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Article

Climate variability and river flow changes in Wundanyi sub-catchment of Taita Hills, Kenya

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Abstract: The Wundanyi sub-catchment of Taita Hills is experiencing a high rate of deforestation due to the conversion of all its original forestland to agriculture and settlement during the last century. The landscape dynamics coupled with rainfall fluctuations in these critical ecosystems may significantly affect water resource distribution and food security in Taita Taveta County and its environs. This study aimed to establish the trends of selected hydroclimatic variables in the Wundanyi sub-catchment from 1970 to 2030 and their specific and combined effects on surface runoff and streamflow during the same period. The analysis was based on statistical trend analysis and dynamic landscape modeling using both historical and primary hydroclimatic data from Wundanyi and Voi weather stations. Results show highly variable mean seasonal and annual values of temperature, rainfall, runoff, and discharge in both Wundanyi and Voi weather stations. Increasing mean temperatures and rainfall were observed during the long dry season (JJAS) while decreasing seasonal discharges were observed during both the JJAS dry season and the OND short rainy season. These anomalies were pronounced in 1980–1981, 1986–1987, and 1992–1993, probably due to both global and local environmental changes affecting Taita Hills in general and the Wundanyi sub-catchment in particular. The predicted effects of rainfall fluctuation were supported by declining surface runoff of 1.3% during JJAS, and an increase of 0.8% during the OND, with similar effects on river discharges. The combined effects of climate variability and land use and cover changes (LUCC) on surface runoff were estimated to increase by 200 mm during JJAS and 370 mm during OND, while river discharges increased by 2.37 m^3/s and 1.93 m^3/s during JJAS and OND, respectively. Consequently, natural forest covers have significant control effects on surface runoff and can boost river discharges amid diverse agricultural cropping practices. Hence, crop diversification, agroforestry, and soil and water conservation structures are recommended to maintain effective control of LUCC on hydrological processes going on in the Wundanyi sub-catchment.

Keywords: catchment management; climate variability; climate change; LUCC; river flow; seasonality; Taita hills

1. Introduction

Climate change and variability have critical implications for global precipitation and temperature levels, which intensify communities' vulnerability to water stress and poverty [1]. Close to a billion people reside in water-stressed countries. Africa bears much of the burden due to extreme climatic events related to changing global climate patterns [2]. Kenya is among the most water-stressed countries in the world, being ranked 152 out of 181 countries in the global vulnerability index as of the year 2019, making it one of the most vulnerable countries to climate change in Africa [3–5].

Temperatures countrywide have been rising steadily, while precipitation has been trending region-specific [6,7].

In Kenya, climate change-induced hydrological changes threaten the country's water availability [8], with nearly 23% of its population having no access to a water system [9]. According to Bernoux et al. [10], these extreme weather events may intensify challenges related to water availability and accessibility in the future due to the ongoing climate change on the African continent. Even though there are notable cross-country differences in exposure to global climate change [11], shifts in temperatures and precipitations may threaten most of the poor countries' vital climate variability indicators, with African countries being among the most exposed. The impacts of climate change on hydrological systems are, however, more pronounced in Sub-Saharan Africa [12]. Past research has established that fluctuations in the two main hydroclimate elements, notably temperatures and precipitations, account for substantial proportions of variations in surface runoff and streamflow thereof [13,14]. Water availability is thus a function of its hydrological processes, including surface runoff and streamflow [15]. These processes are, in turn, influenced by hydroclimatic variables, with temperatures and precipitations being the key among them [16,17]. Thus, climate variability has vital implications for water availability in a catchment area.

Focusing on Taita Hills, the region has been experiencing notable variabilities in its climate for the past decade [18]. Taita Hills, Kenya's sole representative of the Eastern Arc Mountains (EAM), is an important water tower in the country [19]. Although there is little empirical evidence available in this research area, the facts point out the significant effects of climatic variables on river flow regimes, flow rates, and surface runoff [20]. Few studies have assessed how changes in hydroclimatic variables influence surface runoff and streamflow in the Taita Hills. Yet, the sub-catchments surrounding the hills, such as Wundanyi, have been witnessing extreme hydroclimatic variabilities in the past decades [21]. These variabilities have critical implications for the region's hydrological processes. However, with this limited evidence on how these variabilities influence the hydrological cycle in Taita Hills, nobody can tell how rainfall fluctuation and changes in forest cover specifically affect the surface runoff and streamflow in the Wundanyi sub-catchment.

This study aimed to establish the trends of selected hydroclimatic variables in the Wundanyi sub-catchment and their specific and combined effects on surface runoff and streamflow during the same period. Using time series and multivariate models' analysis, the study offers valuable insights into past and predicted trends in key hydroclimatic variables influencing hydrological processes in the Wundanyi sub-catchment, with a focus on the influence of these variables on the catchment's surface runoff and streamflow using simulations for the period ranging between 1970 and 2030.

2. Materials and methods

2.1. Sampling methods and data collection

This study focused on Wundanyi, a medium sub-catchment of about 190 km^2, in the upper elevation of the Taita Hills. The study was recommended by the Climate

Change Impact on Ecosystem Services and Food Security in Africa (CHIESA) project for the EAM sites to account for Taita-Taveta's critical water towers and biodiversity hotspots. It relied on several primary and secondary hydroclimatic data sets, with supplementary data on streamflow and soil moisture near riverbanks in the Wundanyi catchment.

