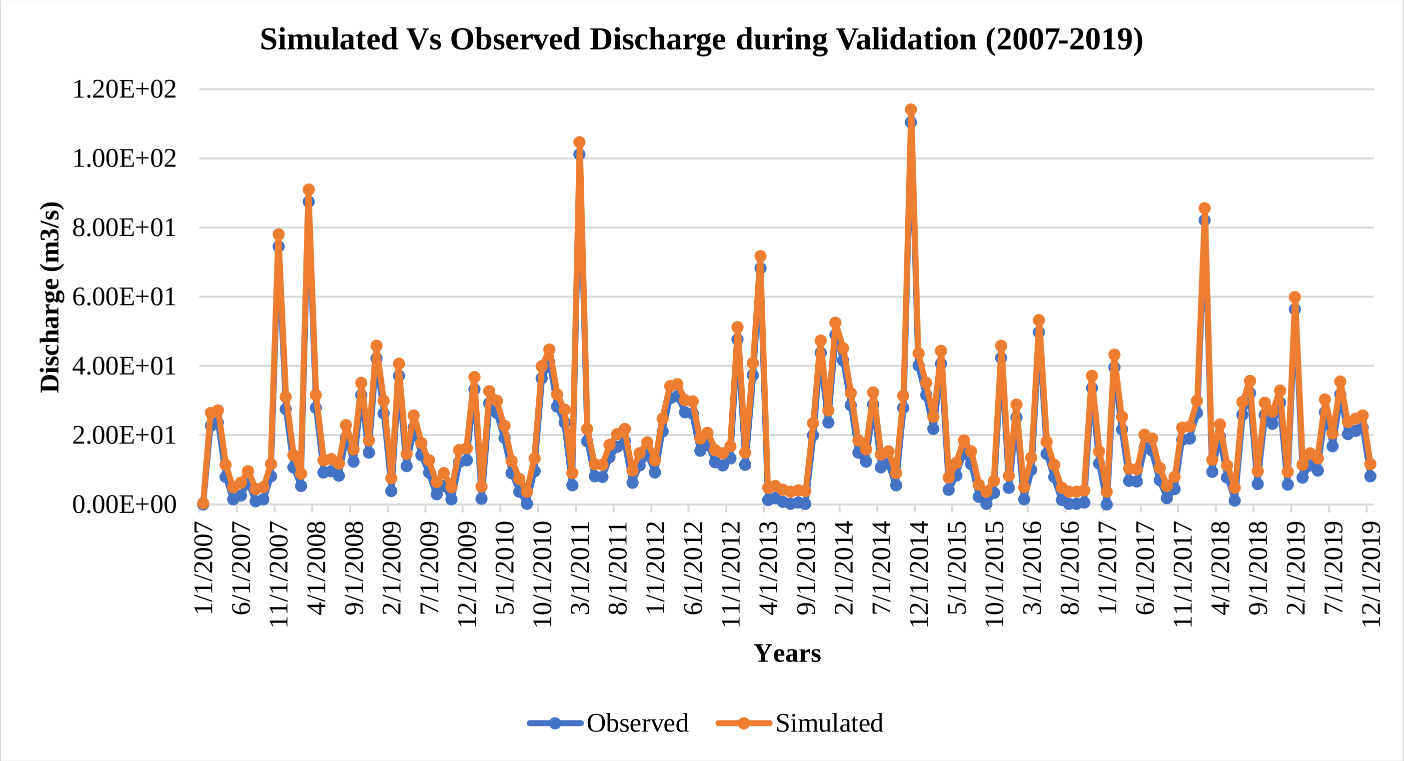

Figure 3

Comparison between Observed and Simulated River Discharge during Validation Process in the Period of 2007-2019 in the Upper Yala Catchment

4.4 Simulating the influence of rainfall variability on discharge in the Upper River Yala Basin

4.4.1 Trends of Rainfall Variability and River Discharge

A time series plot of rainfall and discharge for the period between 1990 and 2020 is as shown in Figure 4. Rainfall variability is a critical factor influencing river discharge in the Upper Yala Basin, characterized by complex interactions with various hydrological and environmental elements. The basin is highly dependent on seasonal rainfall, making it sensitive to changes in rainfall patterns. The mean observed rainfall during the study period was 118.184 mm, with significant variability (maximum of 474 mm, minimum of 0.8 mm, and a standard deviation of 86.94 mm). Correspondingly, the mean river discharge was 48.45 m³/s, with a maximum of 194.34 m³/s, a minimum of 0.328 m³/s, and a standard deviation of 35.64 m³/s. Higher rainfall and discharge levels typically occur between March and May during the long rainy season, while lower values are recorded from October to December during the short rains. The lowest discharge and rainfall were noted during the dry months of January, February, and June in certain years. Rainfall distribution varies across the basin due to topographic influences, with higher elevations receiving more precipitation, affecting total runoff. Observations indicate shifts in the timing, intensity, and duration of rainy seasons, likely attributable to climate change, which directly impacts river discharge. These findings align with the research by Mastrorillo *et al.* (2016), highlighting increased frequency and intensity of extreme rainfall events in the African Great Lakes region, and with Kibret *et al.* (2020), who noted that variability in rainfall and temperature significantly influences river flow patterns in western Kenya, including the Upper Yala River Basin.

