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Article

The impact of land use and cover changes on river flows in Wundanyi Catchment of Taita Hills, Kenya (1970–2030)

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Abstract: Taita Hills are one of the most important biodiversity hotspots of Kenya but are experiencing a high rate of deforestation due to the to the conversion of its original forestland to agriculture and settlement during the last century. These 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 land use/cover change (LUCC) in the Wundanyi catchment from 1970 to 2030 and predict their specific and combined effects on surface runoff and stream flow in the same period. The analysis was based on statistical trend analysis and dynamic landscape modeling using both historical and primary data from the Wundanyi catchment and Landsat TM and ETM+ imagery of Taita Hills for 1990, 2000, and 2010. Results show highly variable mean seasonal and annual values of discharge in Wundanyi catchment, probably attributed to environmental changes affecting Taita Hills in general and Wundanyi catchment in particular. Compared to 1990, major land use/cover changes in 2010 were featured by the expansion of built-up area (250%), plantation forest (23.7%), broadleaved forest (17.4%), and thicket (15.9%). It was also notable the decrease in woodland (−30.3%), cropland (−21.6%), and shrubland (−0.8%). Dynamic spatial trends by the year 2030 will be evidenced by increased thicket by 0.41% per annum (R^2 = 81.6%) and by decreased plantation forests (−0.13%; R^2 = 91.3%), woodland (−0.10%; R^2 = 77.6%), shrubland (−0.11%; R^2 = 85.2%), broadleaved forests (−0.03%; R^2 = 56.6%) and cropland (−0.09%; R^2 of 84.4). These changes will shape the catchment landscape and influence its hydrology, unless the existing forest and agricultural policy interventions are enforced. 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 catchment.

Keywords: catchment management; land-use and land-cover (LULC) change; river flow, seasonality; Taita Hills

1. Introduction

1.1. Background to the study

Access to clean and safe water is a basic human need and is essential for good health and well-being. Yet, worldwide estimates indicate that over two billion individuals live without safely managed water services, more than one billion lack a basic water service level, and close to 0.8 billion reside in countries with high or critical water stress levels [1]. Land use and land cover changes (LUCC) assume vital roles in global water dynamics. Generally, land cover modification through natural and anthropogenic activities has intensified in recent decades and has produced more far-reaching impacts than they did in the past [2]. These changes are the primary drivers of the unprecedented local, regional, and global shifts in hydrological processes through their effects on infiltration, erosion, and evapotranspiration. Given the role of vegetation cover in modulating infiltration, transpiration, and evaporation, LUCC can significantly influence surface runoff and river discharges [4]. Overall research findings suggest that in many places, anthropogenic activities, especially those resulting on LUCC, tend to be more impactful on streamflow than climate variability. But less is known about the magnitude of LUCC's impacts on hydrological processes, which varies considerably across regions, depending on land use intensity [2].

Empirical evidence from across the globe has demonstrated LUCC impacts on various hydrological processes, including surface runoff and streamflow. For example, Chen et al. [4] conducted a meta-analysis of studies on the impacts of climate and LUCC on stream flow in the Loess Plateau, China. The authors noted significant declines in stream flow rates in the catchment during previous decades. According to their estimates, while climate change contributed to 36% of observed decreases, 64% of the decline was due to LUCC. Comparable findings are reported by Shah et al. [5], who examined stream flow predictors in the Han River Basin, South Korea, using data covering 1978–2014. According to their results, climate variability accounted for 36–56% of shifts in stream flows, while human activities contributed to 45%–64% of the changes.

Sub-Saharan African countries experience some of the most extensive LUCC-related degradation in the world. [6,7] Poor and most vulnerable countries in the region are also the most prone to the adverse impacts of water scarcity. Kenya is one of the most water-scarce countries in sub-Saharan Africa, considering that over a fifth of its residents have no access to a reliable water system [8]. The ever-increasing water scarcity and demand have emerged into one of the notable obstacles to sustainable development in the country and have brought forward the critical need to protect its water towers. Land use and cover practices in the country, especially the conversion of forestland for agriculture and settlement, have resulted in water catchment destruction and significant alterations of key hydrologic processes [3,9]. Kipchumba and Cornu [8] reported that climate change's impacts on water availability in Kenya are compounded by various land use activities, such as large-scale deforestations and unsustainable agricultural practices.

The Eastern Arc Mountains (EAM) is a critical water tower, a biodiversity hotspot, and one of the world's most important areas for endemic wildlife conservation [10]. Taita Hills of Taita-Taveta County are Kenya's sole representative of the EAM. The hills are an important water tower in Kenya, serving as a catchment for the expansive Tsavo ecosystem [11]. Despite its vital role in the country's hydrology, Taita Hills is among the most degraded EAM areas, having lost over 98% of its original forest cover during the past two centuries [12]. More recently, Wekesa et al. [9] estimated that the hills' lost over 23% of their forest cover between 1973 and 2016, implying an annual deforestation rate of approximately 0.5% during the period. Much of this loss is attributed to unsustainable land use and land cover changes (LUCC) in the hills' catchments [13]. Long-term deforestation and other land use activities have produced significant impacts on the water resources of the areas served by the hills

[14]. Empirical evidence from various studies points to large-scale water catchment degradations due to unsustainable land use activities around Taita Hills [15]. However, there is limited research on the extent to which these changes have influenced the East African region's hydrology.

Empirical evidence on the effects of LUCC on the East Africa region's water systems reveals mixed findings. In one of the most extensive reviews covering East Africa, Guzha et al. [2] found that although field and modelling studies revealed that land cover loss in the region is accompanied by increased stream discharges and surface runoffs, trend analyses revealed that in most cases, the loss in forest cover had no significant impacts on discharges and streamflows. There were weak correlations between forest cover and mean discharge, peak discharge, and runoff. Such inconsistencies call for additional highly controlled studies to offer further insight into hydrological responses to a catchment's LUCC. The study employs a statistical multivariate trend analysis embedded in the Soil and Water Assessment Tool (SWAT) to assess LUCC impacts on surface runoff and river discharges. Statistical models, such as multivariate trend analyses, predict LUCC by establishing mathematical links between a set of explanatory factors and an outcome variable [16].

