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Assessment of the Impacts of Land Use and Land Cover Changes on the Hydrological Response of the Kilombero River Catchment, Tanzania

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Abstract

Land use and land cover (LULC) change is a major driver of hydrological alteration in tropical river basins, with significant implications for water resources sustainability. This study assessed the influence of historical (1991-2021) and projected (2021-2041) LULC dynamics on the hydrological response of the Kilombero River Catchment (KRC) using the Soil and Water Assessment Tool (SWAT). The model was calibrated and validated against observed streamflow at the Swero (1KB17) gauging station, demonstrating satisfactory and moderate performance, respectively. Results indicated that expansion of cultivated land and grassland at the expense of forests, woodlands, and wetlands has increased surface runoff and sediment yield while reducing groundwater recharge and dry season flows. Between 1991 and 2021, surface runoff increased by approximately 14%, accompanied by a decline in groundwater contribution to streamflow of more than 8%. Future LULC scenarios project further amplification of these trends, with dry season flows falling below recommended e-flow requirements. The findings highlight that unmanaged LULC transformation is progressively weakening hydrological regulation and flow resilience in KRC. Integrating land use planning, ecosystem conservation, and environmental flow considerations into basin-scale water resources management is therefore essential to safeguard long-term hydrological and ecological sustainability.

Keywords

Catchment Sustainability, E-Flow, Land Cover, Land Use, SWAT Model, Water Resources

1. Introduction

1.1. Background on LULC

Global agricultural land and human shelter have grown proportionately in the recent past. This accompanied a large increase in energy, water, and fertilizer consumption, together with substantial losses of biodiversity (Foley et al., 2005; Khan et al., 2019). These kinds of changes in land have enabled humans to appropriate an increasing share of the planet's resources (including water), but they also undermine the capacity of ecosystems to sustain food production, maintain freshwater and forest resources, regulate climate and air quality, and ameliorate infectious diseases (Foley et al., 2005). All these changes result from geogenic and anthropogenic happenings that shape the land use (LU) or land cover (LC) of the surface of the earth. LULC change is a hybrid phenomenon in that, while on one hand LU represents human employment of the land for a number of socioeconomic activities, the LC connotes the physical and biotic character of the land surface as observed naturally or after alteration following the human activities (Liu, 2018; Liu et al., 2005; Meyer & Turner, 1992). The LULC change causes a number of effects manifested in the biodiversity (Lupo et al., 2001; Mbungu & Kashaigili, 2017). Continuous from the previous and in the coming years, LULC dynamics have been playing a critical role as a driving force in the alteration of the global environment (Mbungu & Kashaigili, 2017).

In many parts of Africa, including Tanzania, different researchers have studied and hence indicated a declining state of natural vegetation, which is replaced by altered LULC following human socioeconomic undertakings. Future projections show that LULC changes will have an even greater role in the alteration of the regional hydrologic conditions that will result in a variety of impacts on ecosystem functions (Li et al., 2007; Näschen et al., 2018). The LULC thus presents us with a valid dilemma. On one hand, many LULC practices are essential for human existence because they provide critical natural resources and ecosystem services, such as food, fiber, shelter, and freshwater. On the other hand, some forms of LULC play a role in the degradation of the ecosystems and services upon which humankind depends for their very survival.

1.2. LULC Implications to River Hydrology

The LULC constitutes one of the most important landscape controls on river hydrology, governing how precipitation is intercepted, stored, transformed, and ultimately delivered to river channels (Chilagane, 2017; Sigalla et al., 2024). At the catchment scale, LULC influences the partitioning of rainfall into evapotranspiration, infiltration, surface runoff, subsurface flow, and groundwater recharge, thereby controlling streamflow magnitude, seasonality, variability, and extremes (Babaremu et al., 2024). Changes in LULC, whether driven by agricultural expansion, deforestation, urbanization, or land management practices, modify surface roughness, soil physical properties, vegetation structure, and drainage connectivity, which in turn alter hydrological response mechanisms and water balance components (Babaremu et al., 2024; Herano et al., 2025). Consequently, river flow regimes reflect not only climatic forcing but also the cumulative effects of spatial and temporal LULC dynamics within the watershed.

Vegetation cover plays a critical role in regulating hydrological processes through rainfall interception, root water uptake, and evapotranspiration (Senkondo et al., 2019; Sigalla et al., 2023; Tumbo & Hughes, 2015). Forested and well-vegetated landscapes typically promote higher interception losses, greater soil organic matter content, and enhanced macroporosity, which together increase infiltration capacity and subsurface storage while moderating surface runoff (Tumbo & Hughes, 2015). Conversion of natural vegetation to cropland or grazing land often reduces interception and rooting depth, leading to lower evapotranspiration and increased runoff generation, particularly during high-intensity rainfall events (Senkondo et al., 2019; Sigalla et al., 2023). While such changes may temporarily increase total water yield, they frequently reduce groundwater recharge and dry-season baseflow, resulting in more variable and less reliable streamflow regimes (Herano et al., 2025). Empirical and model-based studies consistently demonstrate that deforestation shifts flow regimes toward higher peak discharges and reduced low flows, increasing flood risk while exacerbating hydrological drought during dry periods (Blöschl, 2022; Herano et al., 2025).

Agricultural land use exerts complex and context-specific impacts on river hydrology, depending on crop type, tillage practice, irrigation, and soil conservation measures (Chilagane et al., 2020; Sigalla et al., 2024). Conventional cultivation often leads to soil compaction, reduced infiltration, and increased overland flow, particularly in intensively farmed catchments (Chilagane et al., 2020; Mutayoba et al., 2018). Expansion of rain-fed agriculture in tropical and semi-arid regions has been widely associated with increased surface runoff and sediment delivery to river systems, altering channel morphology and reducing conveyance capacity (Näschen et al., 2019a; Singh et al., 2015; Twisa & Buchroithner, 2019). Irrigated agriculture further modifies hydrological regimes by introducing artificial abstractions, return flows, and seasonal redistribution of water, which can significantly alter the timing of natural flows and reduce downstream water availability (Näschen et al., 2019b; CDM Smith, 2016). In many basins, agricultural expansion increases wet-season flows while diminishing dry-season baseflows, thereby increasing intra-annual flow variability and placing stress on aquatic ecosystems and downstream water users.

Furthermore, urbanization represents one of the most pronounced forms of LULC change affecting river hydrology due to the proliferation of impervious surfaces and engineered drainage networks (Chilagane et al., 2020; Mutayoba et al., 2018). Replacement of natural or agricultural land with roads, rooftops, and paved areas drastically reduces infiltration and groundwater recharge while accelerating runoff generation and flow concentration (Senkondo et al., 2017; Sigalla, 2009). As a result, urban catchments exhibit shortened response times, elevated runoff coefficients, higher and more frequent peak discharges, and reduced lag times between rainfall and river response (Mazengo et al., 2022). These changes significantly increase flood hazard and overwhelm existing drainage and flood protection infrastructure. At the same time, reduced recharge leads to declining groundwater levels and weakened baseflow contributions, resulting in degraded low-flow conditions and increased vulnerability to water scarcity during dry periods (WREM & RBWB, 2013). Numerous recent studies highlight that even moderate levels of urban expansion can fundamentally alter hydrological signatures, emphasizing the need to integrate land-use planning with flood and water resources management (Blöschl, 2022; Herano et al., 2025).