Secondary data on average monthly temperatures and total rainfall (daily and monthly) were provided by the Voi Kenya Meteorological Department (KMD) station, along with four Taita CHIESA automatic weather stations, and nine rain gauge stations for the 1961–2013 period. For surface runoff, the Theta Probe ML2x meter was used to sample and measure in situ the moisture of 44 specific soil points along river banks and 54 farming field points. Soil moisture data collection occurred mainly during the catchment's long and dry seasons. For streamflow, the Hydrometre current meter was utilized to measure river discharges. In total, ten (10) river discharge points were sampled in September and October 2013 and measured from six (6) micro-catchments of Wundanyi, namely Mdongodongo, Mwanguwi, Wasinyi, Wesu, Ore, and Mlawa. Secondary time series data on river discharge (2011–2013) were obtained from the various stations installed by the CHIESA Project. A long series of streamflow data (1970–2010) was collected from the neighboring Musau gauging station for regionalization purposes [22].

2.2. Key variables and data analysis

Previous research has established that Wundanyi's micro-climate and hydrology are mostly influenced by the catchment's forestry and agricultural activities. Several factors were included in the initial extraction, such as mean annual precipitation in rainy seasons (MAM and OND) and dry seasons (JF and JJAS); minimum, mean, and maximum temperatures; surface runoff, and river discharges/streamflow, as well as various land use and cover change (LUCC) variables.

The first step in analyzing hydroclimatic trends in Wundanyi was to extract key hydrological and meteorological variables shaping the catchment's micro-climate changes. Principal component analysis (PCA) and the homogeneity of variance test were used to this end. Based on Kaiser's eigenvalue scores, several independent variables were isolated to explain the effect of climate variability on hydrological processes. These variables were used to build several regression models that were tested for relevance using the marginal homogeneity (MH) test of variances. Levene's homogeneity test helped cluster the extracted factors as independent and dependent variables based on Levene's heuristic method. A standardized MH statistic value of 2.6 and above indicated the presence of homogeneity.

Then, several hydroclimatic models helped establish seasonal trends and quantify the effects of climate variability on Wundany's hydrological regime. Rainfall, surface runoff, and discharge data were derived from at least 30 years of daily rainfall and streamflow datasets from available weather and gauging stations. For the first step, long-term daily precipitations and streamflow series were used to generate monthly, seasonal, and annual precipitation averages, annual variability, and long-term trends shaping key hydrological processes in the Wundanyi River basin. Auto-regressive integrated moving average (ARIMA) (p, d, q) and (P, D, Q) models were then used to fit time series hydroclimatic variables and predict their future seasonal variations and annual trends, respectively.

To estimate the regression parameters, the general Equation (1) was utilized:

$$\hat{Y}(t) = Y(t-1) + \phi Y(t-2) + \mu \quad (1)$$

where,

$Y(t-1)$ = average value of upstream and downstream flows at period $t-1$,

$\phi Y(t-2)$ = water balance for the previous periods,

ϕ = ARIMA coefficient,

μ = a random coefficient for the error term.

For the second step, dynamic trend analyses were utilized to simulate the effects of rainfall variability on surface runoff and streamflow using multivariate statistical trend analysis. A linear regression model was fitted to model the effects of specific hydroclimatic and LUCC variables on Wundanyi's surface runoff and discharges as per Equations (2) and (3):

$$Q_{rs} = A_1 + B_1 Prec_{MAM} + C_1 ALC + D_1 ALF + E_1 DLC + F_1 DLF + E_1 \quad (2)$$

$$Q_{ds} = A_2 + B_1 Prec_{JF} + C_2 ALC + D_2 ALF + E_2 DLC + F_2 DLF + E_2 \quad (3)$$

where,

Q_{rs} = Surface runoff/discharge during MAM,

Q_{ds} = Surface runoff/discharge during JF,

A_i = Regression constant,

B_i to F_i = Regression coefficients,

$Prec_{MAM}$ = Rainfall during the long, rainy season,

$Prec_{JF}$ = Rainfall during the short, dry season,

ALC = Area of land under cultivation,

ALF = Area of land under forest cover,

DLC = Distance of land under cultivation from the river bank,

DLF = Distance of land under forest from the river bank.

Model parameters were estimated based on partial correlations and partial auto-correlation functions. The models allowed for estimating surface runoff and discharge variations during the MAM and JF seasons. All models were calibrated and validated using a continuous two-year data flow from a randomly selected spot within the basin. The calibration efficiency was verified by comparing the simulated and observed discharge time series at the outlet of the catchment, where a long hydrometrical data series exists. Sensitive model parameters were adjusted within their feasible ranges to minimize prediction errors.

3. Results and discussions

3.1. Variable extraction and model development

Table 1 shows that the Wundanyi sub-catchment micro-climate and hydrology are characterized by highly fluctuating seasonal rainfall, temperatures, surface runoff, and discharges, which were assumed to be influenced by forestry and agricultural activities. The PCA extracted seven (7) factors as the most influential variables shaping the sub-catchment's microclimate and hydrological cycle based on the proportions of variance explained. These seven variables encompassed discharges during JF, JJAS, and MAM; JF and JJAS rainfall, and JF and JJAS runoff.