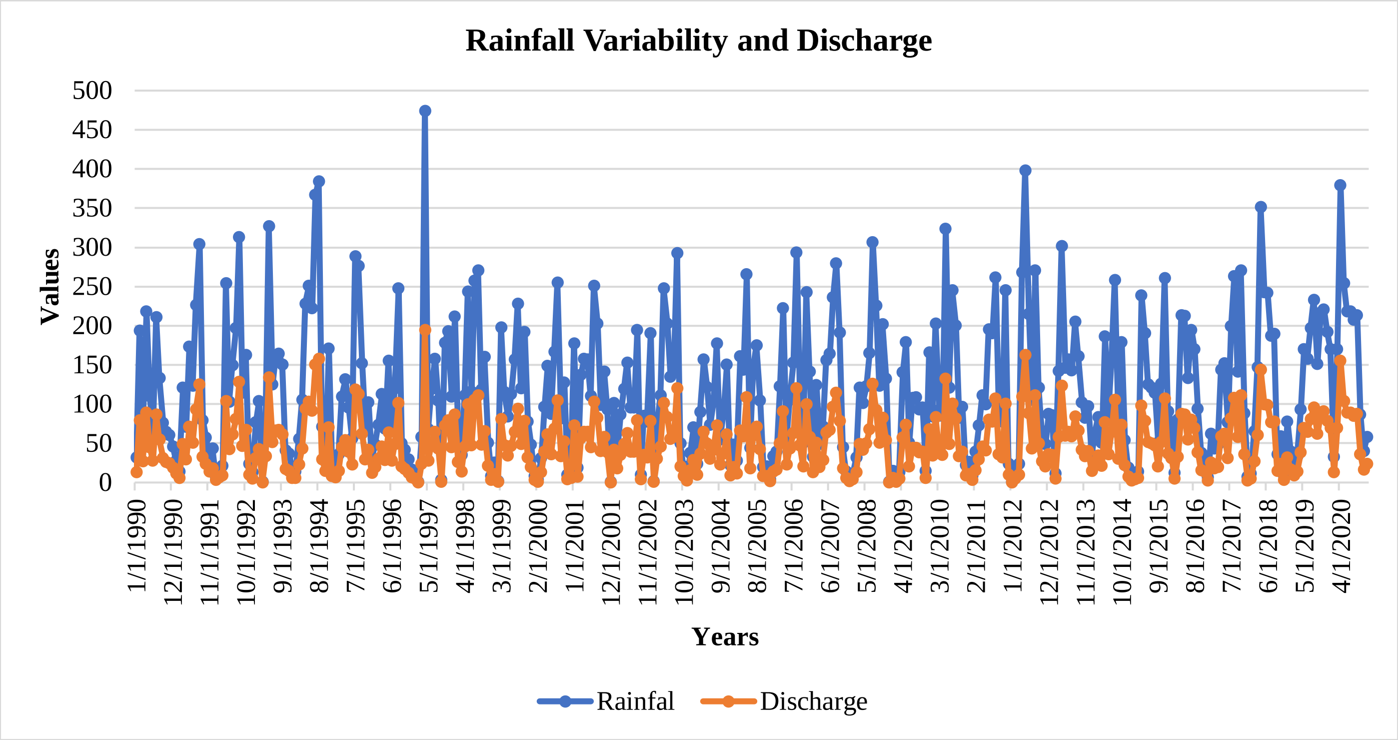

Figure 4
A Time Series Plot of Rainfall and River Discharge

4.4.2 Variability of Discharge in different gauging stations

The Upper Yala River Basin exhibits significant inter-seasonal and inter-annual variations in streamflow, primarily driven by fluctuations in climatic conditions, particularly rainfall. Analysis of streamflow data from January 2000 to December 2019 reveals notable differences in river discharge, particularly in the years 2007, 2008, and 2016. The year 2016 recorded the highest streamflow across the basin, with discharge peaking at 337 m³/s for the main Yala River, especially between April and June, aligning with the long rainy season. Conversely, lower streamflow was observed from January to March 2016, corresponding with the period of least rainfall, which typically occurs from December to February and often extends into March. This seasonal variability in streamflow mirrors the patterns of seasonal rainfall in the region.

