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Effect of Land Use Land Cover on the Hydrology of Rwizi River Catchment located in Southwestern Uganda

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ABSTRACT: Changes in land use and land cover usually affect the hydrological processes of river flows, sediment transport, and water quality on a global scale. Hence, the objective of this paper was to investigate the effect of Land Use Land Cover (LULCC) on the Hydrology of Rwizi River Catchment located in South-western Uganda using appropriate standard techniques and procedures including Soil and Water Assessment Tool (SWAT). Model calibration and validation demonstrated good agreement ($R^2 = 0.76\text{-}0.86$, NSE = 0.75-0.78). LULC analysis revealed significant increases in built-up areas and forestland, with declines in grazing land and wetlands. These changes were driven by socio-economic factors and hydro-climatic influences. The study found strong correlations between LULC types and sediment yield, highlighting the implications for water quality and erosion control. The results show that urban growth raises surface runoff and peak flows as a result of a rise in impervious surfaces, whereas agricultural intensification raises water demand and lowers base flow, especially during dry spells. Deforestation has led to increased sedimentation rates, degrading water quality. These findings underscore the significant anthropogenic and climatic impacts on LULCC dynamics and hydrological processes in the catchment. The study emphasizes the critical need for integrated watershed management strategies to mitigate these impacts and ensure sustainable water management practices. By advancing understanding in hydrological sciences, this research informs policy and management decisions for sustainable development in tropical river basins globally.

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The need to meet increased socio-economic needs, food demand and changing food habits due to the increasing human population has exerted enormous pressure on the global water, land and soil resources (Pointent, 2022; Carvalho, 2017; Baig *et al*., 2019). It is believed that sustainable agricultural practices have the potential to ease these pressures and contribute to global Sustainable Development Goals (Gil *et al*., 2019; Winkel *et al*., 2019; Nicholls *et al*., 2020). This can be achieved through obtaining accurate data (Piñeiro *et al*., 2020; Kamble *et al*., 2020; Saiz-Rubio and Rovira-Más, 2020) and a paradigm shift in how these resources are managed and by maximising synergies and minimising trade-offs (Dandabathula *et*

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al., 2021; Zwetsloot, 2024; Chu *et al*., 2023). Land and water are natural resources with cross – cutting issues that are key for livelihoods and sustainable development (Clark *et al*., 2016; Chaudhary and Hanif, 2022). The risk of water resources depletion is a matter of global concern as it threatens sustainable agricultural and industrial development (Zhang *et al*., 2020; Kılıç, 2020; Barbier, 2019). Catchment land use/ land cover change (LULCC) influences river hydrology at both spatial and temporal scales (Kayitesi *et al*., 2022; Hachemaoui *et al*., 2022), because it contributes to the rate of hydrological processes like runoff, infiltration, precipitation, sedimentation and flooding (Sugianto *et al*., 2022; Erima *et al*., 2024; Kayitesi *et al*., 2022). Accurate data and a paradigm shift in resource management are crucial for ensuring sustainable development and livelihoods. Water scarcity in both quantity and quality aspects compromises health (Mishra *et al*., 2021; Adams *et al*., 2020; Leal *et al*., 2022), limits economic development (Rosa, 2020; Heal *et al*., 2021) and causes deterioration in natural ecosystems (Kılıç, 2020; Assegide *et al*., 2022). The global demand for food is projected to increase by 50% by the year 2050, with developing countries contributing a higher percentage of this; due to their population trends (Van *et al*., 2021; Aryal *et al*., 2022). However, achieving this target will not necessarily be a measure of success (Sachs *et al*., 2019; Cassman, 2016) rather it will be the ability to sustain the environment of productive land and water systems and satisfy livelihoods of both rural and urban populations that will be considered as a success (Barbier 2020; Maja and Ayano, 2021; Mrabet, 2023). River Rwizi covering a catchment of about 8,346km^2 supports livelihoods of more than five million people but has dried up by about 80% due to catchment-based degradation (Muhangane *et al*., 2024; Katusiime, 2023). Despite advancements, comprehensive studies on the combined effects of multiple LULCC drivers in tropical river basins remain limited. This study addresses this gap by focusing on the Rwizi River catchment, employing SWAT to analyze how urban expansion, agricultural intensification, and deforestation influence hydrology over three decades. By providing insights into the cumulative effects of LULCC on river flow dynamics, this research contributes to advancing hydrological sciences and informs policy and management decisions for sustainable development in tropical river basins globally. Gaining an understanding of these processes is essential in creating policies that effectively reduce negative effects on water resources and foster resilience in environments that are rapidly changing. Hence, the objective of this paper is to investigate the effect of Land Use Land Cover (LULCC) on the Hydrology of Rwizi River Catchment located in Southwestern Uganda.

MATERIALS AND METHODS

Study Area: The study focused on the Rwizi River catchment, located in southwestern Uganda (Figure 1). Encompassing approximately 4,704 square kilometers, the catchment is located between longitudes 29° 30' and 30°00' East and latitudes 0° 30' and 1°00' South. Low-lying plains and fairly mountainous areas make up the terrain, with an elevation between 1,200 and 2,000 meters above sea level. Meteorological stations within the basin include: Station 1 (0.318°S, 30.721°E), Station 2 (0.537°S, 30.646°E), Station 3 (0.640°S, 30.751°E), Station 4 (0.713°S, 30.832°E), and Station 5 (0.813°S, 30.902°E).