LULC changes also strongly influence the spatial distribution and connectivity of hydrological processes within river basins. Alterations in upper catchment land cover often have disproportionate downstream impacts, as increased runoff and sediment production in headwaters propagate through the river network, amplifying flood peaks and sediment loads in downstream reaches (Senkondo et al., 2017). Similarly, degradation of riparian zones and wetlands reduces natural flow attenuation and storage capacity, weakening the buffering role these systems play during extreme hydrological events (Näschen et al., 2019b). Loss of wetlands and floodplains due to cultivation or settlement reduces overbank storage, increases flow velocities, and diminishes groundwater-surface water interactions that are essential for sustaining baseflow and ecological integrity (Senkondo et al., 2017, 2019). Such connectivity-driven responses highlight that LULC impacts on hydrology are not solely local but operate across scales, affecting basin-wide water availability and risk (Dwivedi et al., 2025).

Seasonal hydrological responses to LULC change are particularly important in tropical and semi-arid regions, where rainfall is highly variable, and water resources are already under stress (Mahay et al., 2025a). In these environments, land cover degradation commonly intensifies hydrological extremes by increasing wet-season runoff and flood magnitude while reducing dry-season flows and groundwater contributions (Senkondo et al., 2017). This seasonal asymmetry has significant implications for water supply reliability, irrigation planning, hydropower generation, and ecosystem services. Reduced baseflow during dry seasons affects riverine habitats, water quality, and the availability of water for domestic and agricultural use, while enhanced wet-season flows increase erosion, sedimentation, and flood damage (Mahay et al., 2025b). As climate variability and change interact with LULC dynamics, these effects are expected to intensify unless mitigated through sustainable land management and integrated watershed planning (Herano et al., 2025).

Advances in hydrological modeling, supported by remote sensing and geographic information systems (GIS), have significantly improved the ability to quantify and attribute hydrological changes to LULC dynamics (Mbungu & Kashaigili, 2017). Physically based and semi-distributed models such as SWAT, SWAT+, and VIC are widely applied to simulate the impacts of historical and projected land-use scenarios on runoff, evapotranspiration, groundwater recharge, and streamflow components (Arnold et al., 2012; Mbungu & Kashaigili, 2017; Sisay et al., 2017; Tumbo & Hughes, 2015). Recent modeling studies consistently demonstrate that unmanaged land conversion leads to increased runoff volumes, reduced infiltration, declining baseflow, and greater flow variability, while conservation-oriented land uses such as reforestation, agroforestry, and riparian buffer restoration can partially restore hydrological regulation functions (Guzha et al., 2018). These tools provide critical evidence for scenario analysis, supporting land-use planning decisions that balance development objectives with hydrological sustainability (Price et al., 2011).

The implications of LULC-hydrology interactions extend beyond flow quantity to encompass water quality, sediment transport, ecosystem health, and long-term water security (Blöschl, 2022; Blöschl et al., 2019; CDM Smith, 2016). Increased runoff from degraded or impervious landscapes enhances the transport of sediments, nutrients, and pollutants into river systems, degrading water quality and increasing treatment costs (Blöschl, 2022; CDM Smith, 2016). Altered flow regimes disrupt ecological processes that depend on natural variability, such as fish migration, sediment flushing, and floodplain inundation. From a water resources management perspective, failure to account for LULC dynamics can lead to overestimation of available water, under-designed infrastructure, and maladaptation to future climate and development pressures (Sigalla et al., 2024). Consequently, integrating LULC considerations into hydrological assessments, environmental impact studies, and basin-scale planning is essential for achieving resilient and sustainable water resources management under conditions of rapid land transformation and climate uncertainty (Sigalla et al., 2024).

1.3. Objectives

The main focus of this study was to investigate the specific implications of the catchment LULC dynamics in the flow of Kilombero River as gauged at Swero 1KB17.

Specifically, the study was guided by the following specific areas of focus:

i) To set up a SWAT model and identify the important parameters for hydrologic modeling.

ii) To evaluate the hydrologic response of the Kilombero river at the most downstream gauging station, i.e., the Swero 1KB17 gauging station.

iii) To characterize the dry season river flow against the recommended minimum e-flow.

2. Methodology

2.1. Study Area

The current assessment focused on the hydrologic boundaries of the Kilombero

River Catchment (KRC) (**Figure 1**). This is part of Tanzania's largest hydrologic basin, i.e., the Rufiji River Basin (RRB), which is spread across the 177,420 km^2 (about 20% of Tanzania). KRC, in particular, extends between Longitudes 34˚00'E - 37˚20'E and Latitudes 07˚40'S - 10˚00'S and covers an area of approximately 40,000 km^2 (WREM & RBWB, 2013). Although KRC forms the second largest of the RRB catchments, it's the most important in terms of flow contribution (**Table 1**). The cross-section of the catchment (**Figure 2**) is characteristic of a graben structure with Udzungwa mountain ranges and Mbarika escarpments forming the northerly and southerly crests, respectively, while the middle part (the flood plain) forms the trough extending around 1967 km^2 (Kato, 2007; Mombo et al., 2011). This middle portion of the catchment constitutes one of the largest wetlands in East Africa, i.e., the Kibasira wetland, which is at around 300 m above mean sea level (Kangalawe & Liwenga, 2005), and most of its area is internationally designated as a Ramsar site for its environmental significance (Wilson et al., 2017). KRC is the most important catchment in respect of agricultural development potential, energy production, natural resources, and flow to RRB (Wilson et al., 2017). Tributaries that form the

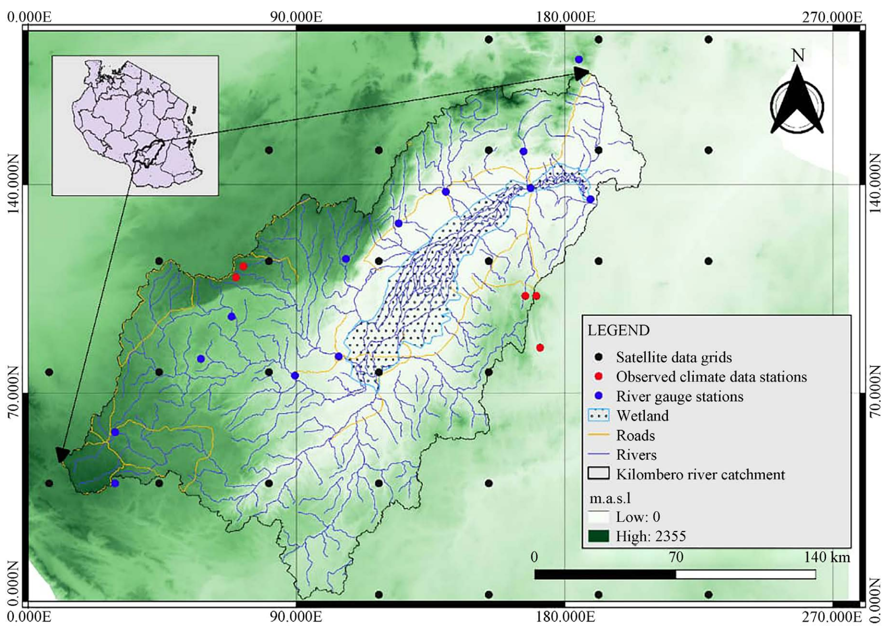

Figure 1. Map of Kilombero River Catchment showing the surveyed villages/wards.