The SWAT model developed by Arnold et al. [17] is one of the most robust models available for watershed modelling. When used to model hydrological processes in large watersheds, SWAT considers water storage in different layers, as well as surface runoff, infiltration, soil moisture redistribution, evapotranspiration, lateral subsurface flow, storage in reservoirs and ponds, transmission losses in the stream, and return flow [18]. A statistical multivariate trend analysis is embedded in the SWAT model to assess the various LUCC forms and their correlations with the catchment's hydrological processes. The analysis uses the modified curve number (MCN) approach, which is the core mechanism for determining excess rainfall [17]. The SWAT model can be used in ungauged catchments and, hence, allows evaluation of hydrology changes resulting from LUCC in areas without gauges [19].

The SWAT model has been successfully applied in various studies across the globe to assess the impacts of changes in land use and management practices on water quantity and quality at different scales and environmental conditions, even in areas with limited data [18–20]. The model is also capable of simulating various hydrologic processes of a catchment, such as runoff and stream flow. Digital Elevation Models (DEMs), ERDAS, ILWIS, and ArcGIS were used to analyse historical LUCC patterns. Similar to SWAT, these tools have been successfully used to analyse and classify LUC patterns [21,22]. The findings sometimes reveal unexpected shifts in the landscape's LUC, including changes that have had notable impacts on the catchment's hydrological processes.

1.2. Research scope and rationale

The main purpose of this study is to assess the effects of land cover changes on the hydrological processes in the Wundanyi catchment of Voi catchment, within the Taita Hills of Kenya. Specifically, the study aims to:

a) assess past and future patterns of land use/cover changes in Wundanyi catchment from 1970 to 2030; and to

b) determine the effects of forest cover change in Wundanyi catchment's surface runoff and streamflow.

In fact, Wundanyi, like other catchments within Taita Hills, is experiencing rapid deforestation-related environmental deterioration [23]. The catchment is also experiencing a vicious drought-flood cycle, which may have impacted its hydrological processes remarkably. Part of the prolonged droughts and frequent floods in the catchment may be attributed to sustained land use-related environmental degradation. Assessing how land use changes affect Wundanyi's hydrological processes may help develop informed policies to alleviate water stress levels among the populations served by the catchment. Yet, few studies have evaluated specific LUCC impacts on Wundanyi's surface runoff and streamflow.

Yes! There is insufficient knowledge of the implications of human activities on hydrological processes in the Wundanyi catchment under the changing climate scenarios. Besides, the available studies in Wundanyi catchment are based on old data and may not reflect the present scenario, given that the catchment's population and land use activities are rapidly changing [24]. In addition to supplementing existing studies, this study also simulates future changes in the Wundanyi catchment. The study simulates Wundanyi's past and future land use and/or cover (LUC) scenarios for 1970–2030 using a dynamic landscape model of satellite images of the catchment. Various studies have been conducted on environmental degradation in Taita Hills [12,13,25]. This study models and predicts seasonal runoff and discharges using a set of LUCC parameters, such as area under cultivation, area under forest cover, and seasonal rainfall, using statistical multivariate trend analysis. The choice of these models was justified by their ease of implementation and the capacity to create a general LUCC representation where data, time, and other resources are scarce [16,26]. However, these statistical models ideally need to be combined with spatial models to display LUCC, especially for catchments with scarce data such as Wundanyi, and possibly project their impacts on the whole regional hydrology.

2. Materials and methods

2.1. Description of the study area

The study was conducted in Wundanyi, a medium catchment of about 190 km^2, in Taita Hills' upper elevation, within Taita-Taveta County of Kenya. Taita Hills cover an area close to 1000 km^2, which is located in South-Eastern Kenya at latitude 03°020′ S and longitude 38°20′ E (**Figure 1**), about 150 km off the Indian Ocean's coastline and isolated from other mountainous areas by the Tsavo plains. The elevations range from 700 to 2208 m a.m.s.l. (above mean sea level). Due to the altitudinal differences, the area has very variable rainfall, vegetation cover, and land use practices. The population in the catchment was estimated to be about 370,000 and 280,000 people in 2023 and 2010, respectively; that's an increase of nearly 517% (2023) and 370% (2010) since the 1960s [23,24,27]. The rapid population growth is considered the main driver of biodiversity loss and environmental degradation in the catchment [9,28].