With distinct wet and dry seasons and an average annual precipitation of 1,000 to 1,500 millimeters, the Rwizi catchment experiences a tropical climate. The long rainy season (March to May) and the short rainy season (September to November) are the periods of high precipitation with an average range of annual temperatures of 18°C to 25°C. Natural vegetation includes tropical savannas, woodlands, and montane forests at higher elevations. Land cover comprises croplands, grazing lands, forest patches, wetlands, and water bodies such as rivers and small lakes. The catchment supports diverse human settlements, from rural villages engaged in subsistence agriculture to urban centers like Mbarara, experiencing rapid growth due to its role as a regional hub. Infrastructure development includes major roads connecting urban centers and agricultural areas, influencing land use patterns. Historically, the Rwizi catchment has undergone significant LULCC driven by agricultural expansion, urbanization, and infrastructure development. Population growth and demographic shifts have impacted land use practices and natural resource management. Previous studies have provided foundational knowledge on LULCC dynamics, hydrological processes, and socio-economic factors influencing environmental change in the region.

SWAT Model: The assessment of the effects of LULCC in the Rwizi River catchment and simulation of hydrological processes were done using the Soil and Water Assessment Tool (SWAT). The data used for modelling included hydrologic features data; Digital elevation model (DEM), Land Use Land Cover (LULC), meteorological data, river Rwizi flow data and soil data (Sempewo *et al*., 2024; Nyesigire, 2021; Nseka *et al.*, 2023), Landsat imagery data were downloaded from U.S Geological Survey (USGS)

Center for Earth Resources Observation and Science (EROS) (https://earthexplorer.usgs.gov/), DEM data with 12.5 m cell size was obtained from Aster Global Digital Elevation Map (http://gdex.cr.usgs.gov/gdex/), and used to delineate the watershed boundary using ArcGIS, rainfall data was obtained from Uganda National Meteorological Authority (UNMA), river flow data was obtained from the Directorate of Water Resources Management (DWRM) of the Ministry of Water and Environment (MWE) and Soil data was obtained from the Food and Agriculture Organization (FAO).

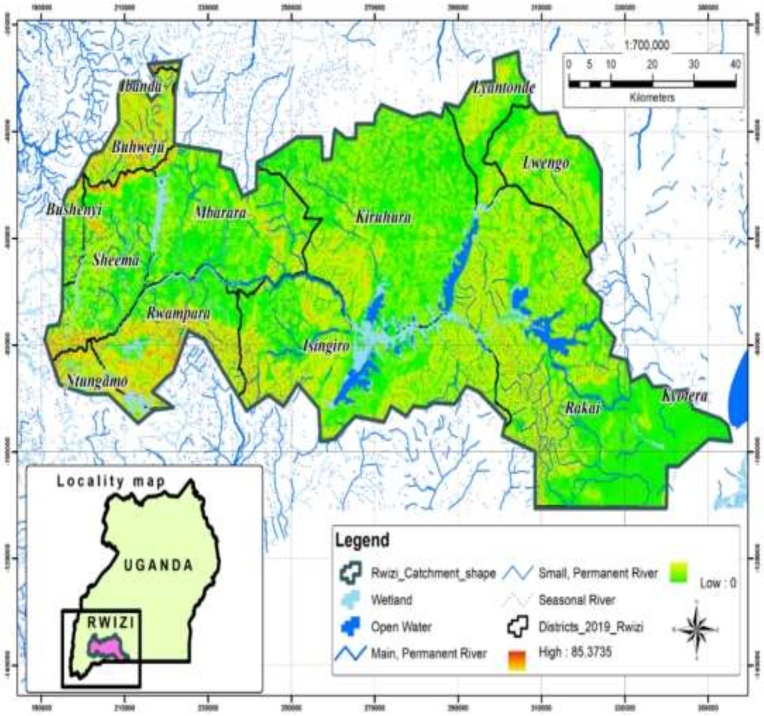

Fig 1: Map of the Rwizi catchment (Source National Forestry Authority (NFA), 2016)

Data Pre-Processing: The river networks within the Rwizi basin were digitized from google satellite imagery. The slope map was generated from the DEM, which was further used to develop Hydrological Response Units (HRUs) that could be treated as primary hydrological units having uniform soil, land use, and slope (Ajidiru, 2022; Costa *et al*., 2023). Supervised classification was performed using Random Forest Classifier Algorithm. Random forests are widely popular because of their ability to classify large amounts of data with high accuracy (Shah *et al*., 2020; Palimkar *et al*., 2022; Riss *et al*., 2021). The soil map, LULC map, and DEM were projected into UTM coordinate system (Kinattinkara *et al*., 2022; Biswas and Giri, 2023). The source digital elevation model used in the SWAT model is illustrated in figure 2.

Digital Elevation Model (DEM): A 30-meter ASTERDEM from the United States Geological Survey (USGS) provided elevation, slope, and aspect data necessary for hydrological modeling. Topographic parameters facilitated accurate delineation of the watershed and sub-basins within the Rwizi River basin, enhancing modeling precision (Figure 2 and 3).

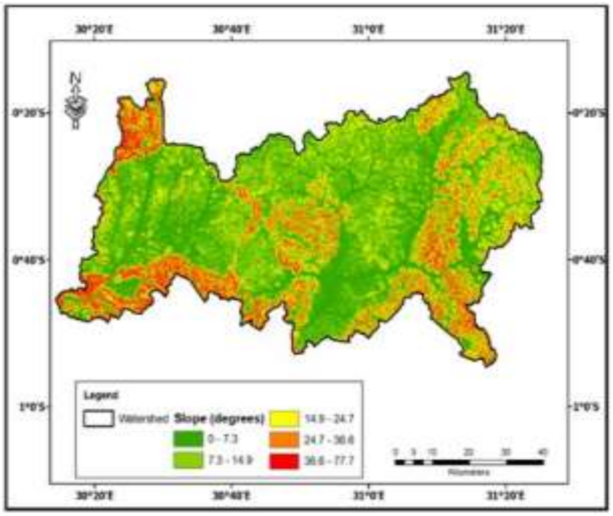

Fig 2: Rwizi catchment map used in model building: Slope map (source: Field data in ArcSWAT)