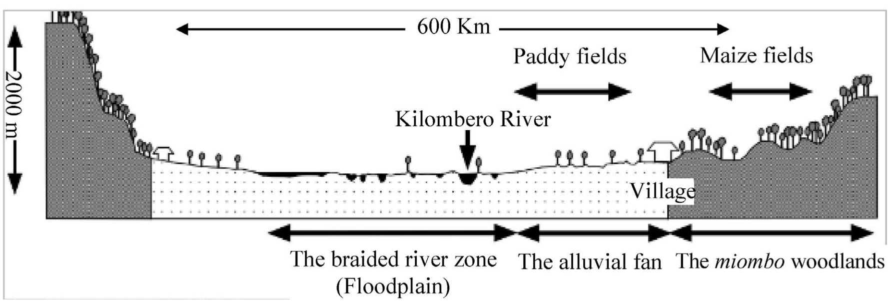

Figure 2. Cross-section of the Study area—adopted from Kato (2007).

Table 1. Attributes of the river catchments in the larger Rufiji River Basin.

No	Sub Basins	Catchment Area	% of Drainage Area	% of Annual Runoff
1	Great Ruaha	85,554	47	15
2	Kilombero	40,430	23	62
3	Luwegu	26,300	15	18
4	Rufiji	27,160	15	5
5	**Total**	**183,791**	**100**	**100**

*Source: WREM & RBWB (2013)—IWRMD plan exercise.

Kilombero River are Lumemo, Luipa, Mngeta, Kihansi, Mpanga, Mnyela, Ruhuji, and Furua. Most areas of KRC are situated in the administrative region of Morogoro, where its most developed center (Ifakara) is found some 230 km from Morogoro town or 400 km from Dar es Salaam, the commercial city of the country.

2.2. Data Collection, Tools, and Techniques

2.2.1. Data Used

This research work used daily observed climatic and river discharge data from the Tanzania Meteorological Authority (TMA) and the Rufiji Basin Water Board (RBWB), respectively. The data, its pattern, trend, and magnitude of trend have been adopted from Sigalla et al. (2023). The monthly temperature and precipitation projected data were obtained from the Regional Climate Models (RCMs), which are under the Coordinated Regional Climate Downscaling Experiment (CORDEX) AFR-44 domain, ranging from 2021 to 2050 with a resolution of 0.44˚ east and 0.44˚ north. This helped all three major climatic zones of Udzungwa: the escarpment, the Mahenge escarpment, and the lower-lying Kilombero Valley. These satellite data were accessed and downloaded on 23rd August 2025 from respective online platforms as summarized in **Table 2** below. The justification of the suitability of the historical satellite data was carried out by Dinku et al. (2018) and Gebrechorkos et al. (2018), whereas that of the projected data was performed by Nikulin et al. (2012). The same data have also been extensively used by previous scholars, such as Borhara et al. (2020), Luhunga et al. (2018), and Näschen et al. (2019b).

Table 2. The data set used in this study includes observed and satellite data.

N	Station Name	Range	Data Type	Resolution	Source
1	Kilombero at Swero	1957-1981	Observed Discharge	Daily	RBWB
2	Ifakara MET	2017-2019	Observed Precipitation & Temperature	Daily	
3	Mngeta MET			Daily	
4	Echidna	1951-2009	Observed Precipitation		TMA
5	Kwiro	1933-2009			
6	Mahenge Hosp	1950-2008		Daily	

Continued

7	Mahenge RF	1993-2019			
8	Matugutu	1961-2015	Observed Precipitation		TMA
9	Ruaha Mission	1950-2002			
10	Mahenge	1993-2019	Observed Temperature	Daily	
11	29 Satellite Station Grids	1981-2020	Precipitation	Daily	CHIRP
			Temperature		ORH
			Evaporation		From Temp.
		2021-2050	Precipitation	0.44˚ East and 0.44˚ North (Monthly)	CORDEX AFR-44
			Temperature		
			Evaporation		
12	DEM	N/A	Elevation	30 m × 30 m	SRTM

The details of LULC data and analysis are adopted from a parallel study by the corresponding author that assessed LULC between 1991 and 2021and projected to 2041 (Sigalla et al., 2024). Soil data and information on related soil properties were obtained from the Food and Agriculture Organization (FAO) soil map (FAO, 2005).

2.2.2. Model Selection and Setup

The Soil and Water Assessment Tool (SWAT) was used to accomplish this objective. This tool is a continuous time and spatially distributed basin-level framework designed to simulate the quality and quantity of surface and groundwater and predict the ecosystem impact of LULC, land management practices, and climate change on a daily time step, monthly, or even annually (Arnold & Fohrer, 2005; Gassman et al., 2007). It uses hydrologic response units (HRUs) that consist of specific land use, soil, and slope characteristics (Sisay et al., 2017). HRUs are used to describe spatial heterogeneity in terms of land cover, soil type, and slope class within a watershed. The relevant hydrologic parameters, e.g., evapotranspiration, surface runoff, groundwater flow, and sediment yield for each HRU unit, are estimated by the model. The model is very useful because it has a weather engine to generate the precipitation within an un-gauged watershed based on stochastic and probabilistic methods (Chilagane et al., 2021).

Scholars such as Shope et al. (2014) have attempted to assess the capability of the SWAT model to capture event-based and long-term rainfall-runoff processes in complex terrain. Results showed the robustness of the model even though it is influenced by the scale-dependent sensitivity of hydrologic partitioning and the substantial influence of engineered features (Shope et al., 2014). The SWAT model has been extensively used for thirty years of experimentation by the Agriculture Research Service (ARS) of the United States Department of Agriculture (USDA) (Arnold & Fohrer, 2005; Gassman et al., 2007). Since then, the tool has been used in numerous river basins globally, especially in the tropical Tanzania case across the majority of the nine river and lake basins (Cheema et al., 2014; Parajuli et al., 2018; Senkondo et al., 2019; Wambura et al., 2018). SWAT is an extension of a GIS interface, such as Arc-SWAT, which is an extension of ArcGIS based on the water balance Equation (1) below.

$$SW_t = SW_o + \sum_{i=1}^{t}\left(R_{day} - Q_{sur} - E_a - W_{seep} - Q_{gw}\right) \tag{1}$$

where: SW_t is final soil water content (mm), SW_o is the initial soil water content in day i (mm), t is time in a day, R_{day} is precipitation amount on specific days i (mm), Q_{sur} is the runoff amount on specific days i (mm), E_a is evapotranspiration amount on day i (mm), W_{seep} is the amount of water percolated into the vadose zones on a day i (mm) and Q_{gw} is the return amount of flow on a day i (mm).