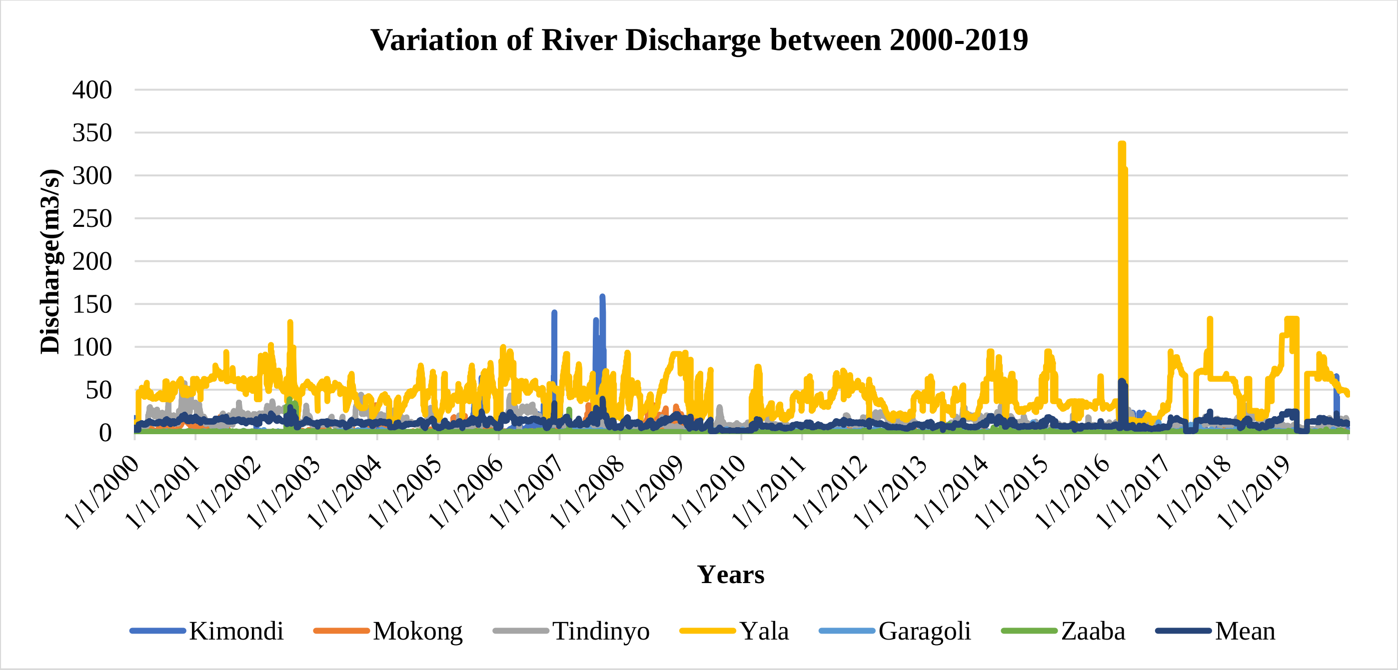

Figure 5
Variation of River Discharge in Different Gauging Stations

Analysis of streamflow data in the Upper Yala River Basin indicates notable changes in seasonal patterns, particularly concerning the short and long rainy seasons. Streamflow is generally higher during the short rainy seasons, with a significant extension observed, as discharge levels begin to rise earlier than usual, starting in August and peaking in October. Following this peak, streamflow declines rapidly until the February-March period. Conversely, streamflow during the traditional long rainy season (March-April-May) has been unusually low. These observed shifts in streamflow patterns are believed to be influenced by climate change. The short rainy season appears to be starting earlier (in July-August) and extending into February and March, while the dominance of the long rainy season is diminishing. Additionally, there are significant variations in discharge levels among the different rivers in the Upper Yala River Basin, indicating that no two rivers exhibit the same streamflow characteristics.

4.4.3 Double Mass Curve Analysis

The study employed a double mass curve analysis to assess the consistency of river discharge data from various monitoring stations. This involved plotting the cumulative river discharge data from the Tindinyo River Gauging Station (RGS) against the cumulative monthly averages from other stations within the study area. This method helps to identify any discrepancies or inconsistencies in the data collected from different sources, ensuring the reliability of the discharge measurements used in the analysis. The analysis resulted in a coefficient of determination (R^2) of 0.99 and a correlation coefficient (r) of 0.99, indicating a high level of consistency in river discharge data across all monitoring stations during the study period. This strong correlation confirms the reliability of the discharge measurements obtained from the various stations.