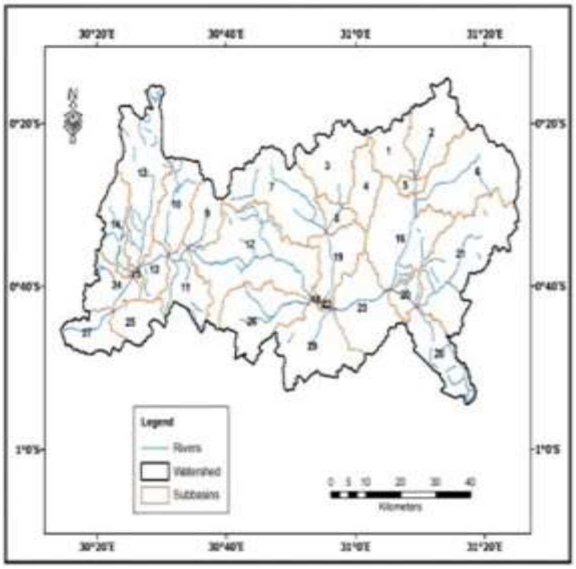

Fig 3: Rwizi catchment map used in model building: delineated sub-basins (source: Field data in ArcSWAT)

Catchment Delineation: The stream network for the study area was created from a pre-defined drainage layer (Castro & Maidment, 2020; Roostaee and Deng, 2020). Following the definition of the stream network, the entire catchment outflow was selected, and the catchment was created based on the outlets. The catchment was delineated into several sub-basins for modelling purposes. The catchment delineation process included five major steps, DEM setup, stream definition, outlet and inlet definition, catchment outlets selection and definition, and calculation of sub-basin parameters (Asitatikie, 2020; Kebede, 2019). The first catchment was delineated into 29 sub-basins.

Hydrological Response Units (HRU) Analysis: Following the definition of the catchment, the HRU analysis was performed, and soil and land-use classes were reclassified per the SWAT model's data requirements. The term "hydrologic response units" (HRU) refers to lumped land areas in a sub-basin with unique land cover and soil types (Abdi & Ayenew, 2022). HRUs allow the model to account for variations in evapotranspiration and other hydrologic conditions for various land uses and soil types (Khorn *et al*., 2022; Zhang *et al*., 2020; Jin *et al*., 2019). The sub-basin was subdivided into 119 HRUs. The LULC, soil layer, and slope delineation were loaded into the project through the HRU analysis tool in Arc SWAT. Arc SWAT's HRU analysis divides HRUs into different slope classes and considers land use and soil types. The multiple slope option was selected. Next, the slope, soil, and LULC layers were reclassified to match the Arc SWAT database's parameters. After reclassifying the land use, soil, and slope in the Arc SWAT database, all of the input datasets were overlaid (Khorn *et al*., 2022; Zhang *et al*., 2020; El Harraki *et al*., 2021; Jin *et al*., 2019). HRU definition is a further stage of HRU analysis. In order to determine the HRU distribution, different HRUs were assigned to each sub-watershed.

Weather Data Definition and Weather Generator: Meteorological information was gathered, encompassing solar radiation, temperature, humidity, and precipitation from five meteorological stations strategically located within and around the River Rwizi basin. These stations were strategically chosen based on their spatial distribution and data completeness over the study period. Data consistency was ensured by cross-verifying information from multiple sources and addressing any discrepancies or missing data through interpolation or consulting additional meteorological archives. After HRUs were defined, the next step involved importing the climatic data, which was computed in SWAT's write input table.

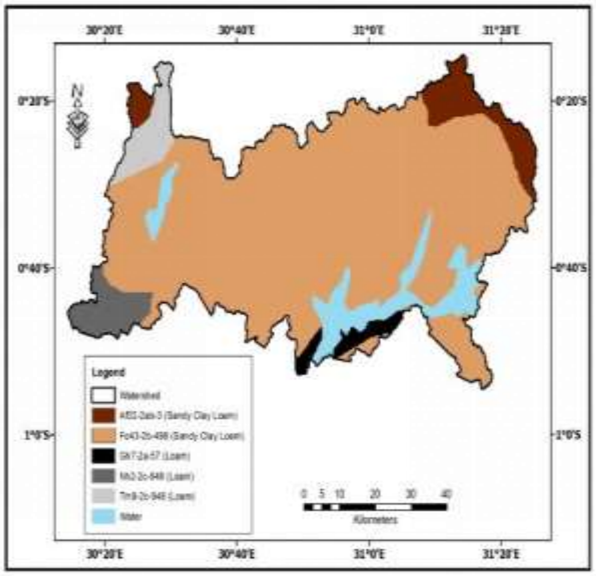

Fig 4: Rwizi catchment maps used in model building: soil map (source FAO data, ArcSWAT)

Soil Map: A soil map from the Food and Agriculture Organization of the United Nations website was used for the study region This map was projected to match the coordinate system used in the study, clipped to the River Rwizi basin catchment, and overlaid to ensure precise spatial alignment. The soil map revealed five predominant soil types within the catchment: Af32-2ab-3, Fo43-2b-498, Gh7-2a-57, Nh2-2c-846 and Tm9-2c-948 (Figure 4). Each of these soil types was thoroughly characterized to support the SWAT model's requirements. To improve hydrological process models, a comprehensive database of soil parameters such as depth, available water content, soil texture, and hydrologic soil group was created using Microsoft Access.

Meteorological Data: Meteorological information was gathered, encompassing solar radiation, temperature, humidity, and precipitation from five meteorological stations strategically located within and around the River Rwizi basin. These stations were strategically chosen based on their spatial distribution and data completeness over the study period. Data consistency was ensured by cross-verifying information from multiple sources and addressing any discrepancies or missing data through interpolation or consulting additional meteorological archives.