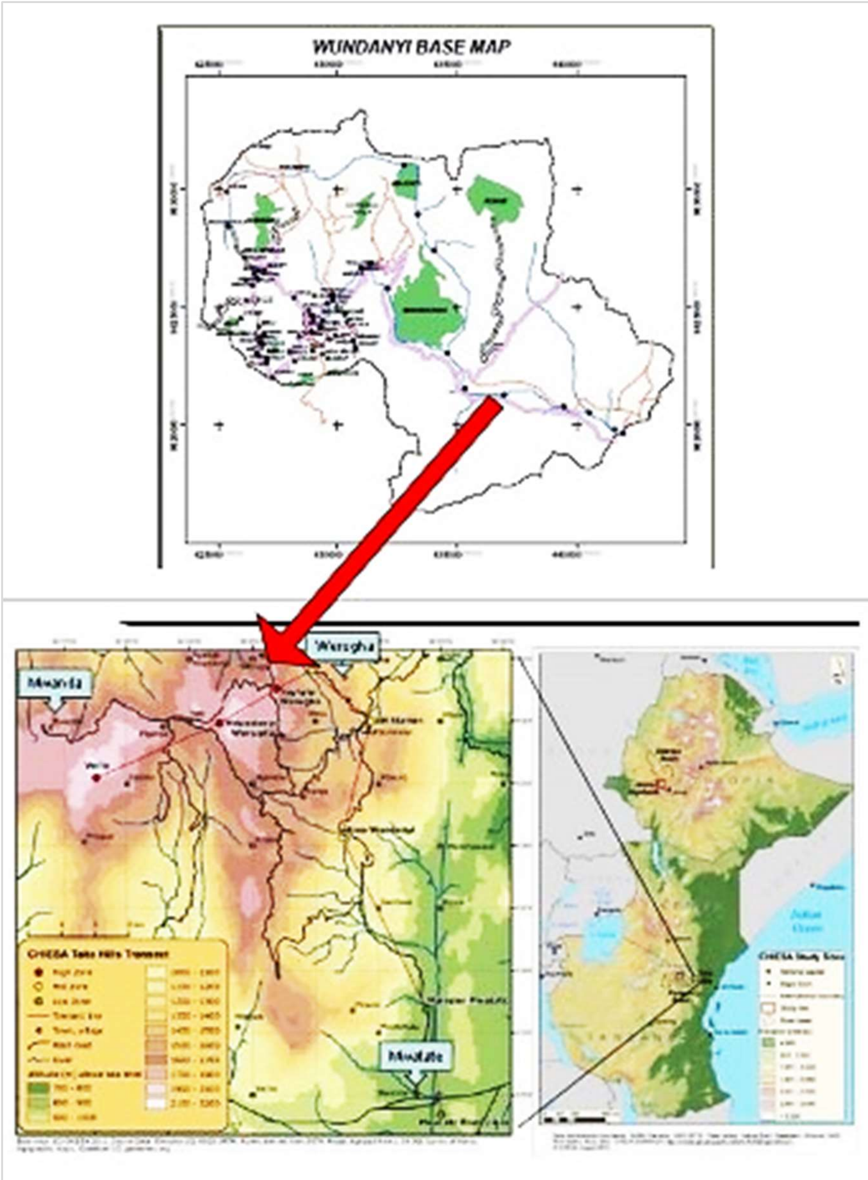
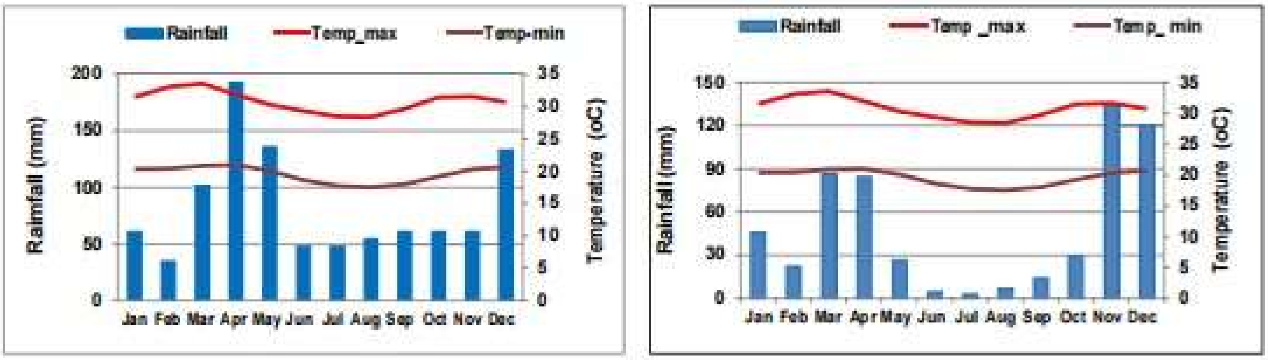


Figure 1. Map of Wundanyi catchment drawn from soak and chiesa maps (Source: Data analysis by authors from KNBS) [27].

Wundanyi catchment belongs to a semi-arid climate influenced by the Inter-Tropical Convergence Zone and differences in altitude and relief. The topography affects rainfall distribution significantly both vertically and horizontally. Annual precipitation in Taita-Taveta ranges from approximately 1000 mm to 1750 mm [14]. There are some variations throughout the country, with the hills around Wundanyi experiencing slightly wetter conditions [23]. Wundanyi's rainfall distribution is bi-modal, with longer rainy seasons occurring from March to May and short rains from October to December (**Figure 2**). The bi-modal pattern determines the growth of all vegetation and agricultural practices. Temperatures range between 23 °C and 27 °C, with slightly cooler conditions experienced around Wundanyi than in other parts of the county [14]. The potential evaporation is about twice the annual rainfall in the semi-arid area, while in the humid upper basin, rainfall exceeds potential evaporation in most parts of the year [24].



(a) **(b)**

Figure 2. Climate diagrams of **(a)** Wundanyi dc's office; **(b)** Voi station (Source: Data analysis by authors).

The major soils in the study area are of volcanic origin. They are young and have weak, unstable structures, making them vulnerable to physical degradation. The catchment's soils and major rocks are on undifferentiated basement system rocks, predominantly gneisses. They are generally well-drained, moderately deep to deep, reddish brown to brown, stony, friable sandy clay loam to clay, with humic topsoil (1.2–1.8 m) and vary from dark reddish brown to dark brown, clay loam to loamy soils with thick acid humic topsoil in shallow to moderately deep and rocky places [29].

Land cover/use types are determined by the hydro-climatic and ecological zonations of Taita Hills. The hills have seven agroecological zones, each characterized by distinct land use activities. Wundanyi catchment is within a zone characterized by a transition from a semi-arid to a semi-humid climate depending on the altitude [30]. The upper highland zone has 115 to 145 growing days and means a temperature of 15–18 °C, while the lower highland zone has 75 and 104 growing days and means annual temperatures of 21–24 °C. The lowland around the hills has a different landscape, mostly flat with limited rainfall and savannah vegetation. The climatic conditions and soils support intensive cultivation, while the landscape mosaic is constructed of abundant small-scale farms, exotic tree species patches such as Cupressus lusitanica, Pinus spp., Eucalyptus spp., and Grevillea robusta, and indigenous forest patches (1% of total land area). Only three larger hilltop indigenous forest remnants exist: Mbololo (ca. 179 ha), Ngangao (ca. 136 ha), and Chawia (ca. 94 ha) [29].