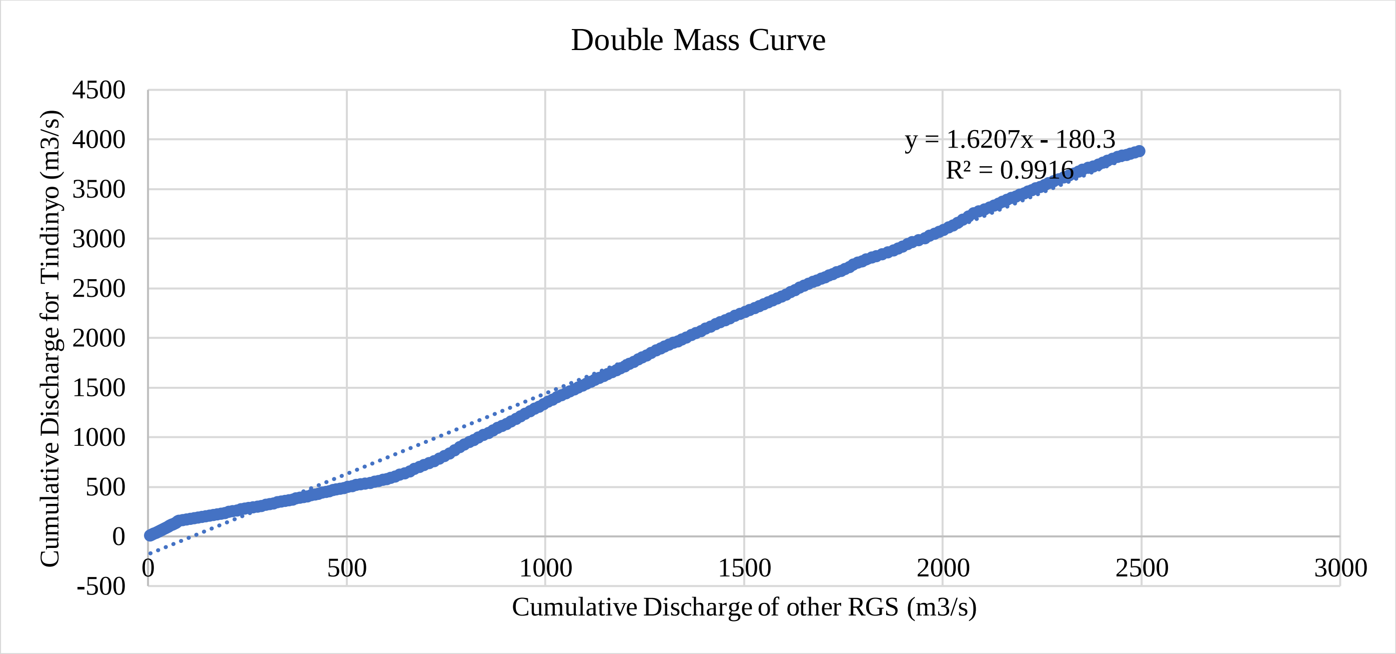

Figure 6

Double Mass Curve (DMC) Analysis for the Cumulated Discharge from Tindinyo and other RGS for Data Consistency Check in Upper Yala River Catchment

4.4.4 Modelling Rainfall Variability and Discharge of the Upper River Yala Basin

The study aimed to model rainfall variability and river discharge in the Upper River Yala Basin using SWAT simulations. Figure 6 presents the comparison between simulated and observed discharge values, illustrating the effectiveness of the model in capturing the relationship between rainfall patterns and river flow dynamics in the basin.