Analysis of Rainfall Data: Precipitation data was analyzed to understand temporal and spatial patterns within the River Rwizi basin. This investigation was essential for calibrating the SWAT model to appropriately reflect local rainfall patterns and assessing the effects of variability in precipitation on hydrological systems. Three decades (1989 – 1999, 1999 – 2009 and 2009 – 2019) were created from the rainfall data collected from meteorological stations located within the catchment region. The daily rainfall totals and occurrences were described using a variety of statistical techniques, such as time lag comparisons, moving averages, and linear trend analysis; precipitation was classified as a rainfall event which measured one millimeter or greater (Asfaw *et al*., 2018).

These analyses were conducted at a daily time step to assess temporal patterns and trends in rainfall. Specifically, the last three decades (1989–2019), coinciding with the availability of land use maps, were pivotal for the detailed analysis of rainfall characteristics and their implications for hydrological processes within the study area.

*Simulation:*To run the simulation, the starting and ending date and end date were defined. This was then followed by setting a warm-up period and printout setting (daily, monthly, or yearly), (Ayalew, 2020; Xue *et al*., 2019); then setup SWAT run and run SWAT. For this specific study, the starting and ending period was from 1997 to 2019, with a warm-up period of three years (1997-1999).

Sensitivity Analysis: To perform sensitivity analysis, Latin hypercube sampling with a monthly time step was used in the SWAT-CUP model. The SWAT-CUP model was run a thousand times to get the desired results for model calibration and sensitivity analysis. Using the p-value and t-stat indicators, the relevance of each parameter was assessed during the sensitivity analysis procedure (Oduor *et al*., 2021). Highly sensitive parameters are those that exhibit smaller p-values and higher t-stat values. The following were chosen for calibration: CN2, ALPHA BF, GW DELAY, GWQMN, CH N2, CH K2, ESCO, SOL K, SOL AWC, and SURLAG (Table 5). Among these, the base flow alpha factor (ALPHA BF) was the most sensitive parameter.

Model Performance: Numerous statistical metrics, such as overall accuracy, Kappa coefficient, coefficient of determination (R^2), and Nash–Sutcliffe Efficiency (NSE), were used to evaluate the effectiveness of the SWAT model and the precision of its simulated outputs.

1. $$\text{Overall Acurracy} = \frac{\text{Number of correctly classified pixels}}{\text{Total number of validation points}}$$
2. $$\text{Kappa Coefficient} = \frac{(\text{Observed accuracy} - \text{Expected accuracy})}{1 - \text{Expected accuracy}}$$
3. $$R^2 = \left(\frac{\sum_{i=1}^{n}(Q_{\text{Observed},i} - \bar{Q}_{\text{Observed}}) - Q_{\text{Simulated},i} - \bar{Q}_{\text{Simulated}}}{\sqrt{\sum_{i=1}^{n}(Q_{\text{Observed},i} - \bar{Q}_{\text{Observed}})^2 \sum_{i=1}^{n}(Q_{\text{Observed},i} - \bar{Q}_{\text{Observed}})^2}}\right)^2$$
4. $$\text{NSE} = 1 - \frac{\sum (Q_{\text{Observed}} - Q_{\text{Simulated}})^2}{\sum (Q_{\text{Observed}} - Q_{\text{Observed}})^2}$$

When assessing the degree of agreement between simulated and observed streamflow data, such metrics are frequently employed. The reliability of the SWAT model underwent rigorous calibration using both manual and automatic methods through SWAT Calibration and Uncertainty Procedures (SWAT-CUP) integrated with SUFI-2 (Prajapati *et al*., 2024; Singh, 2022). Extensive simulation runs were performed to achieve high-performance metrics. The calibration period extended from 2000 to 2014, followed by a validation period spanning from 2015 to 2019. These evaluations demonstrated how well the model could replicate the hydrological processes in the River Rwizi basin, thereby enhancing the reliability of simulated outputs crucial for water resource management and decision-making. NSE quantifies the replication capability of the model's observed data, ranging theoretically from $-\infty$ to 1. Values proximate to 1 indicate a high degree of model accuracy in replicating real-world conditions (DiRenzo *et al*., 2023; Upadhyay and Gupta, 2024). R^2 measures the proportion of the variance in the dependent variable (observed data) that is predictable from the independent variable (simulated data). An R^2 value of 1 denotes a perfect match between observed and simulated values (Fanta and Tadesse, 2022; Halefom *et al*., 2020). The Kappa coefficient assesses the accuracy of land use/land cover classification by comparing the agreement between observed and classified data, accounting for agreement occurring by chance (Foody, 2020; Gu and Congalton, 2021). Calibration utilized SWAT-CUP, while uncertainty analysis employed the Sequential Uncertainty Fitting Algorithm (SUFI-2), ensuring robust calibration and validation processes.