Hydrologically, Wundanyi falls within the Athi River catchment, one of the six major basins in Kenya. The area is considered semi-arid and dependent on erratic rainfall patterns that fall within the two rainy seasons. With an annual per capita renewable water resource of 464 m^3, Athi River has less water than the 1000 m^3 per capita global benchmark [31]. Wundanyi has a single river (Wundanyi/Voi River) and many small stream tributaries. Lagale and Rahai are the river's main tributaries. Wundanyi has ten sub-catchments: Wesu, Shigaro/Wushimbo, Suguluu. The study was conducted within the recommended Climate Change Impact on Ecosystem Services and Food Security in Africa (CHIESA) project sites in the EAM. Wundanyi catchment was purposefully selected because of the complexity of hydro-geomorphologic processes going on in that part of the EAM. Yet, this catchment is one of the critical water towers and biodiversity hotspots of Taita-Taveta County. This study enabled the building of water availability scenarios vis-a-vis climate variability and land use/cover change, which have been subjected to sustained LUCC and are in the semi-urban stage, characterized by intensive agriculture and a rapid increase in construction activities.

2.2. Sampling strategy

The study was conducted within the recommended Climate Change Impact on Ecosystem Services and Food Security in Africa (CHIESA) project sites in the EAM. Wundanyi catchment was purposively selected because of the complexity of hydro-geomorphologic processes going on in that part of the EAM. Yet, this catchment is one of the critical water towers and biodiversity hotspots of Taita-Taveta County. This study enabled the building of water availability scenarios vis-a-vis climate variability and land use/cover change.

2.3. Data collection technique

Several primary and secondary geophysical and hydrological data were collected to address the research objectives. Computational LUCC data was abstracted from remotely sensed satellite images and their ground truthing. Landsat images were acquired from the Kenya Forest Service (KFS), the Department of Remote Sensing and Resource Surveys (DRSRS), and the Institute of Resource Assessment (IRA). An inquiry was performed on the ground to ascertain the results of the satellite imagery conducted earlier in the Wundanyi catchment. These activities were conducted simultaneously in five administrative, six forest, and ten water catchment areas.

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, mostly during Wundanyi’s long, dry season (JJAS). For streamflow, the Hydrometer current meter was utilized to measure ten river discharges across ten (10) discharge points sampled from six (6) sub-catchments within the Wundanyi catchment between September and October 2023. 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 neighbouring Musau WRMA gauging station for regionalization purposes.

2.4. Key techniques of data analysis

2.4.1. Detecting past patterns and predicting future trends of LUCC (1970–2030) in Wundanyi

The first objective involved developing spatial simulation models for temporal LUCC patterns in the catchment. Three Digital Elevation Models (DEMs) (ERDAS, ILWIS, and ArcGIS) helped generate streamlines, flow direction, accumulation, slope, catchment boundary, and other relevant catchment attributes. Topographic maps (scale = 1:250,000) were used to geo-reference the images, while satellite image processing involved geometric rectification and radiometric normalization. Past and future LUCC scenarios were then simulated using statistical trend analyses of the satellite images.

For LUCC classification, FAO’s Land Cover Classification System (LCCS) [32] was used. Based on the collected data, different LUCC types were identified and verified using various DRSRS-produced maps and corrected following a ground-truthing conducted in September to October 2013. Ground control points were selected based on easily identifiable features (e.g., junctions, bridges, and prominent buildings) to re-geo-reference the images. A dynamic landscape model was then built to analyze historical LUCC trends, assess LUCC driving forces and simulate future scenarios.

To evaluate the driving forces, remote sensing and GIS tools were integrated with explicit dynamics in Wundanyi's landscape and hydrology using LUCC maps and ancillary data from ArcGIS 10.1. The dynamic landscape model was embedded in the IDRISI software with the following key inputs: land use transition rates, landscape parameters, and selected LUCC variables. Other factors linked to explanatory variables (i.e., distance from riverbanks, croplands, and roads) were included. Finally, a confusion matrix was used to assess the accuracy of the classification. Overall, producer and user accuracies and kappa coefficients were obtained from the ENVI/QGIS manual and other remote sensing and image analyses.

2.4.2. Simulating the effects of LUCC on Wundanyi's surface runoff and streamflow

For the second objective, dynamic trend analyses were utilized to simulate the effects of LUCC on Wundanyi's surface runoff and streamflow. For the second objective, dynamic trend analyses were utilized to simulate the effects of LUCC on Wundanyi's surface runoff and streamflow. A Soil and Water Assessment Tool (SWAT) model was used to subdivide Wundanyi into sub-catchments, which were linked by a river system network and further delineated into Hydrologic Response Units (HRUs). The HRUs comprised unique land cover-soil combinations within each of the ten (10) sub-catchments of Wundanyi. But the model failed to conclusively simulate surface and sub-surface flows using commonly available parameters due to limited data. This technique was not ideal for small catchments like Wundanyi. Hence, a multivariate statistical trend analysis was conducted to simulate the effects of LUCC on Wundanyi's surface runoff and streamflow. Estimated best fitting models used a univariate Weighted Least Squares (WLS) regression without a constant term (Weighting factor: River Distance_To_Forest), following the simplified model design below:

$$Y_s = bx \tag{1}$$

or,

$$Y_s = \beta t \tag{2}$$

where Y_s, the regression dependent variable, is represented by a seasonal runoff/discharge linear or exponential model (validated by a coefficient of determination (R^2) and a F statistical test at 1% significance level); $\log Y_s$, the regression dependent variable, is represented by a seasonal runoff/discharge logarithmic or power model (validated by a coefficient of determination (R^2) and a F statistical test at 1% significance level); x = land use/cover size (area); t = time with j = JJAS and o = OND; b and β, regression parameters (validated by a t-test at 1% statistical significance level).