2.2.3. Model Calibration

Model calibration and validation to reduce the prediction uncertainty were performed by using the Sequential Uncertainty Fitting (SUFI-2) within the SWAT-CUP (Abbaspour et al., 2007). Calibration and validation were conducted using monthly flow data for the period 1962-1965 and 1966-1969, respectively. 3 years prior to 1962 were used as a warm-up period to provide a steady-state condition and mitigate unknown initial conditions to the model. Four objective functions, namely, Nash-Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2), Probability Bias (PBIAS), and Root Mean Square Error (RMSE), were employed to assess the performance of the model (Chilagane et al., 2021; Mazengo et al., 2022; Mutayoba et al., 2018). The general performance rating statistics for the selected objective function, as proposed by Gyamfi et al. (2016) and Moriasi et al. (2007), were used to determine the performance of the model.

The Nash-Sutcliffe efficiency (NSE) determines the relative size of the residual variance in relation to the measured data variance (Nash & Sutcliffe, 1970). It is used in the model to indicate how well the plot of observed versus simulated data fits the 1:1 line (Moriasi et al., 2007). Nash-Sutcliffe efficiency range from −∞ to 1 where efficiency of one ($E = 1$) corresponds to a perfect match of modeled discharge to the observed data, efficiency of zero ($E = 0$) indicates that the model predictions are as accurate as the mean of the observed data, and efficiency less than zero ($E < 0$) occurs when the observed mean is a better predictor than the model. Principally, the closer the model efficiency is to 1, the more accurate the model is. The NSE is calculated following Equation (2):

$$NSE = 1 - \frac{\sum_i \left(Q_i - Q_s\right)^2}{\sum_i \left(Q_i - \overline{Q_i}\right)^2} \tag{2}$$

The coefficient of determination (R^2) measures the strength of the linear correlation between the predicted and measured variables. It ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Van Liew et al., 2003). It is calculated as Equation (3):

$$R^2 = \left[\frac{\sum_i (Q_i - Q_s)(Q_s - \overline{Q_s})}{\left(\sum_{i=1}^{n} (Q_i - \overline{Q_i})\right)^{0.5} \left(\sum_{i=1}^{n} (Q_s - \overline{Q_s})\right)^{0.5}} \right]^2 \quad (3)$$

Root mean square error—observed standard ratio (RSR) is the measure of goodness of fit between observed and simulated time series data, and is the ratio of the Root Mean Square Error (RMSE) and standard deviation of measured data. According to Legates & McCabe Jr (1999), RSR standardizes RMSE using the observations' standard deviation. It combines an error index and the additional information recommended. It is commonly accepted that the lower the RMSE, the better the model performance. RSR is calculated as Equation (4):

$$RSR = \frac{RMSE}{STD_{obs}} = \frac{\sqrt{\sum_{i=1}^{n} (Q_i - Q_s)^2}}{\sqrt{\sum_{i=1}^{n} (Q_i - \overline{Q_i})^2}} \quad (4)$$

Probability BIAS (PBIAS) is the indicator of how much (in percentage) the simulated variable is larger or smaller than its observed counterparts (Gupta et al., 1999). The optimum value of PBIAS is zero, where low magnitude values indicate better simulations, positive values indicate model underestimation, and negative values indicate model overestimation (Gupta et al., 1999). It is calculated as Equation (5):

$$PBIAS = \frac{\sum_{i=1}^{n} (Q_i - Q_s)}{\sum_{i=1}^{n} Q_i} \times 100\% \quad (5)$$

where: Q_i is the observed variable (e.g., discharge), Q_s is the simulated variable, and $\overline{Q_i}$ is the mean of observed variables, RMSE is the root mean square error, and STD_{obs} is the standard deviation of the observed variable.

2.2.4. Simulation Analysis

To assess the impacts of LULC change on the hydrology of the Kilombero Catchment, the fixed-change scenario was used, as proposed by Gyamfi et al. (2016) and Yan et al. (2013). In this scenario, the calibrated and validated model was used to simulate stream flows under changed land-use/cover conditions for the years 1991, 2001, 2011, 2021, and 2041, while maintaining the same meteorological data, soil data, and digital elevation model as described in section 2.2.1 above. The influences of the land use land cover change on water resources and other hydrological components were quantified by comparing SWAT outputs for the different scenarios. The differences between observed outputs were used to represent the effects of land use and land cover changes on water resources in the catchment. Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) in the SWAT model was used to simulate the sediment yield from the catchments (Neitsch et al., 2011). The simulated sediment yield results for the time periods 1991, 2001, 2011, and 2021 were compared to generate the difference that was then deduced to reveal the impact of LULC change on sediment yields.

3. Results and Discussions

3.1. Sensitive Parameter

The general assessment compiled the sensitive parameters, which are presented in Table 3, which gives a summary of parameters that were deemed most sensitive to flow prediction in the SWAT model. The groundwater delay (GW_DELAY), which indicates the time in days taken for water to move past the lowest depth of the soil profile by percolation was found to be the most sensitive parameter, followed by the available water capacity of the soil layer (SOL_AWC), base flow alpha factor, threshold depth of water in the shallow aquifer required for return flow, and surface runoff lag time.

Table 3. List of model-sensitive parameters indicating their respective fitted values.

Rank	Parameter	Parameter Definition	Fitted Value
1	GW_DELAY.gw	Groundwater delay	50.368050
2	SOL_AWC	Available water capacity of soil layer	0.376560
3	CN2.mgt	SCS runoff curve number	0.262836
4	ALPHA_BF.gw	Base flow alpha factor	0.866660
5	GWQWN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	1.430101
6	SURLAG	Surface runoff lag time	6.342687
7	GW_REVAP	Threshold depth of water in the shallow aquifer for "revap" to occur	0.069006

3.2. Model Accuracy

As pointed out above, the accuracy assessment was performed by comparing the results between the observed and simulated stream flows. Following the model performance evaluation criteria by Moriasi et al. (2015), this showed a good performance during calibration and moderate performance during validation, indicating reasonable simulation capability despite increased uncertainty during the validation period. Table 4 gives a summary of the statistical performance of the model during calibration and validation. Assessment results show that during the years of calibration from 1962 to 1965, the mean observed was 669.81 m^3/s, whereas that of the simulation was 672.61 m^3/s. In addition, the generated results for the validation period 1966 to 1969 also show that the values of these same parameters are 547.70 m^3/s for observed flow and 649.70 m^3/s for simulated flow. In addition, although the model demonstrated a consistent overestimation of stream flow, it adequately reproduced the temporal pattern and variability of observed flows (Figure 3 and Figure 4). The reduced performance during validation is attributed to data limitations, including sparse and inconsistent historical hydro-climatic records, which introduced uncertainty in model inputs and parameterization.