Model Calibration and Validation: The effectiveness and dependability of the results generated by hydrological models have been examined using a variety of statistical measures (Dhami *et a*l., 2018; Uniyal *et al*., 2020). The calibration and validation outcomes in this study were assessed based on two statistical measures; the coefficient of determination (R^2) and Nash-Sutcliffe Coefficient (NSE). The observed data from 2000 to 2014 were used for calibration of the model, and finally validation of the model was carried out using the remaining 5-year data from 2015 to 2019. The NSE shows the extent to which the simulated values approximate the observed values and it is also known as the efficiency ratio. It can range from $-\infty$ to 1. If NSE is close to 1, the model successfully replicates the real action/ situation on ground (Sisay *et al*., 2017; Katipoğlu *et al*., 2024). R^2 ranges from 0 to 1, and it is optimal for a value equal to 1, which indicates that the estimated values match the observed values (Sisay *et al*., 2017). SWAT-CUP was employed for model calibration and SUFI-2 technique was used for uncertainty analysis. Sequential Uncertainty Fitting algorithms (SUFI2) was employed for this study and is an optimization algorithm that calibrates and validates the model. Statistical parameters such as coefficient of determination (R^2) and Nash–Sutcliffe Efficiency (NSE) have been used to evaluate the model performance. The maximum and minimum values for the parameters are listed in table

Land Use Land Cover Maps: LULC maps derived from Sentinel and Landsat imagery (TM, ETM+, OLI) provided data for 1989, 1999, 2009, and 2019 (Figure 5). A Sentinel land use map, alongside Landsat images, enabled supervised classification to identify six primary land use categories. These categories included built-up areas, croplands, forestlands, wetlands, grazing lands and open water bodies. Ground-truthing validated classifications, refining categories into agricultural lands, forest, and grassland. This detailed classification underpinned subsequent hydrological modeling and analysis.

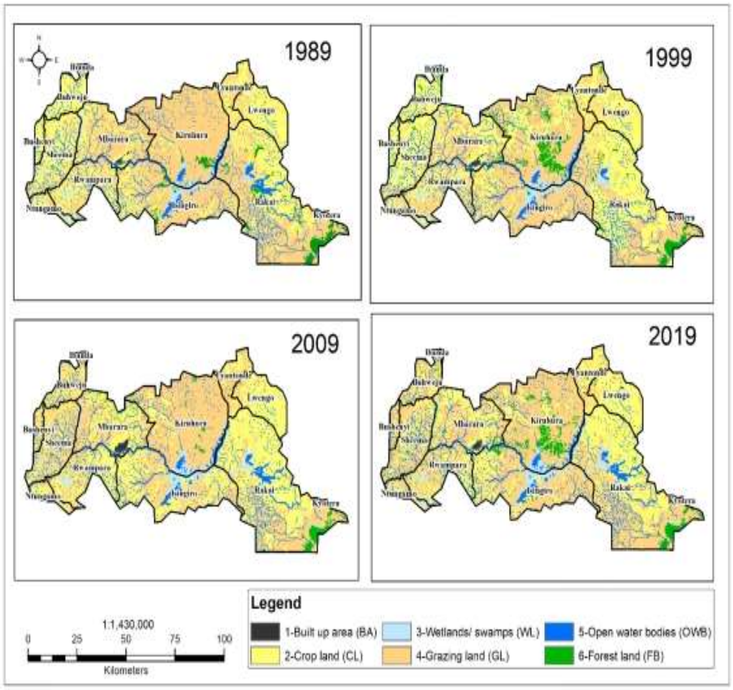

Fig 5: Land use/ land cover maps of Rwizi catchment for 1989, 1999, 2009 and 2019 (Source: Field data in ArcGIS)

Management Practices: The calibrated SWAT model made it possible to analyze scenarios involving modifications to land use and various management techniques. Different scenarios were created to represent a particular intervention, such as changing how land is used, impounding water on agricultural land, or using techniques for conserving soil water. The study also examined various land management practices within the basin, including agricultural activities, urban development, and conservation efforts. The impact of these practices on hydrological dynamics was assessed through SWAT simulations, providing information on strategies for managing water sustainably in the River Rwizi basin.

RESULTS AND DISCUSSION

Overview: This section presents the outcomes of the study, focusing on the main objectives and methodologies employed. The main objective was to use the SWAT model to evaluate the hydrological responses of the Rwizi watershed to land use land cover change. Methods included runoff simulations, model validation, land use land cover change analysis, LULC change scenario analysis and management practice analysis, as well as topography, soil, land use dynamics, and rainfall data analysis. These approaches were instrumental in conducting robust modeling efforts tailored for data-scarce environments typical of developing countries like Uganda.

SWAT Modelling: To determine the impact of land use/ land cover change and climate variability on river flow, a SWAT model was used that followed the following steps. The processed land cover for the Rwizi catchment in 2019, covering grazing land, forest land, cropland, built up area, open water bodies and wetlands showed built-up area the least land cover class while cropland and grazing land are the largest land cover classes in terms of percentage composition by area of catchment. Slope, delineated sub-basins and soil map are shown in figures 2,3 and 4. Calibration was performed based on the agreement between observed and simulated discharge time series. The calibration period used was 2000-2014, and a warm-up period of three years (1997 -1999). The overall performance of the model for calibration was evaluated with R^2 and NSE whose values were 0.87 and 0.76 respectively. Figure 6 shows scatter plot of the observed and simulated flow for the calibration period. The R^2 value is 0.87 implies that there is a strong positive relationship between the observed and simulated river flow. Model validation was carried out from 2015-2019. This was computed through the same parameters which were used and adjusted during the calibration process. The parameters are used without further adjustment. The R^2 and NSE values were 0.87 and 0.75 respectively. The scatter plots for the measured and the simulated flow for the validation period is shown in figure 7. In general, the daily observed and simulated validation indicates a very good agreement between the measured and simulated flow as evidenced by the R^2 value of 0.87, and the model is very suitable for predicting river flow trends.