Different linear and nonlinear regression models were tested for specific effects of LUCC variables on Wundanyi's surface runoff and discharges. 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 OND, JF MAM, and JJAS seasons.

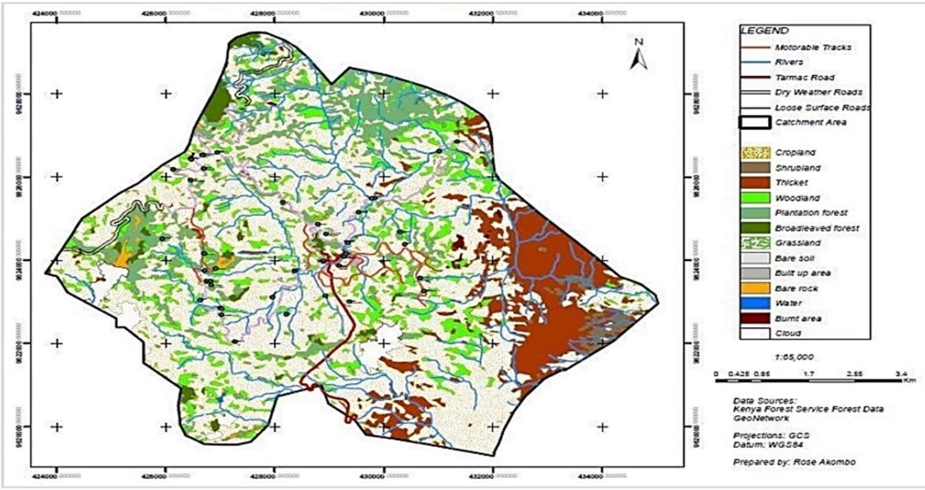
3. Results of the study

3.1. Study sample description

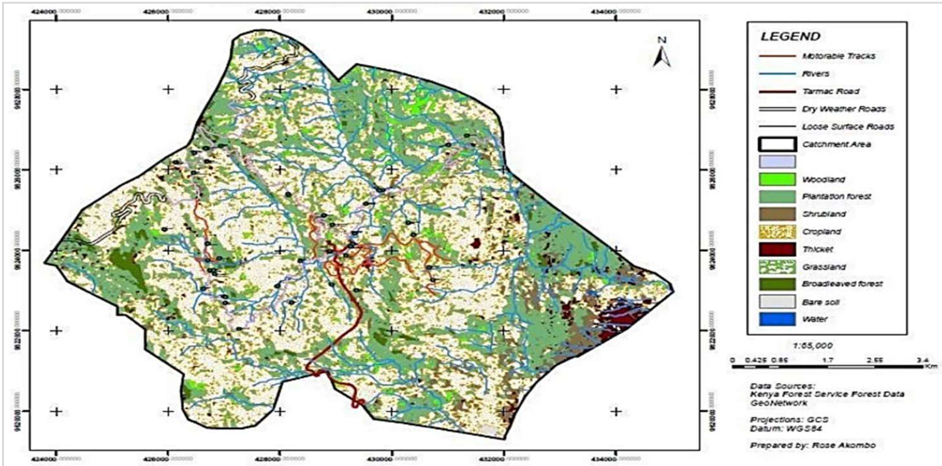
The first step in data analysis involved identifying key land use and cover (LUC) categories that play influential roles in Wundanyi's hydrological cycle. Principal Component Analysis (PCA) and the homogeneity of variance test were used to this end. Previous research has established that Wundanyi's micro-climate and hydrology are mostly influenced by the catchment's forestry and agricultural activities [14]. Several such factors were included in the initial extraction. Levene's homogeneity test helped cluster the extracted factors as independent and dependent variables based on Levene's F statistic and using the heuristic method. *F*-values below 2.6 were interpreted to indicate the presence of homogeneity.

A quick outlook of Wundanyi's landscape from a vantage point showed that the catchment had some fragments of natural forest along with extended hydrographical and road networks. Landsat TM and ETM+ satellite images of Taita Hills for 1990, 2000, and 2010 were used to enable categorization of land use/cover types thereof. In addition to these satellite images, topographical maps, DEM, and other field data were used to ensure the accuracy of this classification. Based on these spatial data and the FAO land use/cover classification system [32], a spatial raster modeling extracted 12 major classes of land use/cover (LUC) types from the three-epoch satellite images. These 12 LUC classes encompassed: (i) cropland; (ii) shrubland; (iii) thicket; (iv) woodland; (v) plantation forest; (vi) broad-leaved forest; (vii) grassland; (viii) bare soil; (ix) bare rock; (x) water body; (xi) burnt area; and (ii) built-up area (**Figure 3**).

According to the ENVI software suggested rules for the ranges of class signatures' separability values, a "good" signature separability was achieved for each image classified, the average Bhattacharyya distance ranging from 1.979 to 1.987. This classification got an overall accuracy of 82.3% for the 1990 Landsat TM image, 83.4% for the 2000 Landsat ETM+ image, and 89.5% for the 2010 Landsat TM image. The lowest values of accuracy corresponded to shrubland, thicket, woodland, and broad-leaved forest categories. These four groups were very similar in terms of spectral signatures assigned to these categories. They may have resulted in misclassifications due to similar stages of development. However, we decided to classify them as such using an algorithm that easily differentiated all categories of vegetation.