Figure 3 and Figure 4 present the flow hydrograph for the period during calibration and validation, respectively. In addition, Figure 5 represents the comparison of measured and simulated stream flow during model calibration and validation.

Table 4. Evaluation statistics for calibration and validation for Kilombero at Swero 1KB17.

Calibration				Validation				Calibration		Validation	
NSE	R^2	RSR	PBIAS	NSE	R^2	RSR	PBIAS	Ob-Flow (m^3/s)	Sim-Flow (m^3/s)	Ob-Flow (m^3/s)	Sim-Flow (m^3/s)
0.65	0.66	0.60	0.4	0.42	0.46	0.76	18.6	669.81	672.81	547.70	649.70

*Ob-flow is observed flow, sim-flow is simulated flow.

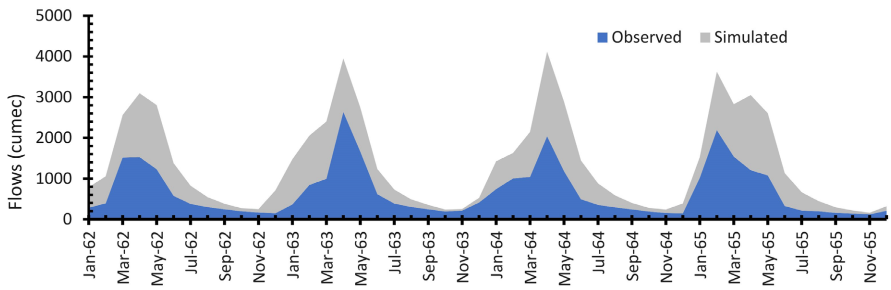

Figure 3. Measured and simulated flow data for the calibration period.

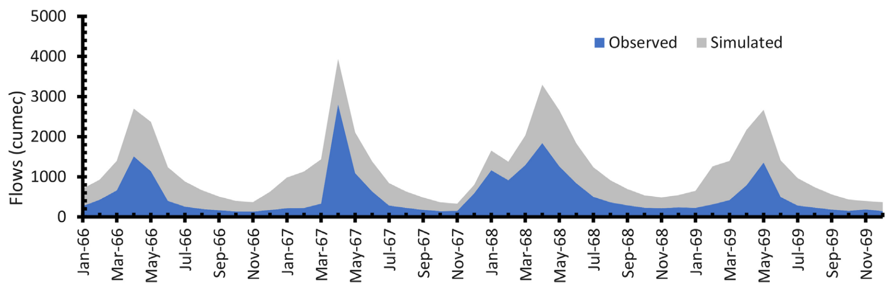

Figure 4. Measured and simulated flow data for the validation period.

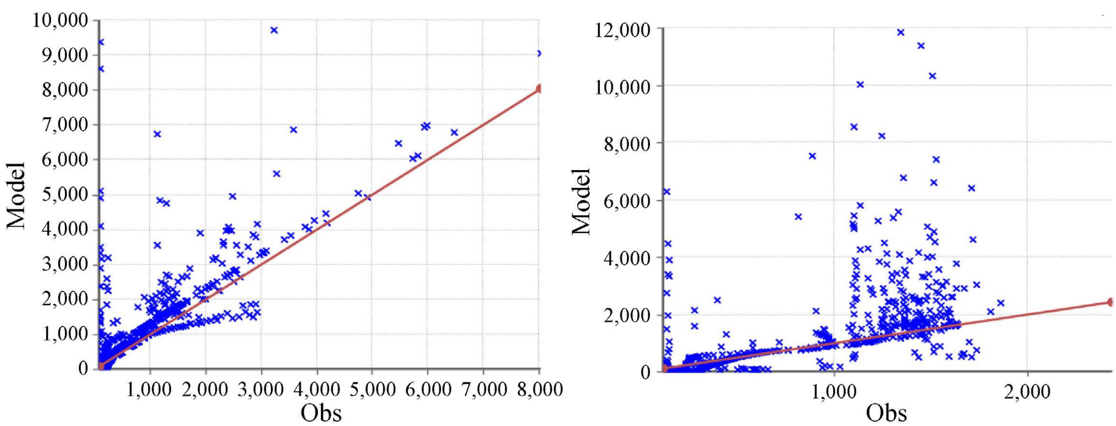

Figure 5. Measured vs simulated stream flow data for model calibration (left) and validation (right).

3.3. Basin Water Balance

The model output shows average annual water balance components (WBCs) in mm, such as precipitation, evapotranspiration, surface runoff, lateral flow, percolation, return flow, etc., as illustrated in **Figure 6**. The water balance within SWAT involves considering precipitation as inflow to the watershed unit while accounting for evapotranspiration and deep percolation as losses and surface runoff, return flow, and lateral flow as outflows. According to the model results, the catchment typically receives an average of 1339 mm of annual precipitation. This precipitation is then distributed among various components, including evapotranspiration, surface runoff, lateral flow, shallow aquifer storage, and deep aquifer recharge. The analysis shows that 482 mm/yr of rainfall is lost from the Kilombero catchment through evapotranspiration, representing the largest component of the water balance and accounting for 36% of the rainfall received. Furthermore, it's noted that 408 mm/yr, representing 30% of precipitation, flows out from the catchment as surface runoff and 3% as lateral flows. The remaining portion of about 395 mm/yr, representing 29% of received precipitation, percolates to the shallow aquifer, whereby only 19.79 mm/yr, accounting for 5% of it, recharges the deep aquifer while the remaining flows outside the catchment as return flows.

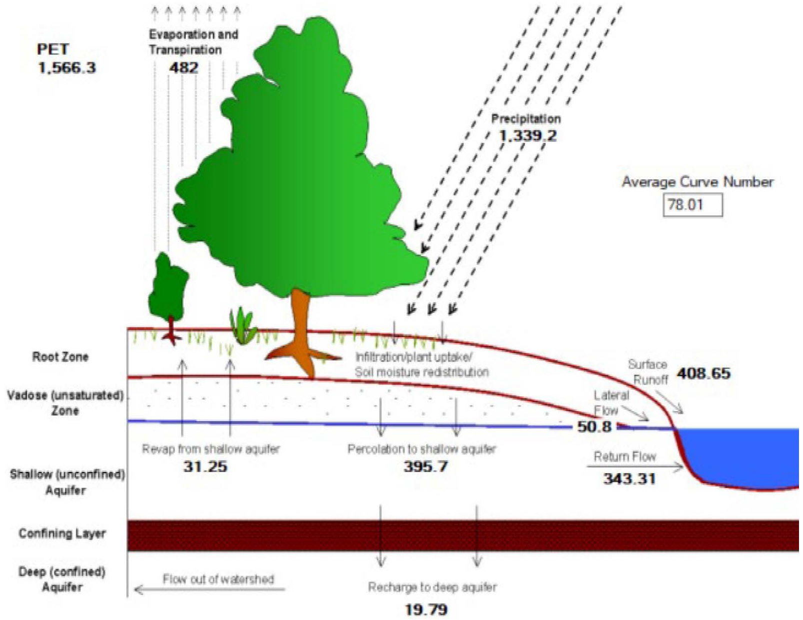

Figure 6. Modeled water balance for Kilombero River Catchment showing all the important components of a hydrologic system (all units are in mm).