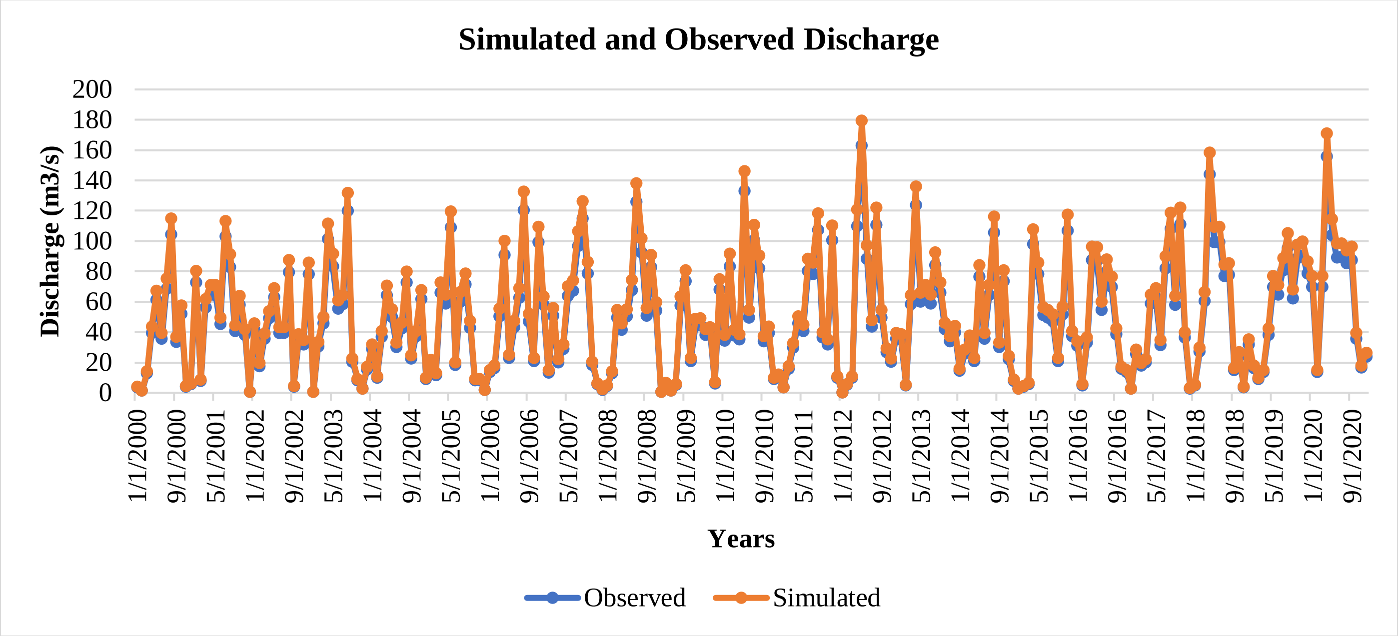

Figure 6
Simulated and Observed Discharge

Figure 6 illustrates a strong fit between the simulated and observed discharge data for the Upper River Yala Basin. The mean observed discharge was 48.69 m^3/s, with maximum and minimum values of 163.09 m^3/s and 0.328 m^3/s, respectively, and a standard deviation of 34.28 m^3/s. In comparison, the simulated discharge had a mean of 53.56 m^3/s, with maximum and minimum values of 174.41 m^3/s and 0.360 m^3/s, and a standard deviation of 37.87 m^3/s. The minimal differences between the observed and simulated discharge values indicate the model's effectiveness in capturing the impacts of rainfall variability on river flow.

4.4.5 Influence of Rainfall Variability on Discharge in the Upper River Yala Basin.

Regression analysis was conducted to assess the relationship between rainfall variability and river discharge, as presented in Table 2 This analysis aimed to quantify how changes in rainfall patterns impact the amount of discharge in the Upper River Yala Basin. The findings from this regression analysis provide insights into the extent to which fluctuations in rainfall contribute to variations in river flow, highlighting the importance of understanding these dynamics for effective water resource management and planning in the region.

Table 2
Regression Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.963[a]	.942	.939	27.234047815553860

a. Predictors: (Constant), Rainfall

Table 2 presents regression analysis results indicating a strong correlation (R = 0.963) between rainfall variability and river discharge in the Upper River Yala Basin. The coefficient of determination ($R^2 = 0.942$) suggests that 94.2% of the variance in river discharge can be explained by variations in rainfall, demonstrating a strong positive linear relationship between the two variables. The ANOVA statistics further support the significance of the regression model, with an F-value of 133.285 and a p-value less than 0.001, indicating a 0.0% probability of the model providing false information. This reinforces the model's robustness and significance in explaining the relationship between rainfall variability and river discharge.

Table 3
Analysis of Variance (ANOVA)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	405475.907	1	405475.907	511.865	.000[b]
	Residual	293096.980	370	792.154		
	Total	698572.887	371			

a. Dependent Variable: Discharge
b. Predictors: (Constant), Rainfall

The regression model established from Table 4 is expressed as:
Discharge = 49.348 + 0.614 * Rainfall

Table 4
Regression Coefficients

Model		**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**
		B	Std. Error	Beta		
1	(Constant)	49.348	6.880		8.048	.000
	Rainfall	.614	.936	.582	14.029	.000

a. Dependent Variable: Discharge

The regression analysis indicated that when rainfall is zero, the river discharge would be 49.348 m³/s. With the introduction of rainfall as an independent variable, river discharge increased by 0.614 m³/s for each unit of rainfall, a change that was statistically significant ($p < 0.000$). This underscores that rainfall variability has a positive and significant impact on river discharge at the 95% confidence level. In the Upper River Yala watershed, rainfall variability accounts for 94.2% of the variations in river discharge quantity, with a strong correlation coefficient of 0.963. This strong positive linear relationship suggests that fluctuations in rainfall are closely linked to changes in river discharge. The findings highlight that heavy rainfall events generate significant runoff during wet seasons, further emphasizing the critical role of rainfall variability in influencing river flow dynamics in the watershed.

Multiple studies have highlighted the significant relationship between rainfall variability and river discharge across various river basins. Zhang *et al.* (2020) found that increasing temperatures and precipitation were key factors in streamflow variations in the Heihe River Basin, China. Similarly, Sok *et al.* (2022) attributed rising runoff in the Minjiang River Basin to increased precipitation and reduced potential evaporation, while Njogu and Kitheka (2017) established a strong correlation ($r = 0.9$) between river discharge and rainfall in the upper Tana Catchment. Kitheka *et al*. (2019) noted a growing frequency of above-normal rainfall and discharges, emphasizing the complex interplay between these factors. Odiero (2019) also identified a direct link between rainfall variability and increased flood risks in the mid-block of River Yala Basin, advocating for improved flood management strategies.