(a)



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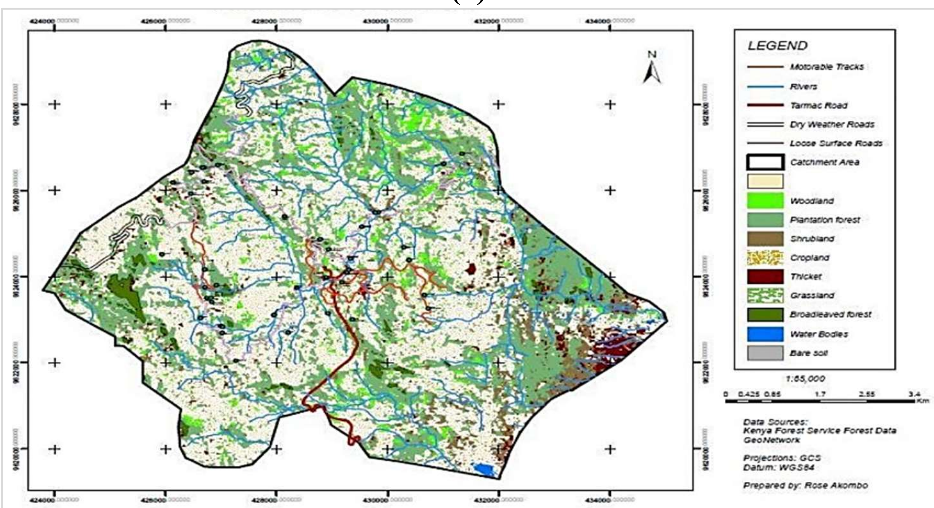

(c)

Figure 3. Wundanyi's land use/cover classes for **(a)** 1990; **(b)** 2000; and **(c)** 2010 (Source: Data analysis by authors).

To validate this classification accuracy, a ground control point (GCP) procedure was applied in the field alongside a user/producer classification accuracy assessment. According to **Table 1**, the average percentage of correctly classified pixels (Apcc) were 95%, 86%, and 96% for 1990, 2000, and 2010, respectively, with Kappa coefficient statistics of 0.96, 0.82, and 0.95. The user's accuracy for individual classes ranged from 85% to 98%, and the producer's accuracy ranged from 87% to 99%. These values were all greater than 75% (or 0.75 ratio), which is the lowest limit for a good classification system, thus validating the accuracy of the classification.

Table 1. Producer and user accuracy of the classification (Source: ENVI/QGIS image processing, data analysis by authors).

Years	Image	Apcc	Overall Kappa
1990	Landsat TM	95	0.97
2000	Landsat ETM+	86	0.82
2010	Landsat TM	96	0.95

3.2. Predicting land use/cover changes in Wundanyi (1970–2030)

Spatial modeling identified plantation forests and cropland as the major LUC types in Wundanyi in 2010 (**Table 2**). However, the catchment has undergone notable changes in the areas under specific LUC types since 1990. As of 2010, plantation forests had overtaken cropland as the leading LUC type, having experienced a growth in its share from 25.7% (1990) to about 31.8%. In contrast, cropland decreased from 37.7% to 29.1%. This reforestation may have positively impacted broadleaved forests, whose share grew by 17.4%. Other LUC types whose acreage increased were thicket, grassland, bare soil, built-up area, and burnt area. Woodland and cropland registered the highest declines, while shrubland's share decreased slightly.

Table 2. Land use/cover types distribution in Wundanyi (1990–2010) (Source: Data analysis by authors).

Land use/cover	1990		2000		2010		Growth (%)
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	
Cropland	3248.21	37.1%	2615.17	29.9%	2543.52	29.1%	−21.6%
Woodland	577.38	6.6%	457.11	5.2%	401.46	4.6%	−30.3%
Plantation forest	2245.54	25.7%	2788.85	31.9%	2780.18	31.8%	23.7%
Broadleaved forest	199.26	2.3%	137.53	1.6%	231.77	2.7%	17.4%
Shrubland	1172.79	13.4%	1394.78	16.0%	1164.48	13.3%	−0.8%
Thicket	1204.40	13.8%	1225.67	14.0%	1401.48	16.0%	15.9%
Grassland	4.53	0.1%	31.54	0.4%	31.49	0.4%	300%
Bare soil	14.96	0.2%	12.31	0.1%	46.19	0.5%	150%
Bare rock	47.58	0.5%	45.32	0.5%	41.74	0.5%	0.0%
Built up area	18.32	0.2%	23.20	0.3%	65.40	0.7%	250%
Water	1.65	0.0%	0.54	0.0%	1.53	0.0%	0.0%
Burnt area	9.92	0.1%	12.53	0.1%	35.31	0.4%	300%
Total Area	8744.55	100.0%	8744.55	100.0%	8744.55	100.0%	-

Statistical modelling (**Figure 4**) confirmed that plantation forests had overtaken cropland and grassland, while woodland, broadleaved forests, and built-up areas showed slight stability. Shrubland decreased substantially, while the other LUC classes exhibited no major acreage shifts. Projected scenarios (**Table 3**) showed that areas under all LUC types will decrease (in absolute terms and relative proportions) by 2030, except thicket. Thicket's acreage is expected to grow by 0.41% annually (R^2 = 0.816), while plantation forests, shrubland, and woodland will witness the largest declines. The high R indicated that the model accounted for a substantial proportion of variations in LUC. However, dynamic modeling (**Table 4**) showed that Wundanyi will undergo tremendous increases in acreages of its grassland (+1613.2%), plantation forest (+293.7%), and thicket (+97%) by 2030, while woodland broadleaved forests, shrubland, and cropland will experience substantial declines.

Table 3. Statistical trend analysis of land use/cover in Wundanyi (2010–2030) (Source: Data analysis by authors).

Land use/cover	2010		2030		R^2
	Area (ha)	Percent (%)	Area (ha)	Percent (%)	
Cropland	2543.52	29.09%	2384.18	27.26%	0.844
Woodland	401.46	4.59%	233.04	2.66%	0.776
Plantation forest	2780.18	31.79%	2552.32	29.19%	0.913
Broadleaved forest	231.77	2.65%	176.78	2.02%	0.566
Shrubland	1164.48	13.32%	980.58	11.21%	0.852
Thicket	1401.48	16.03%	2121.67	24.26%	0.816
Other LUC	221.66	2.53%	295.98	3.38%	-
Total area	8744.55	100%	8744.6	100%	-

Table 4. Percentage of land use/cover change by 2030 (Baseline: 1970) (Source: Data analysis by authors).