3.4. Impacts of Land Use/Cover Change on Water and Sediment Yields

The results for the annual averages of the hydrological parameters for the study area are summarized in Table 5. These averages are calculated under changing LULC to build an understanding of how LULC has contributed to hydrological changes in terms of water quality (sediment load) and quantity. The message drawn from the model results for the years between 1991 and 2021, as presented in Table 4, is that the change of LULC has contributed to the increase in average annual surface runoff by 38.66 mm and a decrease in average annual groundwater contribution to stream flow or base flow by 31.67 mm. Water percolation to the soil profile decreased by 1.67 mm, and groundwater contribution to deep aquifers and overall aquifers (shallow and deep) decreased by 1.67 mm and 33.35 mm, respectively. Actual evapotranspiration decreased by 3.9 mm. Based on these, the average annual water yields to stream flow and sediment yield from HRU in the watershed have increased by 4.67 mm and 18.35 Tons/Ha, respectively. SWAT simulations of the future scenarios show similar expected changes in water and sediment yields in the study area for the next two decades from 2021 (**Table 5**). Results show the average annual surface runoff or overland flow will increase by 21.14 mm, water percolation to the soil profile will decrease by 1.27 mm, groundwater contribution to streamflow will decrease by 27.95 mm, groundwater contribution to the deep aquifer, and overall aquifer (shallow and deep) will decrease by 1.23 mm and 24.53 mm, respectively. At the same time, the average annual water yield will decrease by 13.46 mm while sediment yield has slightly increased by 1.83 Tons/Ha, which translates to an increment in soil loss from 42.13 Tons/Ha in 2021 to 43.95 Tons/Ha by 2041. Furthermore, the model revealed that the LULC changes have also impacted the dry seasonal flow of the Kilombero River. SWAT scenarios for LULC of 2001, 2021, and 2041 revealed a decline in the average dry season (June to October) river discharge at the Swero 1KB17 gauge station following LULC transformation (**Figure 7** and **Figure 8**). The monthly averages for different land use scenarios are also presented in **Table 6**. The comparison of the data, as illustrated in **Figure 7** and **Figure 8**, shows that dry season river discharge for the LULC scenarios is already lower than the recommended environmental flow (e-flow) as recommended by (CDM Smith, 2016). This shows that the hydro-climatic parameters that drive catchment hydrology cannot support ecosystem integrity, given the growth of sectors of the economy (led by farming).

Other scholars in Tanzania and elsewhere around the world have also studied and indicated similar relationships between changes in LULC and its manifestations to increased sediment yield and surface (Allan, 2004; Chilagane et al., 2021; Kiersch, 2002). These changes in runoff generation are in agreement with the general knowledge that reducing forest cover decreases the opportunity for infiltration, which in turn leads to an increase in water yield due to increased surface runoff. This phenomenon brings adverse environmental issues in the catchment, including soil erosion and siltation of water bodies, as also observed by (Kashaigili, 2008; Näschen et al., 2019a). Furthermore, the decrease in percolated water and hence recharge of aquifers is the aftermath of vegetation cover removal, which in turn decreases the opportunity of infiltration to the extent that surface flow exceeds the gain in base flow, which results in diminished dry seasonal flow as highlighted by (Chilagane et al., 2021; Kashaigili, 2008). As pointed out in this document, HEP prospects by the government through a mega dam downstream will inevitably suffer the impacts of the sediments generated upstream. Furthermore, the changed flow regime, particularly dry season river flows, will have negative impacts on the biotic components of the ecosystem found within and outside the catchment. This will include smallholder farmers' livelihoods dependent on the Kilombero River and its tributaries and the wildlife ecosystem in the Kibasila wetland and downstream in Nyerere National Park, which will, in turn, impact the tourism industry as a whole.

Table 5. Historical and future annual hydrological summary for the watershed.

Scenarios	SURQ	LATQ	GW_ SHWQ	GW_ DPQ	AQ_ DEEP	AQ_T	WTRYLD	PERC	ET	SDYLD
1991	272.98	55.77	370.62	21.00	20.91	418.11	720.36	417.16	626.40	23.77
2001	274.17	55.80	369.52	20.95	20.85	416.96	720.40	416.01	626.20	24.07
2011	304.53	55.40	344.77	19.64	19.55	390.90	724.32	390.07	622.90	31.16
2021	311.64	55.11	338.95	19.33	19.24	384.76	725.03	383.94	622.50	42.13
2041	332.78	49.64	311.00	18.06	18.01	360.23	711.57	360.55	620.20	43.95
Change (1991-2021)	38.66	−0.66	−31.67	−1.67	−1.67	−33.35	4.67	−33.22	−3.90	18.35
Change (%)	14.16	−1.18	−8.55	−7.95	−7.99	−7.98	0.65	−7.96%	−0.62%	77.19%
Change (2021-2041)	21.14	−5.47	−27.95	−1.27	−1.23	−24.53	−13.46	−23.39	−2.3	1.826
Change (%)	6.78	−9.93	−8.25	−6.57	−6.39	−6.38	−1.86	−6.09%	−0.37%	4.33%
Change (1991-2041)	59.80	−6.13	−59.62	−2.94	−2.90	−57.88	−8.79	−56.61	−6.20	20.18
Change (%)	21.91	−10.99	−16.09	−14.00	−13.87	−13.84	−1.22	−13.57%	−0.99%	84.87%

Where: SURQ: Surface runoff contribution from stream flow from HRU (mm). LATQ: Lateral flow contribution to streamflow in watershed for the day, month, or year (mm). GW_SHWQ: Groundwater contribution to stream in watershed on day, month, year (mm). GW_DPQ: Amount of water moving from shallow aquifer to plants/soil profile in watershed during simulation (mm). AQ_DEEP: Groundwater contribution to deep aquifer (mm). AQ_T: Total amount of water entering both aquifers in the watershed during simulation (mm). WTRYLD: Water yield to streamflow from HRUs in watershed for simulation (mm). PERC: Water percolation past the bottom of the soil profile (mm). ET: Actual evapotranspiration in watershed (mm). SDYLD: Sediment yield from HRUs in the watershed for the simulation (Tons/Ha).