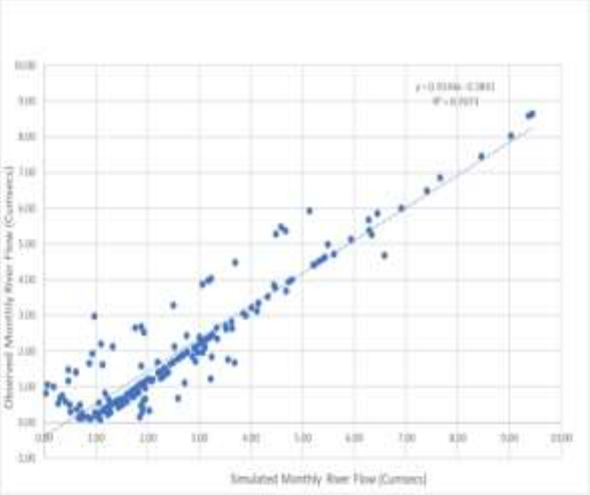

Fig 6: Scatter plots for the observed and simulated river flow for the calibration period 2000-2014

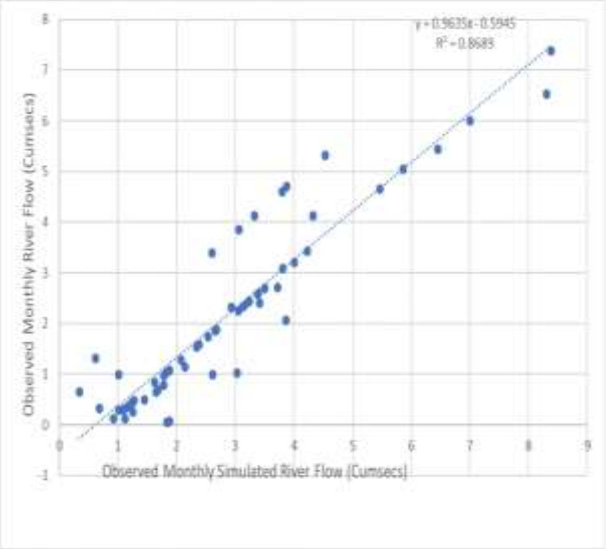

Fig 7: Scatterplots for the observed and simulated flow for the validation period 2015-2019

Table 1: Calibration Parameters and Their Values

Parameter	Minimum value	Maximum value
ALPHA_BF	0	1
CN 2	-0.2	0.2
GW_DELAY	30	450
GWQMN	0	2
SOL_K	0	92
CH_K2	-0.01	500
CH_N2	-0.01	0.3
CANMX	0	100
ESCO	0	1
SURLAG	0.05	24

Land Use /Land Cover Change: Overview of LULC Changes (1989-2019): Significant changes are revealed by analyzing the changes in Land Use Land Cover (LULC) within the Rwizi catchment from 1989 to 2019. Built-up areas showed the most dramatic increase, surging by 947.19%. Forestland also experienced a substantial rise of 171.80%, followed by cropland (25.74%), wetlands (21.47%), and open water bodies (4.43%). Conversely, grazing land decreased by 29.73% (Table 2, Figure 8).

Table 2: Catchment Land use land cover for the period 1989 -2019

Year	1989		1999		2009		2019	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Built up area	1208.7	0.16	1557.09	0.21	3841.02	0.51	12657.42	1.67
Cropland	266701.9	35.29	340136.55	45.01	317059.56	41.96	335352.33	44.37
Forest land	22482.09	2.97	29793.24	3.94	13000.32	1.72	61105.86	8.09
Grazing land	422155.2	55.86	342804.69	45.35	370445.58	49.02	296659.71	39.25
Open water Bodies	14663.79	1.94	10191.6	1.35	15002.1	1.99	15313.59	2.03
Wetland	28527.75	3.78	31256.19	4.14	36297.9	4.80	34652.25	4.59

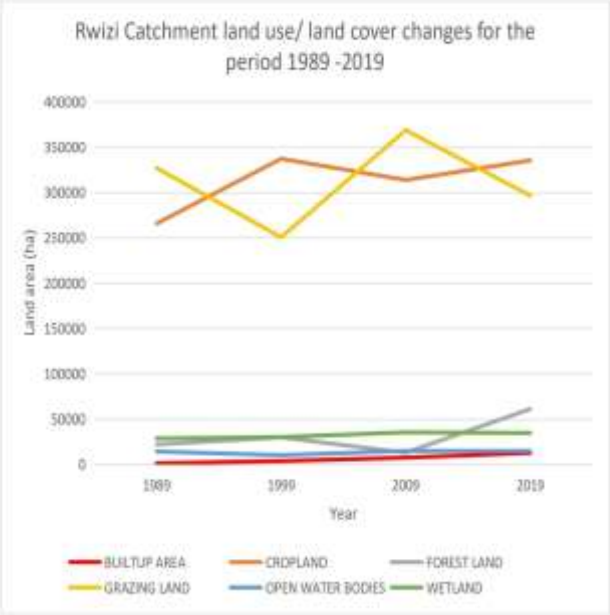

Fig 8: Rwizi catchment land use/ land cover change trend through 1989, 1999, 2009 and 2019.

Decadal LULCC Trends: The proportion of Built up areas in the total catchment area rapidly grew from 0.18% to 1.67% between 1989 and 2019. With increases of 28.82% between 1989 and 1999, 146.68% between 1999 and 2009, and 229.53% between 2009 and 2019, the pace of expansion rose throughout the decades, averaging 381.819 ha/year (Table 3). Cropland exhibited cyclical fluctuations, with 1989–1999 seeing the largest yearly increase (2288.35 ha/year). With an overall change rate of 1287.43 ha/year between 2009 and 2019, forest land showed the highest rise in land area. The decrease between 1999 and 2009 was ascribed to the need for fuel wood, the growth of settlements, and the clearing of land for building and farming. Grazing land showed cyclical fluctuations, showing positive growth only from 1999 to 2009 and an overall decline of -4183.183 ha/year as a result of a shift towards commercial crop farming and zero grazing. Open water Bodies decreased at a rate of 21.66 ha/year overall, but declined only between 1989 and 1999. Between 2009 and 2019, there was a 204.15 ha/year overall change rate in wetlands. Drought, population growth, industrial encroachment, and rising agricultural demand account for the decrease in wetland area.