The MH statistical tests revealed that the seasonal runoff and discharge data collected were highly homogeneous with their seasonal rainfall counterparts. **Table 2** suggests the presence of homogeneity, with all the MH statistics being above 2.6 at a 5% significance level. A special relationship needed to be established among the selected meteorological variables in the study. A correlation was thus established between seasonal rainfall and temperatures (max. and min.) with MH statistics significantly above 2.6 (**Table 3**). This homogeneity between seasonal rainfall and temperatures enabled the resizing of the number of meteorological variables in the model to minimize multicollinearity.

Table 1. Total variance explained hydroclimatic variables extracted through PCA.

Component	Initial eigenvalues			Extraction sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
JF_DISC	7.241887	30.17453	30.1745297	7.241887136	30.17453	30.17453
JF_RAIN	4.231294	17.63039	47.8049217	4.231294079	17.63039	47.80492
JF_Runoff	3.034282	12.64284	60.4477629	3.034281892	12.64284	60.44776
JJAS_DISC	2.128163	8.867344	69.3151071	2.128162608	8.867344	69.31511
JJAS_Runoff	2.054945	8.562272	77.8773791	2.054945264	8.562272	77.87738
JJAS_RAIN	1.448967	6.037364	83.9147431	1.448967362	6.037364	83.91474
MAM_DISC	1.045173	4.354887	88.2696296	1.045172761	4.354887	88.26963
MAM_RAIN	0.919887	3.832861	92.1024906	-	-	-
MAM_Runoff	0.639069	2.662787	94.7652779	-	-	-
OND_DISC	0.425491	1.772879	96.5381574	-	-	-
OND_RAIN	0.318887	1.328696	97.8668533	-	-	-
OND_Runoff	0.242313	1.009639	98.8764924	-	-	-
Temp_max	0.147907	0.616278	99.4927709	-	-	-
Temp_min	0.055929	0.233036	99.7258074	-	-	-
Cropland	0.033867	0.141113	99.8669207	-	-	-
Woodland	0.019868	0.082784	99.9497049	-	-	-
Plantation forest	0.010162	0.04234	99.9920453	-	-	-
Broadleaved forest	0.001888	0.007867	99.9999123	-	-	-
Shrubland	2.1×10^{-5}	8.77×10^{-5}	100	-	-	-
Thicket	1.03×10^{-9}	4.28×10^{-9}	100	-	-	-
Grassland	1.99×10^{-16}	8.31×10^{-16}	100	-	-	-
Bare soil	1.07×10^{-16}	4.45×10^{-16}	100	-	-	-
Bare rock	-5.4×10^{-17}	-7.3×10^{-16}	100	-	-	-
Other lands	-6.5×10^{-18}	-3.4×10^{-15}	100	-	-	-
Built up_Area	-1.8×10^{-16}	-7.3×10^{-16}	100	-	-	-
Water	-8.1×10^{-16}	-3.4×10^{-15}	100	-	-	-

Source: Data analysis (Author, 2024).
Note: Variables extracted by the principal component analysis (PCA).

Further examination showed that most LUCC categories and hydroclimatic covariates retained were normally distributed within at least one standard deviation around the mean, except for JF runoff, JF rainfall, grassland, and DLC (distance to the river of cropland). These four variables were eliminated. Using the multivariate regression predictions, the models were able to unveil the combined effects of hydroclimatic variables and LUCC on Wundanyi's hydrology during the short, rainy, and long, dry seasons.

Table 2. Marginal homogeneity (MH) test of variances for hydrological data*.

Component	MAM Runoff	MAM Discharge	OND Runoff	OND Discharge	JF Runoff	JF Discharge	JJAS Runoff	JJAS Discharge
Distinct Values	68	68	68	68	68	68	68	68
Off-Diagonal Cases	34	34	34	34	34	34	34	34
Observed MH Statistic	9649.068	42.678	9215.897	49.367	1535.556	29.738	4607.866	62.040
Mean MH Statistic	12,134.434	7331.239	11,589.688	7006.423	1931.078	1178.169	5794.740	3521.027
Std. Dev of MH Statistic	480.026	1408.601	451.114	1322.947	98.522	287.782	229.380	669.520
Std. MH Statistic	–5.178	–5.174	–5.262	–5.259	–4.015	–3.991	–5.174	–5.168
Asymp. Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Source: Data analysis (Author, 2024)
*: Independent variables: MAM_Rainfall, OND_ Rainfall, JF_ Rainfall, JJAS_ Rainfall, Temp_max, Temp_min, Broadleaved_forest, Woodland,Thicket, Shrubland, Planted_forest, Cropland, Grassland, DLC, DLF.