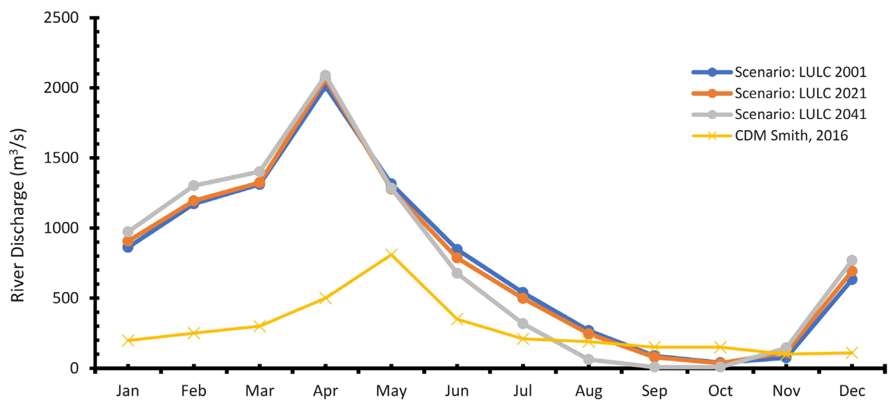

Figure 7. All-season average discharge in the Kilombero River at Swero (1KB17) gauging station showing near-zero dry season flow for scenario 2041 LULC.

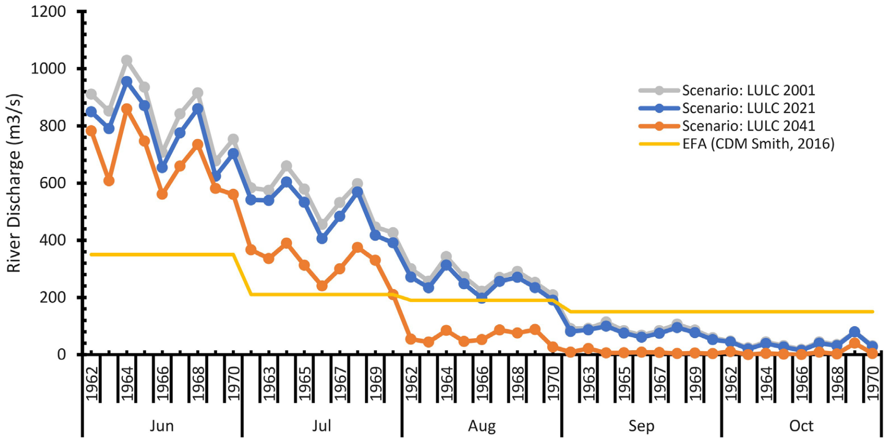

Figure 8. Dry season average discharge in the Kilombero River at Swero (1KB17) shows a consistent decrease in long-term dry season flows.

Table 6. Seasonal river discharge at different LULC scenarios for 1KB17.

Months	Average Discharge (m³/s)		
	Scenario: LULC 2001	Scenario: LULC 2021	Scenario: LULC 2041
Jan	862.44	906.22	972.88
Feb	1172.64	1194.24	1302.12
Mar	1311.34	1324.09	1402.13
Apr	2011.22	2063.11	2088.22
May	1314.17	1278.03	1283.96
Jun	847.03	786.89	677.04
Jul	539.34	498.22	317.89
Aug	268.48	246.10	62.06
Sep	87.14	78.06	8.03
Oct	39.61	35.94	8.08
Nov	74.52	113.96	144.39
Dec	633.06	692.59	769.07
Total	**9161.00**	**9217.46**	**9035.87**
Average	**763.42**	**768.12**	**752.99**

3.5. Contribution of Individual LULC to Surface Runoff and Sediment Yield

The proportional contribution of individual LULC to surface runoff and sediment yield is illustrated in Figure 9 and summarized in Table 7 below. According to these assessment results, it is demonstrated that cultivated land and grassland are the main contributors to both surface runoff and sediment yields, with the former being the highest in both cases, i.e., sediment yield of 66.37 Tons/Ha and water yield of 492.64 mm. These two are followed chronologically by wetlands, built-up areas, woodland, and forests in terms of their contribution to surface runoff generation. However, Bushland, which is the least contributor of water runoff in this second batch, had the highest contribution of sediment yield among all of them in the batch. The change in the landmass occupied by water had negligible contributions to both sediment yield and surface runoff.

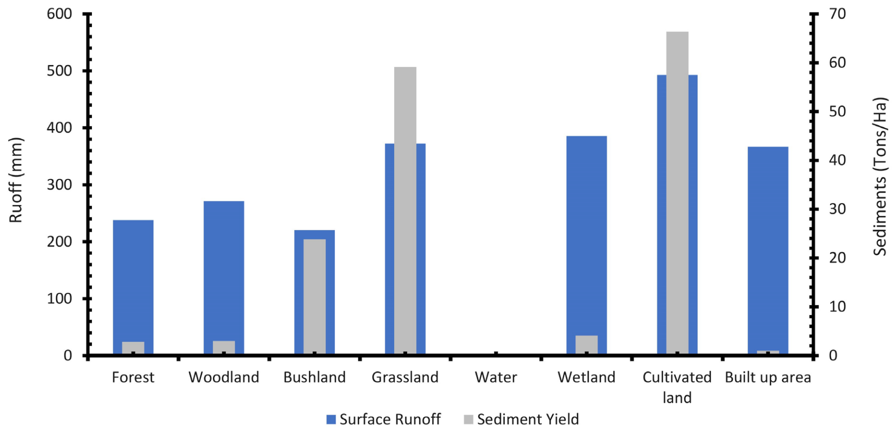

Figure 9. The contribution of individual LULC types to surface runoff and sediment yield shows that farms and grassland are most consequential.

Table 7. The contribution of individual LULC types to surface runoff and sediment yield shows that farms and grassland are most consequential.

N	Individual LULC	Surface Runoff (mm)	Sediment Yield (Tons/Ha)
1	Forest	238.14	2.82
2	Woodland	271.39	2.98
3	Bushland	220.3	23.82
4	Grassland	372.39	59.13
5	Water	0	0
6	Wetland	385.35	4.1
7	Cultivated land	492.64	66.37
8	Built-up area	366.75	1.01

4. Conclusions and Recommendations

4.1. Conclusions

This study has demonstrated that land use and land cover (LULC) dynamics have exerted a significant and measurable influence on the hydrological response of the Kilombero River Catchment. Using a calibrated and validated SWAT model, the research successfully quantified the impacts of historical (1991-2021) and projected (2021-2041) LULC changes on key hydrological components, including surface runoff, groundwater recharge, baseflow, sediment yield, and seasonal river discharge at the Swero (1KB17) gauging station. The model performance statistics indicated moderate and satisfactory validation and calibration periods, respectively. The weak performance during validation is attributable to limitations in data availability, which are characteristic of the Kilombero River catchment. However, the pattern between observed and simulated flows confirms the robustness of SWAT in representing hydrological processes in data-scarce and hydrologically complex catchments such as the Kilombero. However, flow estimation should be cautiously observed as the data limitations introduced some robustness issues by consistently overestimating stream flow.