Land use/cover	Year						
	1970	1980	1990	2000	2010	2020	2030
Cropland	-	+3.8%	−5.3%	−22.8%	−24.9%	−27.7%	−29.6%
Woodland	-	−24.8%	−29.7%	−44.3%	−51.1%	−65.3%	−71.6%
Plantation forest	-	+61.0%	+246.4%	+330.2%	+328.8%	+304.4%	+293.7%
Broadleaved forest	-	−34.1%	−48.3%	−64.3%	−39.9%	−48.7%	−54.1%
Shrubland	-	−9.1%	−47.6%	−37.7%	−48.0%	−51.4%	−56.2%
Thicket	-	+1.1%	+12.1%	+14.0%	+30.4%	+73.6%	+97.4%
Grassland	-	+1.2%	+54.2%	+234.8%	+234.3%	+711.8%	+1613.2%
Bare soil	-	−3.8%	−78.9%	−82.6%	−34.8%	−63.3%	−69.1%
Bare rock	-	+0.6%	+113.4%	+103.2%	+87.2%	−8.9%	−25.9%
Other lands	-	+6.3%	+33.5%	−58.1%	+18.1%	+70.2%	+14.0%
Built up area	-	+6.2%	−66.9%	−58.1%	+18.1%	+14.2%	+10.6%
Water body	-	+5.4%	+26.9%	−58.5%	+17.7%	−13.1%	−34.6%

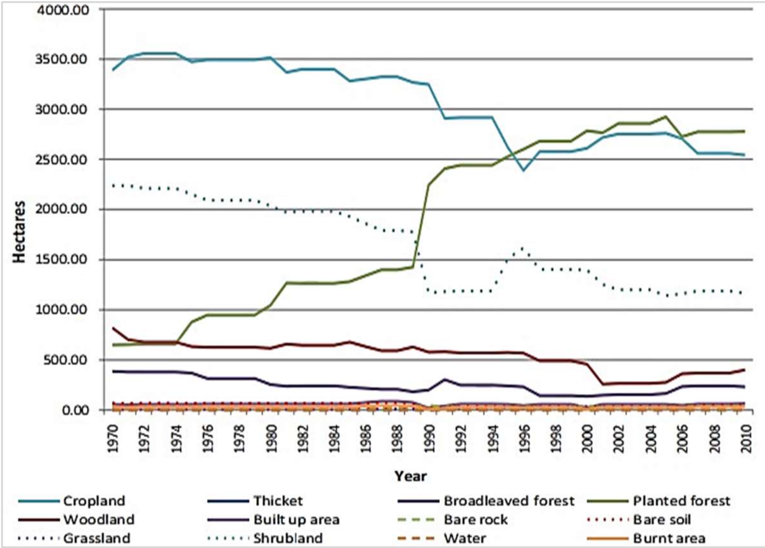

Figure 4. Statistical trend of land use/cover transition (1970–2010) (Source: Data analysis by authors).

3.3. Analysing the effects of forest cover change on seasonal surface runoff

Different regression models (**Table 5**) were tested for the effects of specific LUC categories on Wundanyi's surface runoff based on 1970–2010 JJAS data. All models, except woodland and thicket, explained over 70% of surface runoff variations based on the *R*-squared statistic. Expansions in all LUC types were associated with significant runoff increases ($p < 0.001$). The coefficients indicated that cropland and shrubland produced the largest runoff changes, while broadleaved forest, plantation forest, and woodland had the lowest impacts.

Table 5. Modelling land cover change effect on JJAS runoff in Wundanyi (Source: Data analysis by authors).

Model	Adjusted *R* Square	Factor/covariate	Unstandardized coefficients		Standardized coefficients	*t*	Sig.	*F*	Sig.
			B	Std. error	Beta				
Linear	0.562	Thicket	0.362	0.059	0.728	6.107	< 0.001	37.297	< 0.001
Linear	0.699	Woodland	0.226	0.025	0.841	8.933	< 0.001	79.801	< 0.001
Power	0.984	log(Shrubland)	0.640	0.014	0.992	45.297	< 0.001	2052.066	< 0.001
Linear	0.724	Broadleaved_Forest	0.068	0.007	0.855	9.485	< 0.001	89.968	< 0.001
Power	0.970	log(Cropland)	0.735	0.022	0.986	33.361	< 0.001	1112.923	< 0.001
Power	0.971	log(Planted_Forest)	0.204	0.006	0.986	33.668	< 0.001	1133.990	< 0.001

Notes:
[a]Best fitting models estimated using univariate Weighted Least Squares (WLS) regression without a constant term-Weighting factor: River Distance_To_Forest.
[b]The Dependent variable (Y_j) is JJAS_Runoff for linear and exponential models, and log (JJAS_Runoff) for logarithmic and power models.
[c]Model design: $Y_j = bx$, where x = land cover area.

Figure 5 depicts runoff built-up scenarios from bare land (1970) to large forest covers (2030). Logarithmic cropland (990 mm) and shrubland (810 mm) expansions will produce the highest runoffs in 2030. The effects of other LUC types on runoff will generally be low, ranging from 350 mm (thickets) to 198 mm (broadleaved forest).