Primary Drivers: Socioeconomic variables are the primary causes of LULC in the Rwizi watershed. The two leading drivers were found to be population increase and economic development, with substantial positive correlations (coefficients > 0.9) with the first principal component. In the Rwizi catchment areas, housing, infrastructure, fuel wood, and agriculture required more land due to population growth of 30.5% between 1992 and 2002, 37.3% between 2002 and 2014, and the projected 135% by 2040. The main forces behind changes in land use and cover in the Rwizi watershed are hydro-climatic while temperature (coefficients > 0.83), runoff, and rainfall dispersion were also important secondary variables affecting changes in natural land cover.

Land Cover Class Impact: Built-Up Areas increased due to administrative elevation and urban expansion, particularly in Mbarara District. Forestland recovered between 2009-2019 due to reforestation efforts following deforestation pressures in the previous decade. Grazing Land declined overall due to shifts towards zero grazing and commercial agriculture. A reduction in wetlands and open water bodies was brought about by agricultural growth and industrial encroachment.

Table 3: Annual rate of land use/ land cover change in hectares (ha/year)

Land use/ land cover	Annual rate of change (ha/year)					
	1989 -1999	1999 – 2009	2009 – 2019	1989 – 2019	Pearson	R^2
Built up area	248.041	377.054	520.361	381.819	0.992975	0.986
Cropland	7148.277	-2348.25	2167.746	2288.35	0.658703	0.43389
Forest land	774.072	-1679.26	4816.404	1287.43	-0.53849	0.289974
Grazing land	-7638.74	11814.67	-7200.62	-4183.183	0.348499	0.121451
Open water bodies	-400.149	468.207	43.991	21.66	0.134517	0.018095
Wetland	156.996	530.172	-74.664	204.15	0.954198	0.910493

Effects of LULC Modifications on River Flow: It was found that there is a strong positive correlation (R^2 = 0.93) between runoff and sediment yield, indicating that higher runoff considerably increases sediment yield. This finding suggests that managing runoff is crucial for controlling sediment levels in the river. The largest positive correlation with river flow was seen in wetland cover (R^2 = 0.9587), which was followed by cropland (R^2 = 0.4373) and grazing land (R^2 = 0.2994). Although forestland and open water bodies had lower correlations, they still played a significant role in the hydrological cycle of the catchment. The analysis of sediment yield identified critical erosion areas within the 17 sub-basins of the Rwizi catchment (Figures 9 and 10). Across sub-basins, the average monthly sediment yield was 4.87 t/ha and the districts of Rwampara, Buhweju, Mbarara, and Sheema were determined to be important regions for sediment yield. Because of heavy rainfall and runoff, Rwampara had the largest district-level sediment yield at 63.69 tons/ha/year, while Ntungamo had the lowest yield at 9.7 tons/ha/year.

These results highlight the significance of focused watershed management techniques in reducing soil erosion and guaranteeing the Rwizi catchment's sustainable use of land and water resources. Table 4 presents district-level sediment yield data, with Rwampara district recording the highest sediment yield followed by Kiruhura, Sheema, and Mbarara districts. These findings underscore the influence of topography, land use practices, and climatic factors on sediment yield variability across the catchment. The increase in built-up areas, particularly in Mbarara district, was attributed to administrative elevations and urbanization trends, while fluctuations in cropland and forestland areas reflected dynamic shifts in agricultural practices and reforestation efforts.

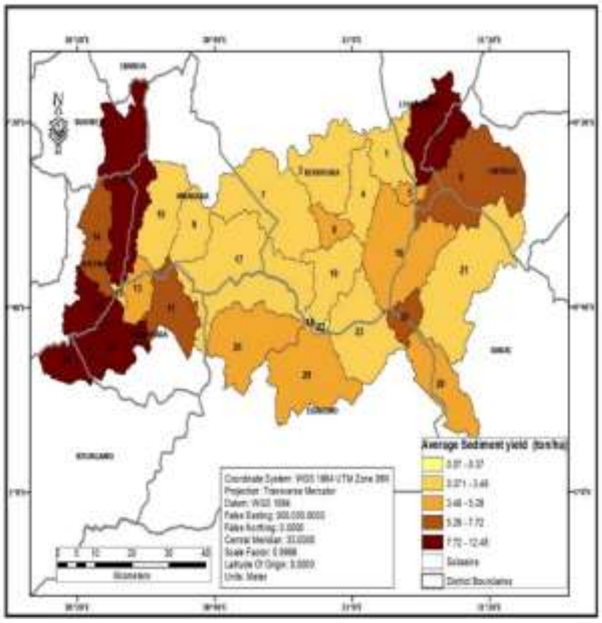

Fig 1: Spatial distribution of sub-basin sediment yield in tons per hectare per year

The findings of this study on alterations in land use and land cover (LULC) in the Rwizi catchment are consistent with several previous research projects conducted across Africa. Studies by Nyesigire (2021), Nseka *et al*., (2022), Walter *et al*., (2019), Bamutaze *et al*., (2017) and Onyutha *et al*., (2021) in the upper Rwizi catchment, as well as those by Njagi *et al*., (2022) in the pastoral area around Lake Mburo, Hussein *et al*., (2023) in the Abbay river basin and Langat *et al*., (2021) in the Tana River Basin, over their individual research periods, all consistently documented reductions in wetlands and pasture land and increases in built-up areas and agriculture.