Hence, based on the results of the PCA and MH tests, the following four models were retained:

OND_Discharge = f (OND_Rain, broadleaved forest, plantation forest, DLF)

OND_Runoff= f (OND_Rain, broadleaved forest, plantation forest, woodland, shrubland, thicket, cropland, DLF)

JJAS_Discharge = f (JJAS_Rain, broadleaved forest, plantation forest, DLF)

JJAS_Runoff = f (JJAS_Rain, broadleaved forest, plantation forest, woodland, shrubland, thicket, cropland, DLF)

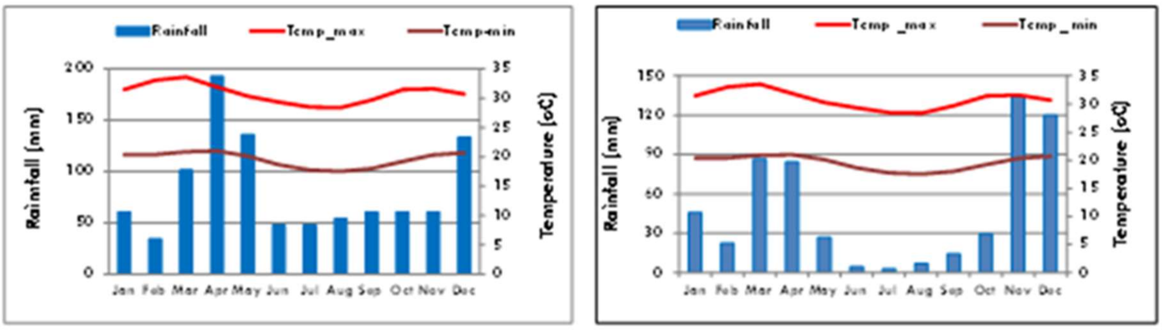
Table 3. Marginal homogeneity (MH) test of variances for selected meteorological data*.

Component	JF Rainfall	JJAS Rainfall	MAM Rainfall	OND Rainfall
Distinct Values	49	49	49	49
Off-Diagonal Cases	33	34	34	34
Observed MH Statistic	2326.601	6981.615	14,619.8	13,963.48
Mean MH Statistic	1672.25	4015.158	7834.25	7506.09
Std. Dev. of MH Statistic	236.869	596.222	1332.76	1246.372
Std. MH Statistic	2.762	4.975	5.091	5.181
Asymp. Sig. (2-tailed)	0.006	0.000	0.000	0.000

Source: Data analysis (Author, 2024).
*: Independent variables: Temp max and Temp min.

3.2. Prediction of hydroclimatic trends by 2030

The Wundanyi sub-catchment belongs to a semi-arid type of climate. Rainfall distribution in the sub-catchment is bi-modal, with longer rainy seasons occurring from March to May (MAM) and short rains from October to December (OND). Based on data collected at Wundanyi DC's Office and Voi weather station, **Figure 1** shows a highly variable mean rainfall distribution with rising mean annual temperatures in both MAM and OND. This bi-modal rainfall pattern determines the growth of all vegetation and agricultural practices.

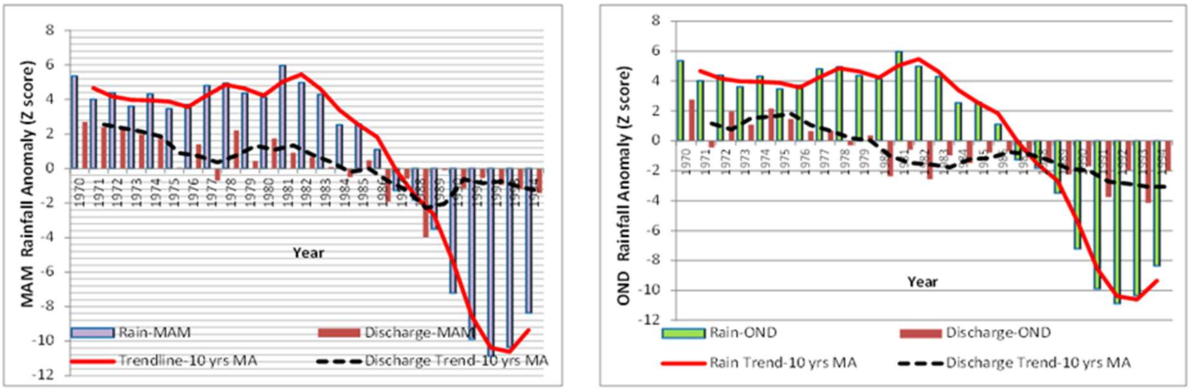


(a) Wundanyi DC's Office diagram. **(b)** Voi weather station diagram.

Figure 1. Climate patterns in the Wundanyi sub-catchment (Author, 2024).

Temperatures range between 23 °C and 27 °C with slightly cooler conditions experienced around Wundanyi town than in other parts of the county. This climate is influenced by the Inter-Tropical Convergence Zone (ITCZ) and differences in altitude and relief. This topographic aspect significantly affects rainfall distribution both vertically and horizontally. Annual precipitations in Taita-Taveta range from approximately 1000 mm to 1750 mm. There are some variations throughout the county, with the hills around Wundanyi experiencing slightly wetter conditions. The potential evaporation is about twice the annual rainfall in the semi-arid area, while in the upper basin humid areas, rainfall exceeds potential evaporation in most parts of the year [18,22,23].