The results clearly show that LULC transformation, particularly the expansion of cultivated land and grassland at the expense of forests, woodlands, and natural wetlands, has led to increased surface runoff and sediment yield while concurrently reducing groundwater recharge and dry-season baseflow. Between 1991 and 2021, surface runoff increased by approximately 14%, while groundwater contribution to streamflow declined by more than 8%, indicating a progressive shift from subsurface-dominated to runoff-dominated hydrological processes. This shift has enhanced annual water yield and sediment export but at the cost of reduced hydrological regulation and diminished low-flow resilience of the river system. Future LULC scenarios to 2041 suggest a continuation of these trends, with further increases in overland flow, continued decline in aquifer recharge, and a projected reduction in total water yield. Most critically, the simulated dry-season flows (June-October) show a pronounced decline under future LULC conditions, with monthly discharges falling well below the recommended environmental flow requirements. This finding indicates that current and projected land use practices threaten the ecological integrity of the Kilombero floodplain and associated wetlands, including the internationally recognized Ramsar site, as well as downstream ecosystems such as the Nyerere National Park and the Rufiji delta mangrove ecosystem.

Furthermore, the analysis of individual LULC contributions revealed that cultivated land and grassland are the dominant sources of both surface runoff and sediment yield, accounting for the largest proportion of hydrological alteration within the catchment. Forests and woodlands, although reduced in spatial extent, were shown to play a critical role in moderating runoff and sediment production, underscoring their importance in sustaining baseflow and catchment stability. The disproportionate contribution of agricultural landscapes to hydrological degradation highlights the central role of land management practices in shaping river flow regimes and sediment dynamics.

Overall, the findings of this study confirm that LULC change is a key non-climatic driver of hydrological alteration in the Kilombero River Catchment, with direct implications for water resources sustainability, environmental flow compliance, agricultural livelihoods, hydropower development, and ecosystem conservation. Without deliberate intervention, continued land conversion is likely to exacerbate hydrological extremes, which will intensify wet-season flooding while deepening dry-season water scarcity. The study therefore emphasizes the urgent need to integrate LULC planning, catchment conservation measures, and environmental flow considerations into basin-scale water resources management frameworks to safeguard the long-term hydrological and ecological functioning of the Kilombero River system.

4.2. Recommendations

The study underscores that hydrological degradation in the Kilombero River Catchment is driven primarily by LULC change rather than climatic variability alone. Sustainable hydrological outcomes will therefore depend on proactive land management, ecosystem protection, and evidence-based water allocation policies. Implementing the list of recommendations below will enhance dry-season flow resilience, reduce flood and sediment risks, and safeguard the long-term ecological and socioeconomic value of the Kilombero basin.

i) Strengthen catchment land use planning and regulation by explicitly incorporating hydrological sensitivity and environmental flow requirements.
   a) Enforce land-use zoning that restricts further conversion of forests, wetlands, and riparian buffers into cultivated or settlement areas, particularly in hydrologically sensitive upper and mid-catchment zones.
   b) Integrate hydrological impact assessments into district and regional land-use plans to evaluate the downstream flow implications of proposed land conversions.
   c) Designate critical recharge zones and wetland areas as protected landscapes under national land and environmental legislation.

ii) Promote sustainable agricultural land management by limiting agricultural expansion and promoting intensification with a strong link to soil and water conservation principles so as to reduce runoff and sediment losses.
   a) Promote conservation agriculture practices, including minimum tillage, contour farming, mulching, and crop rotation, especially in cultivated and grassland-dominated sub-catchments identified as major runoff and sediment contributors.
   b) Support agroforestry systems that combine crop production with tree cover to enhance infiltration, reduce erosion, and stabilize baseflow.
   c) Introduce incentives (e.g., subsidies, extension services) for farmers to adopt best management practices that improve catchment hydrological performance.

iii) Restore and protect forests, woodlands, and wetlands as a cost-effective hydrological regulation strategy.
   a) Implement targeted reforestation and afforestation programs in degraded upper catchments and riparian corridors to restore infiltration capacity and reduce peak flows.
   b) Protect and rehabilitate wetlands within the Kilombero floodplain to enhance natural flow buffering, groundwater recharge, and sediment trapping.

c) Strengthen enforcement against illegal logging and encroachment in forest and wetland reserves.

iv) Safeguard Environmental flows by formally incorporating them into water allocation and abstraction frameworks.

a) Establish and enforce minimum environmental flow thresholds at key gauging stations, particularly during the dry season when model results indicate critical flow deficits.

b) Review and adjust water abstraction permits for irrigation, hydropower, and other uses to ensure compliance with environmental flow targets.

c) Integrate environmental flow monitoring into routine basin water resources assessments.

v) Enhance Hydrological Monitoring and Data Management for better adaptive catchment management.

a) Upgrade and expand hydrometeorological monitoring networks (streamflow, rainfall, sediment) across the catchment, with priority given to data-scarce sub-basins.

b) Establish a centralized basin-wide hydrological and LULC database to support modeling, planning, and decision-making.

c) Promote routine use of remote sensing and GIS tools for near-real-time monitoring of LULC changes and floodplain dynamics.

vi) Institutionalize Integrated Modeling and Scenario Analysis by embedding hydrological modeling into planning and policy evaluation processes.

a) Institutionalize the use of SWAT or similar basin-scale models within the Basin Water Board and related agencies for evaluating land-use, climate, and development scenarios.

b) Regularly update LULC datasets and recalibrate hydrological models to reflect ongoing land transformation and infrastructure development.

c) Use scenario analysis to inform long-term investment decisions in irrigation schemes, flood control infrastructure, and hydropower development.

vii) Strengthen cross-sectoral coordination and governance.

a) Establish and/or empower the formal coordination mechanisms between water, land, agriculture, forestry, and environmental institutions to harmonize policies and interventions.

b) Engage local communities, conservation authorities, and private-sector stakeholders in participatory catchment management initiatives.

c) Align basin-level strategies with national development plans, climate adaptation strategies, and international conservation commitments (e.g., Ramsar Convention).

Author Contributions

Conceptualization: O.Z.S and M.T.; Methodology: O.Z.S., N.A.C., and M.T.; Software: N.A.C.; Validation: M.T. and N.A.C.; Formal analysis: O.Z.S. and N.A.C.; Investigation: O.Z.S. and N.A.C.; Resources: O.Z.S. and M.T.; Data curation: O.Z.S. and N.A.C.; Writing of original draft: O.Z.S.; Writing-review and editing: M.T. and O.Z.S.; Visualization: O.Z.S. and N.A.C.; Supervision: M.T.; Project administration: M.T.; Funding acquisition: M.T. and O.Z.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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