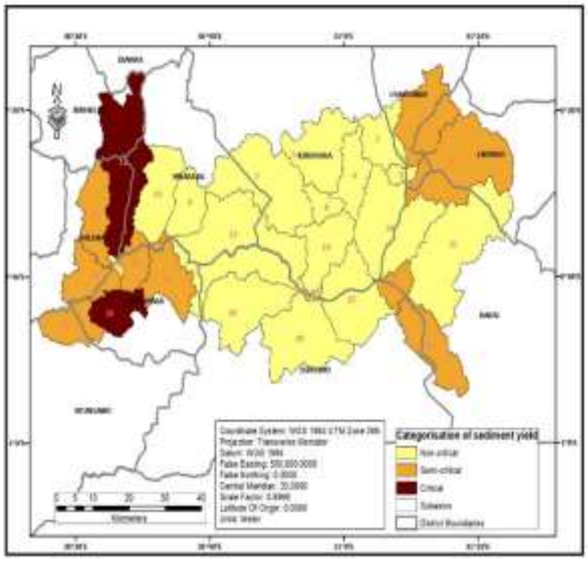

Fig 2: Spatial distribution of different categories of sediment yield within the sub-basins

Table 4: Sediment Yield per District in tons per hectare per year

No	District	Sediment Yield (ton/ha/year)
1	Buhweju	16.7
2	Isingiro	27.13
3	Kiruhura	53.67
4	Lwengo	19.84
5	Lyantonde	23.62
6	Mbarara	35.46
7	Ntungamo	9.7
8	Rakai	33.87
9	Rwampara	63.69
10	Sheema	37.85

These findings point to a general pattern that is impacted by both overt and covert causes of changes in land cover in various African geographic contexts. Cropland and grazing land emerged as the dominant LULC classes in the Rwizi catchment throughout the study period, with significant conversions observed between these categories. The stability of these land use classes progressively decreased from 1989-1999 to 2009-2019, mirroring trends documented in similar studies within the catchment and beyond. For instance, Onyutha *et al*., (2021) noted an expansion of cropland at the expense of other land cover types, while Njagi *et al*., (2022) highlighted conversions from wetlands to farmland in the Lake Mburo pastoral area. These findings underscore the substantial impact of anthropogenic activities on land cover dynamics, driven primarily by population growth and agricultural expansion.

In the Rwizi catchment, population increase has been a major driver of land cover conversion, with population increases of 30.5% between 1992-2002 and a 37.3% increase for the period 2002 to 2014, and is projected that by 2040 it will have increased to 135% (UBOS, 2017). Variations in the population growth rates across districts illustrate differential pressures on land resources, with Kiruhura district experiencing the highest increase (80.6%) and Lwengo the lowest (14%) between 1992-2002, highlight differential pressures on land resources across the catchment. Economic factors such as food security, soil quality, and agricultural productivity were cited as key drivers influencing land use decisions, with bananas and milk emerging as predominant agricultural commodities due to their economic viability and local demand.

The modeling of sediment yield using the SWAT model revealed critical erosion areas within the Rwizi catchment, particularly in sub-basins characterized by steep slopes and intensive land use practices. According to categories of non-critical, semi-critical, and critical sediment yield areas (Panda *et al*., 2021), the spatial distribution of sediment yield shown in Figure 7 emphasized sub-basins with strong erosion potential. For focused treatments meant to reduce soil erosion and enhance general watershed management techniques, this information is essential.

Policy and Management Implications: Policy Implications: Policymakers and watershed managers looking to enhance sustainable land and water resource management in the Rwizi catchment will find great value in the study's conclusions. Implementing zoning laws to protect high sediment yield zones is one of the main recommendations, especially for areas like Rwampara, Buhweju, Mbarara, and Sheema.

These regulations should effectively limit activities such as deforestation and unsustainable agricultural practices that exacerbate soil erosion. Furthermore, encouraging sustainable urban planning practices, especially in rapidly expanding urban centers such as Mbarara District, is essential. Policies promoting the adoption of green infrastructure and effective storm water management can mitigate adverse impacts on water quality and quantity.

Supporting reforestation and afforestation efforts, particularly in areas where forest cover has shown recovery post-2009, is crucial for enhancing water retention capacity, reducing erosion, and preserving biodiversity. Additionally, strengthening policies to protect remaining wetlands and water bodies from further encroachment and degradation is imperative. If wetland conservation is included in more thorough land use planning schemes, it will continue to be essential for managing water flow and maintaining water quality.

Promoting integrated watershed management approaches that consider socio-economic drivers and hydro-climatic factors is essential. Facilitating collaboration among stakeholders to develop and implement sustainable land use practices that balance agricultural productivity with environmental conservation will contribute significantly to long-term sustainability goals.

Management Implications: It is crucial to set up reliable monitoring systems to keep track of changes in hydrological parameters, sediment output, and land use/cover. Early warning systems based on these data can provide timely alerts to authorities about potential environmental risks, enabling prompt intervention and mitigation measures. Investing in capacity building programs for local communities and stakeholders on practices that sustain water and land resources is crucial. Empowering communities with knowledge and skills fosters stewardship and encourages compliance with regulatory measures aimed at protecting natural resources. Implementing adaptive management strategies that allow for flexible decision-making based on evolving environmental conditions and feedback from monitoring systems is essential. Continual assessment and adjustment of policies based on new information and emerging challenges are vital to effectively address sustainability goals in the Rwizi catchment and guarantee the long-term wellbeing of its ecosystems.

Conclusion: The study established that management techniques and LULC modifications have a major impact on the hydrology of the Rwizi watershed more than climatic variability. Changes in cropland and grazing land area greatly affects hydrology of the Rwizi river since they are the dominant catchment land cover types. Rainfall and temperature are the two key climatic factors that influence river hydrology and their fluctuations need regular and consistent monitoring to design appropriate interventions. Lastly, evaluating the effectiveness of current policies and governance structures in achieving sustainable land and water management goals is essential.

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