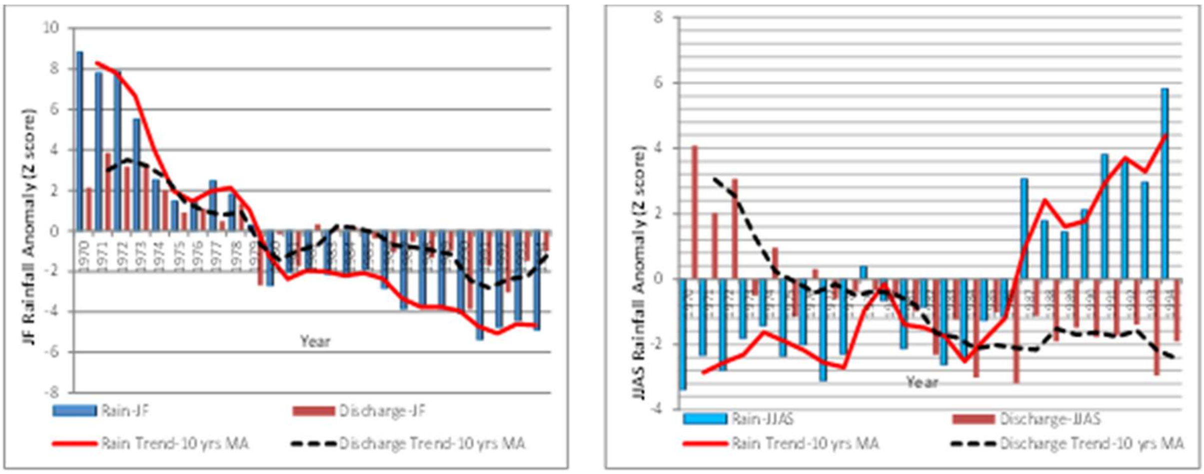
Correlational anomalies between seasonal rainfall and seasonal discharges in Wundanyi revealed sharp discharge increases during the short rains (OND) of 1980 and the long rains (MAM) from 1970 to 1981 (**Figure 2**). Rainfall and discharges started decreasing from 1982 to become below-normal rainfall during the OND and MAM rainy seasons, until 1993, when they started increasing again. A different scenario was evident for the long dry season (JJAS) (**Figure 3**). During that season, rainfall rose vis-à-vis falling discharges, while the short dry season (JF) witnessed both declining rainfall and discharges.



(a) Anomalies during the MAM rainy season. **(b)** Anomalies during OND rainy season).

Figure 2. Hydroclimatic anomalies in Wundanyi during the rainy seasons (Author, 2024).

Note: Analysis based on 10-year moving averages.



(a) Anomalies during JF dry season. **(b)** Anomalies during the JJAS dry season.

Figure 3. Hydroclimatic anomalies in Wundanyi during the dry seasons (Author, 2024).

Note: Analysis based on 10-year moving averages.

These findings suggest that climate change in Wundanyi is characterized by drier and wetter periods on one end and wet and dry ones on the other. Ironically, increased JJAS rainfall did not correspond with increased discharges. Thus, even if Wundanyi is to witness above-normal rainfall and runoff in JJAS, they may not translate into increased discharges. The JF rainfall and discharges decreased consistently from 1970 to 1994. Overall, Wundanyi witnessed above-normal rainfall from 1970 to 1981, which, together with discharges, began falling from 1982 to 1992 (**Figure 4**).

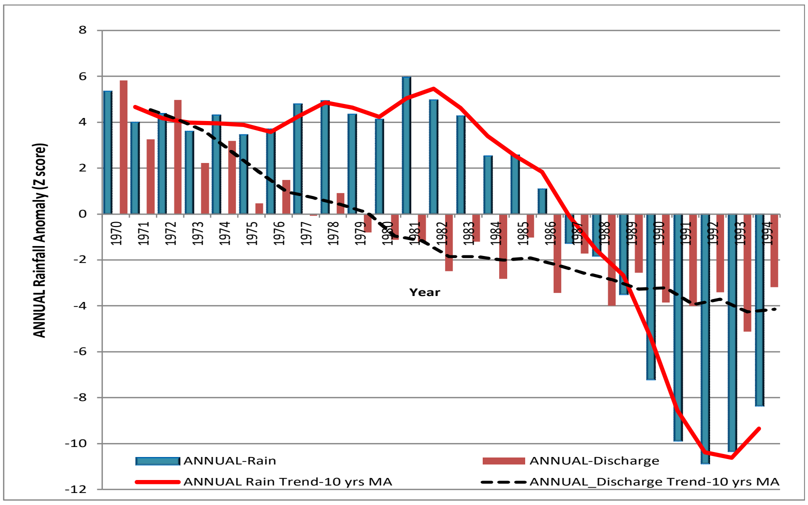


Figure 4. Annual rainfall anomaly in Wundanyi (Author, 2024).

Note: Analysis based on 2-year moving averages.

The seasonal and annual rainfall prediction models for Wundanyi were also strong enough and fit for predicting pertinent Wundanyi hydroclimatic patterns by 2030. They displayed very low Residual Mean Square Error (RMSE) and mean Average Percentage Error (MAPE), along with very significant Ljung-Box, stationary R^2, and *t*-test statistics (**Table 4**).

All the prediction models for rainfall exhibited high goodness of fit statistics, except for the JF dry season. ARIMA models were used to forecast Wundanyi's rainfall trends up to 2030 and predicted rising rainfall during the OND and MAM rainy seasons, with no apparent pattern for the dry seasons (JF and JJAS). Interestingly, higher seasonal rainfall was expected in JJAS (mean = 205.34 mm) than in OND (mean = 200.34 mm) seasons. The highest mean seasonal rainfall was predicted in MAM (mean = 352.53 mm) and the lowest in JF (mean = 94.89 mm) (**Tables A1** and **A2**).

Table 4. Best-fitting models for time series seasonal rainfall.