4.4.6 Prediction of Future Trends in Rainfall and Stream Flow

The SWAT simulation for the Upper Yala River Basin was conducted to project rainfall and river discharge from 2024 to 2043, as depicted in Figure 7. The simulation results aim to provide insights into future hydrological patterns in response to anticipated climate conditions. The data generated through this simulation will help in understanding how changes in rainfall patterns may affect river discharge, which is crucial for water resource management and planning in the basin. The findings will serve as a basis for assessing potential impacts on flood risks, water availability, and overall hydrological dynamics in the Upper Yala River Basin.

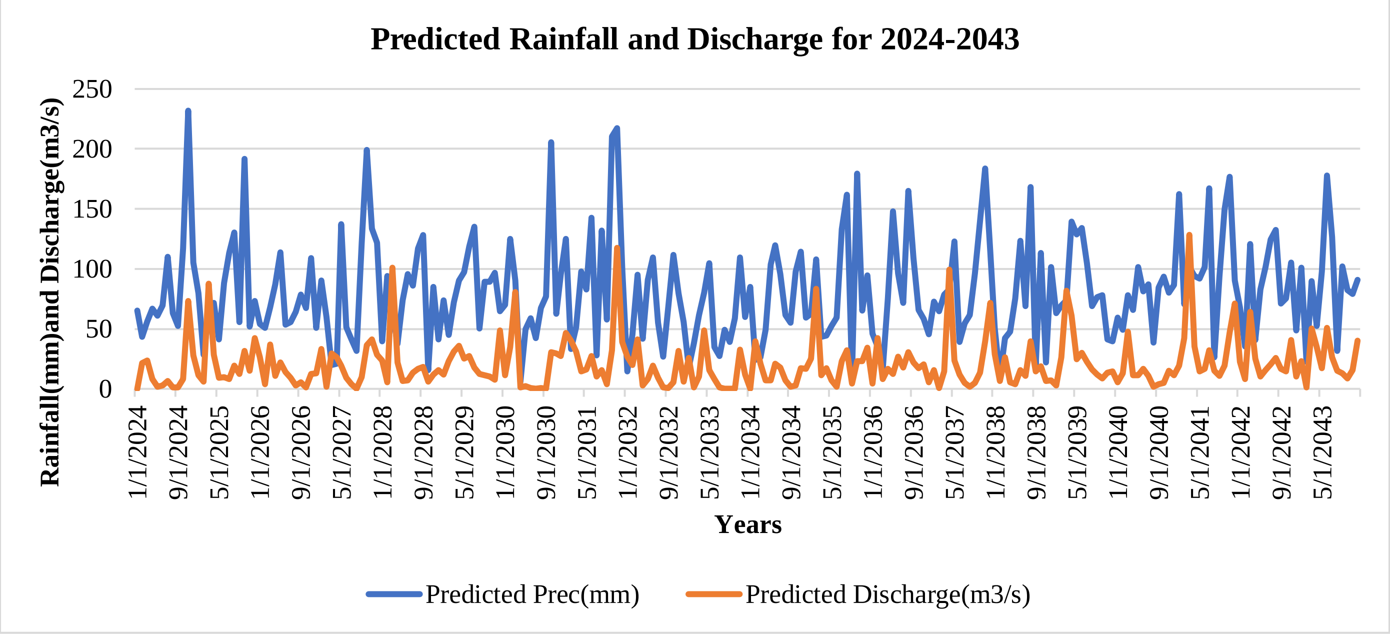

Figure 7
Annual Future Trends on Rainfall, River Discharge

Figure 7 indicates that climate models forecast increased rainfall variability in the Upper Yala River Basin due to climate change, characterized by both more intense rainfall events and prolonged dry periods. This variability is expected to result in significant spikes in river discharge, raising the risk of flash floods, while also enhancing soil erosion and sediment transport, negatively affecting water quality and aquatic habitats. The erratic seasonal rainfall patterns may disrupt the natural hydrological cycle, altering the timing and magnitude of river flows. Prolonged dry spells could lead to reduced river discharge during critical agricultural periods, complicating farmers' ability to predict optimal planting times and irrigation needs, thereby risking crop failures or reduced yields.

The region may face increased occurrences of both droughts and floods as a result of unpredictable rainfall patterns. Droughts could significantly diminish base flow, impacting water availability for drinking, agriculture, and ecosystems. Changes in land use, urbanization, and deforestation may further influence river discharge dynamics, necessitating adjustments to hydrological models to reflect these changing conditions. Future discharge trends may show a complex interplay between increased drought and flood conditions. If droughts become more frequent, low flow conditions may prevail, affecting water supply and ecosystem health. Conversely, a rise in intense rainfall events may elevate average discharge levels, influencing floodplain management practices. These projections align with findings from Shrestha *et al.* (2021), which highlighted that increased rainfall variability is expected to have profound implications for river discharge patterns, with models indicating an increase in peak discharge events during the rainy season and more pronounced low flow conditions in dry periods. To address these challenges, proactive measures such as improved infrastructure, adaptive water management, and community engagement will be essential for sustainable water resource management in light of climate change.

V. CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

In the Upper Yala River Basin, discharge patterns are highly sensitive to seasonal rainfall variability, with shifts in rainfall intensity and timing impacting river flow. Observed data show a mean discharge of 48.69 m^3/s, while the simulated model shows a slightly higher mean of 53.56 m^3/s. A strong correlation (94.2%) was identified between rainfall variability and discharge, indicating that nearly all discharge changes can be attributed to rainfall patterns. This high sensitivity to climate suggests that anticipated increases in extreme rainfall due to climate change could lead to more flash floods, soil erosion, and sediment transport, disrupting the hydrological cycle and affecting water quality, aquatic habitats, and agriculture.

5.2 Recommendations

The study recommends enhancing climate monitoring by adding weather stations and stream gauges in the basin and utilizing remote sensing for tracking land use and vegetation changes. Improved data availability from these measures will enable better discharge predictions and inform water management decisions to mitigate climate impacts on the river basin and surrounding communities. Furthermore, climate adaptation models that integrate hydrological responses to different climate scenarios (e.g., increased temperature, altered rainfall patterns) should be developed and applied. These models should also account for land use changes and their interactions with climate variability. Utilizing climate adaptation models will help stakeholders understand potential future impacts on river discharge and develop strategies to enhance resilience

REFERENCES

Abbas, M., Zhao, L., & Wang, Y. (2022). Perspective impact on water environment and hydrological regime owing to climate change: A review. *Hydrology, 9*(11), 203.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment: Part I. Model development. *Journal of the American Water Resources Association, 34*(1), 73-89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

Bai, Y., Zheng, H., Ouyang, Z., Zhuang, C., & Jiang, B. (2019). Impacts of land use and climate change on water-related ecosystem services in Kentucky, USA. *Science of the Total Environment, 6*(4), 133 https://doi.org/10.1016/j.scitotenv.2019.133640

Bhatti, A. Z., Farooque, A. A., Krouglicof, N., Li, Q., Peters, W., Abbas, F., & Acharya, B. (2021). An overview of climate change induced hydrological variations in Canada for irrigation strategies. *Sustainability, 13*(9), 4833.

Bismark, M. B., Wilson, A. A., Mexoese, N., & Samuel, A. K. (2021). Comparing farmers' perceptions of climate variability with meteorological and remote sensing data: Implications for climate-smart agriculture technologies in Ghana. *American Journal of Environmental Science and Engineering, 5*(4), 104-112.

Chakilu, G. G., Sándor, S., & Zoltán, T. (2020). Change in stream flow of gumara watershed, upper blue nile basin, ethiopia under representative concentration pathway climate change scenarios. *Water, 12*(11), 3046.

Collins, D. B. (2020). New Zealand river hydrology under late 21st century climate change. *Water, 12*(8), 2175.

Domínguez-Tuda, M., & Gutiérrez-Jurado, H. A. (2021). Global analysis of the hydrologic sensitivity to climate variability. *Journal of Hydrology, 3(8)*, 126.

Gudmundsson, L., Leonard, M., Do, H. X., Westra, S., & Seneviratne, S. I. (2019). Observed trends in global indicators of mean and extreme streamflow. *Geophysical Research Letters, 46*(2), 756-766.

Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Jared, O. O (2018). *Simulation of water supply and demand in Yala* (Doctoral dissertation, Masinde Muliro University of Science and Technology).

Kay, A. L. (2021). Simulation of river flow in Britain under climate change: Baseline performance and future seasonal changes. *Hydrological Processes, 35*(4), 141.

Khan, A. J., Koch, M., & Tahir, A. A. (2020). Impacts of climate change on the water availability, seasonality, and extremes in the Upper Indus Basin (UIB). *Sustainability, 12*(4), 1283.

Kibret, K., Seleshi, Y., & Fekadu, S. (2020). Rainfall and temperature variability influences river flow patterns in western Kenya: A case study of the Upper Yala River Basin. *Water, 12*(5), 1372. https://doi.org/10.3390/w12051372

Kitheka, J. U., Mwangi, S., & Mwendwa, P. K. (2019). The effects of rainfall variability and land use/land cover change in a small tropical river basin in Kenya. *International Journal of Hydrology, 3*(1), 307.

Li, C., & Fang, H. (2021). Assessment of climate change impacts on the streamflow for the Mun River in the Mekong Basin, Southeast Asia: Using SWAT model. *Catena, 2*(1), 105.