Variables	Model fit statistics					Ljung-Box Q (18)		
	Model	Stationary *R*-squared	RMSE	MAPE	Normalized BIC	Statistics	DF	Sig.
Rainfall_OND	Exponential[b.]	0.629	0.018	19.857	0.0488	0.174	17	0.04
Rainfall_MAM	Exponential[c.]	0.621	0.016	20.772	0.0776	0.270	17	0.087
Rainfall_JJAS	Exponential[d.]	0.689	0.000	10.829	0.0947	0.182	18	0.009
Rainfall_JF	Exponential[e.]	0.288	0.990	78.429	10.87	10.013	18	0.378

Source: Data analysis (Author, 2013).

Note: Best-Fitting Models according to Stationary *R*-squared (larger values indicate better fit).

b. $b = 0.218$; $t = 7.664$ (Sig. = 0.000)

c. $b = 0.215$; $t = 7.357$ (Sig. = 0.000)

d. $b = 0.197$; $t = 8.729$ (Sig. =0.000)

e. $b = 0.202$; $t = 3.843$ (Sig. = 0.001)

These findings signaled changing hydroclimatic patterns in Wundanyi, especially during the drier periods. They provided tangible evidence of the changing hydroclimatic trends in the Wundanyi sub-catchment. The prediction models for seasonal hydroclimatic trends depicted high rainfall increases, especially during the dry seasons, which were also associated with highly water-stressed streamflow in the

Wundanyi sub-catchment during any particular season of the year, except during the OND short rains. These predictions corroborate those of Hulme et al. [24] and Rockström [25], who anticipated high rainfall in some parts of the globe with wide-scale water disasters in the year 2050. These authors suggested that about 60% of the world's population will face a shortage of water, with nearly one billion people lacking access to clean drinking water, and more than two billion people living in drought-stricken areas across the globe.

The impact of climate change on temperatures and precipitation will likely bring about major changes in the terrestrial water cycle. This may affect the availability of water resources and, consequently, their accessibility by the societies relying on them. Bates et al. [26] and Kundzewicz et al. [27] attributed this situation to poor policies resulting in the a of control of the changing patterns of local land use and cover change (LUCC) patterns, coupled with large-scale microclimatic changes. The latter is expected to lead to more severe droughts in parts of Southeast Asia and Sub-Saharan Africa, especially in the western and eastern African regions of the Wundanyi sub-catchment of Taita Hills in Kenya, not being spared [28,29].

3.3. Specific effects of rainfall fluctuation on hydrology by 2030

The assumption of changing hydroclimatic trends was reinforced by the ARIMA prediction models for surface runoff and river discharges in Wundanyi. Throughout the period of prediction, **Table 5** indicates that all surface runoff models had significant Ljung-Box statistics. Although the OND discharge model showed low RMSE and MAPE, it was fit for prediction by 2030 at a 5% significance level; only the OND discharge model did not meet that standard.

Table 5. Best-fitting ARIMA models for seasonal surface runoff and discharge in Wundanyi.

Variables	Model fit statistics					Ljung-Box Q (18)		
	Model	Stationary R-squared	RMSE	MAPE	Normalized BIC	Statistics	DF	Sig.
Runoff_OND[b]	ARIMA (0,1,0)	0.974	0.005	0.004	–6.071	33.834	18	0.013
Runoff_JJAS[c]	ARIMA (0,0,0)	0.718	30.015	111.537	–1.299	33.437	16	0.006
Discharge_OND[d]	ARIMA (0,0,0)	0.598	0.554	50.037	–0.759	20.499	17	0.250
Discharge_JJAS[e]	ARIMA (0,0,2)	0.337	0.627	38.621	–0.83	30.377	17	0.024

Source: Data analysis (Author, 2023).
Note: Best-Fitting Models according to Stationary R-squared (larger values indicate better fit) and independent variable (i.e., seasonal rainfall).
b. $b = 0.00398$; $t = 111.667$ (Sig. = 0.000); $F = 54.13$ (Sig.= 0.001)
c. $b = –0.00637$; $t = –3.726$ (Sig. = 0.001); $F = 76.195$ (Sig. = 0.000)
d. $b = 0.02037$; $t = 2.19$ (Sig. = 0.037); $F = 0.8743$ (Sig. = 0.1157)
e. $b = –0.0349$; $t = –2.378$ (Sig. = 0.025); $F = 14.772$ (Sig. = 0.001)

The time series of annual seasonal runoff in Wundanyi shows persistently declining trends from 2004 to 2030 during the JJAS season. The 2004 JJAS surface runoff was 62.03 mm and was projected to decrease by about 1.27% every two years to settle at 53.11 mm in 2030. A reverse pattern is observed for the OND season, whereby surface runoff will rise by about 0.8% every two years to reach 228.51 mm in 2030 from 209.86 mm in 2004 (**Table 6**).

Similar trends were evidenced by the JJAS seasonal discharge model, with the OND model being unfit for predictions from 2010 up to 2030. Based on the data displayed in **Table 7**, the JJAS discharge decreased from 1.119 m^3/s in 2004 by about

7% to settle at 1.041 m^3/s from 2006 up to 2030. Though inconclusive and unfit for predictions beyond 2010, the OND discharge increased from 0.863 m^3/s in 2004 to 1.009 m^3/s in 2010.

Table 6. Seasonal runoff trends under rainfall variability in Wundanyi.

Year	OND Runoff [b]			JJAS Runoff [c]		
	Forecast	**LCL [d]**	**UCL [e]**	**Forecast**	**LCL [d]**	**UCL [e]**
2004	209.86	–169.02	588.74	62.03	–52.44	176.51
2006	211.53	–167.50	590.55	61.24	–53.36	175.83
2008	213.14	–166.02	592.31	60.46	–54.25	175.18
2010	214.72	–164.58	594.02	59.71	–55.12	174.54
2012	216.25	–163.18	595.68	58.98	–55.98	173.93
2014	217.74	–161.82	597.31	58.26	–56.81	173.33
2016	219.20	–160.49	598.90	57.57	–57.62	172.75
2018	220.62	–159.20	600.45	56.88	–58.42	172.19
2020	222.01	–157.93	601.96	56.22	–59.21	171.64
2022	223.37	–156.70	603.44	55.57	–59.97	171.11
2024	224.70	–155.49	604.89	54.94	–60.72	170.59
2026	225.99	–154.31	606.30	54.31	–61.46	170.09
2028	227.26	–153.16	607.69	53.71	–62.18	169.60
2030	228.51	–152.03	609.04	53.11	–62.89	169.12

Source: Data analysis (Author, 2024).
Notes: For each model, forecasts start after the last non-missing in the range of the requested estimation period, and end at the last period for which non-missing values of all the predictors are available or at the end date of the requested forecast period.
b. $F = 54.13$ (Sig. = 0.001)
c. $F = 76.195$ (Sig. = 0.000)
d. LCL = Lower Class Limit
e. UCL = Upper Class Limit

Table 7. Seasonal discharge trends under rainfall variability in Wundanyi.

Year	OND Discharge [b]			JJAS Discharge [c]		
	Forecast	**LCL [d]**	**UCL [e]**	**Forecast**	**LCL [d]**	**UCL [e]**
2004	0.863	–0.288	2.014	1.119	0.371	2.894
2006	0.898	–0.315	2.051	1.041	0.352	2.243
2008	0.901	–0.345	2.071	1.041	0.352	2.243
2010	1.009	–0.355	2.088	1.041	0.352	2.243
2012	-	-	-	1.041	0.352	2.243
2014	-	-	-	1.041	0.352	2.243
2016	-	-	-	1.041	0.352	2.243
2018	-	-	-	1.041	0.352	2.243
2020	-	-	-	1.041	0.352	2.243
2022	-	-	-	1.041	0.352	2.243
2024	-	-	-	1.041	0.352	2.243
2026	-	-	-	1.041	0.352	2.243
2028	-	.	-	1.041	0.352	2.243
2030	-	-	-	1.041	0.352	2.243

Source: Data analysis (Author, 2024).
Notes: For each model, forecasts start after the last non-missing in the range of the requested estimation period, and end at the last period for which non-missing values of all the predictors are available or at the end date of the requested forecast period.
b. $F = 0.8743$ (Sig. = 0.1157)
c. $F = 14.772$ (Sig. = 0.001)
d. LCL = Lower Class Limit
e. UCL = Upper Class Limit

Past studies have shown that climate variability has significant bearing on streamflow fluctuations through interactions with human and geophysical factors [30,31]. Rainfall variability may, over time, lead to decreased streamflow in the river basins [13,32]. The observed variabilities may cause significant changes in Wundanyi's hydrology, compromise water availability, and bring about extreme climate-driven events. Yes! Climate change-related variabilities in rainfall patterns may have significant impacts on runoff in larger catchments rather than smaller ones [33]. Hence, runoff and discharge in small catchments may be more likely altered by LUCC than by changes in hydroclimate [34]. These results concur with Luwesi et al. [32], Shah et al. [17], IPCC [8], Sood et al. [5], and Wara et al. [6], who predicted high rainfall increases in some parts of the globe with wide-scale water-related disasters by 2050 and 2100 in others.

4. Conclusion and recommendations

This study's objective was to assess the effects of climate variability on Taita Hills' hydrological processes. The analysis of historical data provided evidence of changing hydroclimatic trends in Wundanyi. Although mean annual temperatures were highly variable, they exhibited on average increasing trends over the prediction period (1970–2030), possibly due to local and global environmental changes. Mean temperatures in the catchment have risen steadily since 1970, and the trend is expected to keep its pace until 2030.

The study got mixed results for rainfall and discharges across different scenarios. While seasonal rainfall variations since 1970 have shown no specific pattern, the study projected that Wundanyi will experience higher mean rainfalls during the long dry season (JJAS) than in the short dry (JF) and wet (OND) seasons. Besides, rainfall variabilities observed in Wundanyi have significant impacts on the catchment's hydrological processes, specifically runoff and streamflow. ARIMA models revealed significant declines in surface runoff and streamflow during the long dry season (JJAS), which shall continue until reverse runoff and streamflow patterns occur in 2030, especially during the short rains.

Based on the above findings, the government and other stakeholders should implement interventions with direct and/or indirect relevance to climate change adaptation and mitigation. The possible interventions cover a wide range of sectors, including agriculture and water resource management. Hence, promoting irrigated and conservation agriculture will add value to agricultural products and support community-based adaptation. On the one hand, water resource management, through increased rainwater capture and retention, water catchment protection, and water quality monitoring, will contribute to the sustainability of water provision in the catchment. Such interventions may help mitigate the disturbance of hydroclimatic impacts on Wundanyi hydrological processes.