Mastrorillo, M., Rojas, C., & Pappenberger, F. (2016). The increasing frequency and intensity of extreme rainfall events in the African Great Lakes region. *Hydrology and Earth System Sciences, 20*(6), 2587-2602. https://doi.org/10.5194/hess-20-2587-2016

Mendez, M., Calvo-Valverde, L. A., Imbach, P., Maathuis, B., Hein-Grigg, D., Hidalgo-Madriz, J. A., & Alvarado-Gamboa, L. F. (2022). Hydrological response of tropical catchments to climate change as modeled by the GR2M model: A case study in Costa Rica. *Sustainability, 14*(24), 16938.

Njogu, J. M., & Kitheka, J. U. (2017). Correlation between river discharge and rainfall in the upper Tana Catchment. *Journal of Water Resource and Protection, 9*(5), 617-628. https://doi.org/10.4236/jwarp.2017.95039

Odiero, J. (2019). *Simulation of rainfall surface runoff-water quality effects on surface water bodies in mid-block of Yala* (Doctoral dissertation, Masinde Muliro University of Science and Technology).

Olaka, L. A., Ogutu, J. O., Said, M. Y., & Oludhe, C. (2019). Projected climatic and hydrologic changes to Lake Victoria Basin rivers under three RCP emission scenarios for 2015–2100 and impacts on the water sector. *Water, 11*(7), 1449.

Olale, K., Yenesew, A., Jamnadass, R., Sila, A., & Shepherd, K. (2019). A simple field-based method for rapid wood density estimation for selected tree species in Western Kenya. *Scientific African, 5*(1), 149.

Paul, S., & Oppelstrup, J. (2020). Hydro-meteorological processes driving solute transport in Lake Victoria. *Water Science, 34*(1), 18-31.

Peters-Lidard, C. D., Rose, K. C., Kiang, J., Strobel, M. L., Anderson, M., Byrd, A., Kolian, M., Brekke, L., & Arndt, D. (2021). Indicators of climate change impacts on the water cycle and water management. *Climatic Change, 165*(1–2), 11-23. https://doi.org/10.1007/s10584-021-03057-5

Pokhrel, Y., Felfelani, F., Satoh, Y., Boulange, J., Burek, P., Gädeke, A., & Wada, Y. (2021). Global terrestrial water storage and drought severity under climate change. *Nature Climate Change, 11*(3), 226-233.

Pörtner, H. O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., & Ibrahim, Z. Z. (2022). *Climate change 2022: Impacts, adaptation and vulnerability* (p. 3056). IPCC.

Pujiono, E., Prasetyo, B. D., Setyowati, R., & Kurniadi, R. (2021, October). Vulnerability assessment of water resources to climate variability in Noelmina watershed, Timor Island, Indonesia. In *IOP Conference Series: Earth and Environmental Science* (Vol. 874, No. 1, p. 012007). IOP Publishing.

Quansah, J. E., Naliaka, A. B., Fall, S., Ankumah, R., & Afandi, G. E. (2021). Assessing future impacts of climate change on streamflow within the Alabama River basin. *Climate, 9*(4), 55.

Rickards, L., Patel, P., & Vaidya, S. (2020). Climate change impacts on water resources in India's Upper Narmada Basin: Projections and implications for water stress. *Science of the Total Environment, 742*, 140460. https://doi.org/10.1016/j.scitotenv.2020.140460

Shamir, E., Tapia-Villaseñor, E. M., Cruz-Ayala, M. B., & Megdal, S. B. (2021). A review of climate change impacts on the USA-Mexico transboundary Santa Cruz River Basin. *Water, 13*(10), 1390.

Shrestha, S., Bae, D. H., Hok, P., Ghimire, S., & Pokhrel, Y. (2021). Future hydrology and hydrological extremes under climate change in Asian river basins. *Scientific Reports, 11*(1), 17089.

Sok, T., Ich, I., Tes, D., Chan, R., Try, S., Song, L., Ket, P., Khem, S., & Oeurng, C. (2022). Change in Hydrological Regimes and Extremes from the Impact of Climate Change in the Largest Tributary of the Tonle Sap Lake Basin. *Water*, *14*(9), 1426. https://doi.org/10.3390/w14091426

Tessema, N., Kebede, A., & Yadeta, D. (2021). Modelling the effects of climate change on streamflow using climate and hydrological models: The case of the Kesem sub-basin of the Awash River basin, Ethiopia. *International Journal of River Basin Management*, *19*(4), 469-480.

Thompson, J. R., Gosling, S. N., Zaherpour, J., & Laizé, C. L. R. (2021). Increasing risk of ecological change to major rivers of the world with global warming. *Earth's Future*, *9*(6), 179 https://doi.org/10.1029/2020EF001795.

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geographical Review, 38*(1), 55-94.

World Water Program. (2019). *Water and climate change: Impacts on sectors such as energy, agriculture, health, and transportation.* United Nations. https://www.unwater.org/publications

Zhang, Y., Li, X., Zeng, Z., & Li, C. (2020). Impact of climate change on water resource availability: A case study of the upper Yellow River Basin. *Water Resources Management*, *34*(5), 1417-1428.