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supervision, JAO; project administration, CNL; funding acquisition, RAA. All authors have read and agreed to the published version of the manuscript.

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Appendix

Table A1. Wundanyi hydroclimatic data for the rainy season (1970–2003).

Year	MAM Rainfall (mm)	MAM Discharge (m^3/s)	MAM Runoff (mm)	OND Rainfall (mm)	OND Discharge (m^3/s)	OND Runoff (mm)
1970	556.40	1.42	367.22	360.70	2.18	238.06
1971	827.78	1.21	546.34	485.02	0.54	320.11
1972	857.18	2.36	565.74	766.61	1.55	505.96
1973	418.01	1.70	275.89	635.45	0.09	419.40
1974	595.12	2.34	392.78	368.36	0.67	243.12
1975	400.32	1.30	264.21	494.87	0.63	326.61
1976	507.87	2.81	335.19	448.33	0.68	295.90
1977	360.39	1.06	237.86	546.63	0.87	360.78
1978	585.13	1.36	386.19	610.16	0.32	402.71
1979	699.86	0.54	461.91	182.93	1.44	120.74
1980	208.93	0.98	137.89	260.06	0.33	171.64
1981	488.55	0.58	322.44	357.24	1.17	235.78
1982	235.17	0.80	155.22	405.11	0.31	267.38
1983	288.62	0.68	190.49	195.10	0.40	128.76
1984	188.90	0.45	124.68	406.03	0.12	267.98
1985	248.89	1.28	164.27	304.29	0.09	200.83
1986	548.41	0.70	361.95	564.50	0.49	372.57
1987	234.47	1.76	154.75	109.02	0.24	71.95
1988	607.06	0.40	400.66	773.43	0.79	510.46
1989	430.60	0.83	284.19	282.90	0.20	186.72
1990	313.79	0.27	207.10	331.65	0.66	218.89
1991	233.97	0.31	154.42	187.53	0.30	123.77
1992	75.35	0.29	49.73	208.77	0.49	137.79
1993	35.23	0.30	23.25	122.54	0.16	80.87
1994	141.60	0.63	93.46	60.09	0.25	39.66
1995	46.24	0.21	30.52	92.78	0.09	61.23
1996	61.51	0.75	40.60	53.85	0.16	35.54
1997	128.96	0.34	85.11	157.78	0.09	104.14
1998	86.13	1.27	56.84	75.63	0.14	49.92
1999	17.95	0.34	11.85	91.02	0.27	60.08
2000	23.10	0.38	15.25	88.67	0.09	58.52
2001	137.82	0.19	90.96	129.77	0.79	85.65
2002	118.10	0.23	77.95	37.15	0.06	24.52
2003	185.90	0.18	122.69	53.46	0.55	35.28

Table A2. Wundanyi hydroclimatic data for the dry season (1970–2003).

Year	JF Rainfall (mm)	JF Discharge (m^3/s)	JF Runoff (mm)	JJAS Rainfall (mm)	JJAS Discharge (m^3/s)	JJAS Runoff (mm)
1970	124.10	0.63	81.91	111.40	1.26	73.52
1971	12.52	0.84	6.47	236.56	0.61	156.13
1972	191.69	0.69	80.32	378.03	2.92	249.50
1973	287.55	1.35	144.01	93.83	0.55	61.93
1974	75.97	1.49	43.69	321.54	1.57	212.22
1975	70.82	0.96	45.61	185.81	0.44	122.64
1976	27.75	1.03	15.91	192.44	0.72	127.01
1977	60.88	0.48	46.86	108.47	0.40	71.59
1978	229.16	2.53	189.75	56.27	0.20	37.14
1979	249.02	0.59	220.11	188.91	0.42	124.68
1980	47.06	1.52	37.42	188.01	0.37	124.09
1981	18.34	0.12	18.15	90.23	0.59	59.55
1982	20.31	0.33	21.12	218.93	0.27	144.49
1983	67.76	0.08	73.79	68.55	0.61	45.24
1984	0.00	0.30	0.00	104.53	0.31	68.99
1985	72.36	0.60	85.60	122.30	0.57	80.72
1986	99.26	0.36	82.24	38.00	0.20	25.08
1987	12.60	0.61	16.04	111.35	0.29	73.49
1988	116.73	0.31	76.36	362.40	0.27	239.18
1989	32.11	1.25	43.63	68.94	0.22	45.50
1990	95.87	0.34	134.24	31.63	0.14	20.87
1991	30.13	0.75	43.43	125.21	0.17	82.64
1992	1.16	0.15	2.18	54.11	0.30	35.71
1993	57.32	0.05	87.19	58.71	0.13	38.75
1994	28.43	0.07	44.35	129.08	0.56	85.20
1995	3.72	0.25	5.94	95.75	0.06	63.20
1996	24.48	0.32	40.06	202.60	0.43	133.72
1997	25.63	0.25	42.90	30.17	0.10	19.91
1998	105.57	0.22	180.58	124.33	0.17	82.06
1999	14.43	0.20	25.21	81.35	0.12	53.69
2000	0.74	0.83	1.32	92.52	0.11	61.07
2001	75.31	0.35	103.69	121.24	0.24	80.02
2002	24.15	0.54	44.75	29.31	0.08	19.35
2003	23.64	0.15	44.62	155.62	0.25	102.71