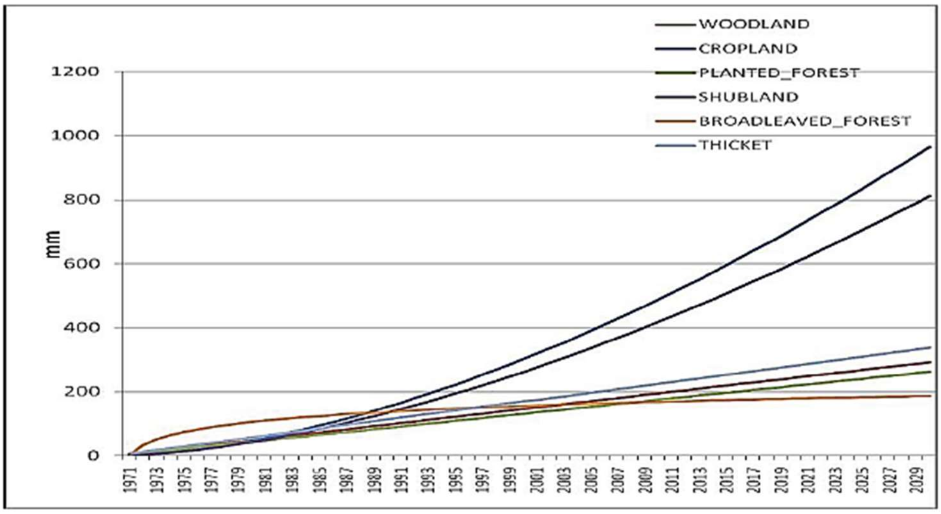

Figure 5. Expected JJAS runoff under specific effects of land cover change in Wundanyi by 2030 (1970 = 0) (Source: Data analysis by authors).

Note: Model design: $Y_j = bt$, where Y_j = JJAS_Runoff, t = time.

Models predicting LUCC effects on OND runoffs based on 1970–2010 data are in **Table 6**. A unit cropland rise increased the runoff by about 99.3%. Other LUC categories with large effects on OND runoff were thicket and shrubland, while the shifts due to broadleaved forest were negligible.

Table 6. Statistical prediction of land cover change effects on OND runoff (Source: Data analysis by authors).

Model	Adjusted R square	Factor/covariate	Unstandardized coefficients		Standardized coefficients	t	Sig.	F	Sig.
			B	Std. error	Beta				
Power	0.990	log(Cropland)	0.993	0.017	0.995	59.12	< 0.001	3495.142	< 0.001
Linear	0.836	Planted_Forest	0.484	0.037	0.917	13.188	< 0.001	173.913	< 0.001
Power	0.992	log(Shrubland)	0.737	0.012	0.996	63.285	< 0.001	4005.310	< 0.001
Linear	0.727	Woodland	0.133	0.014	0.857	9.558	< 0.001	91.350	< 0.001
Power	0.955	log(Thicket)	0.837	0.031	0.978	27.036	< 0.001	730.946	< 0.001
Power	0.988	log(Broadleaved_Forest)	0.002	3.14×10^{-5}	0.994	54.031	< 0.001	2918.951	< 0.001

Notes:
[a]Best fitting models estimated using univariate Weighted Least Squares (WLS) regression without a constant term—Weighting factor: River Distance_To_Forest.
[b]The Dependent variable (Y_o) is OND_Runoff for linear and exponential models, and log (OND _R unoff) for logarithmic and power models.
[c]Model design: $Y_o = bx$, where x = land cover area.

Forecasts of LUCC impacts on OND runoff showed that cropland (2510 mm), shrubland (2250 mm), and thicket (2225 mm) will produce the largest seasonal runoff increases by 2030 (**Figure 6**). Thus, in both JJAS and OND scenarios, much of Wundanyi's runoff changes will be due to shifts in forest covers. Cropping practices will have minimal impacts.

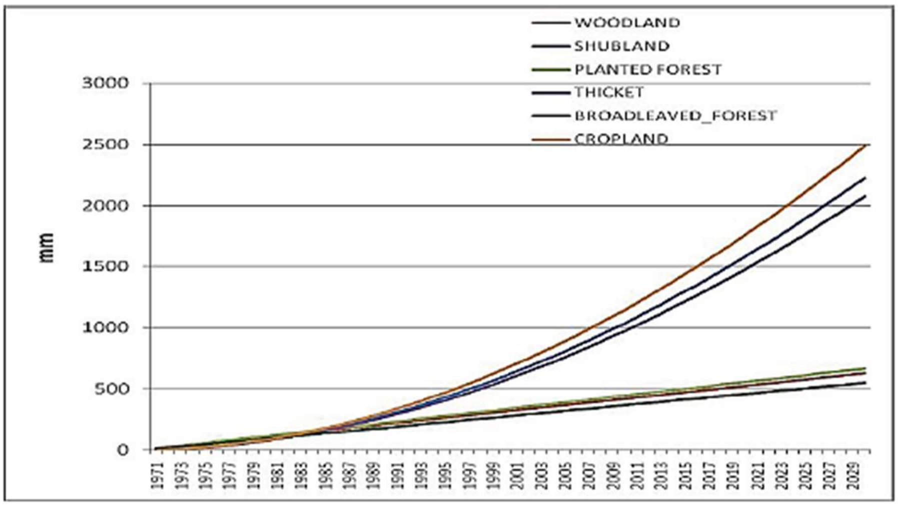

Figure 6. Predicted OND_runoff in 2030 under effect of land cover change in Wundanyi (Source: Data analysis by authors).

Note: Model design: $Y_o = bt$, where t = time, Y_o = OND_Runoff.

3.4. Analyzing the effects of forest cover change on river discharge

A homogeneity test of the study variables revealed that only plantations and broadleaved forests correlated significantly with Wundanyi's river discharges. **Table 7** shows that from 1970 to 2010, a unit change in plantation forest during the JJAS season increased/decreased river discharges by 27.4% against 0.5% for a unit increase/decrease in broadleaved forest.

Table 7. Statistical models for effects of land cover change on JJAS discharge (Source: Data analysis by authors).

Model	Adjusted R square	Factor/covariate	Unstandardized coefficients		Standardized coefficients	t	Sig.	F	Sig.
			B	Std. error	Beta				
Linear	0.546	Broadleaved_Forest	0.005	0.001	0.748	6.466	< 0.001	41.806	< 0.001
Logarithm (base e)	0.644	log(Planted_Forest)	0.274	0.035	0.809	7.909	< 0.001	62.553	< 0.001

The situation is likely to reverse by 2030, with broadleaved forests overtaking forest plantations (**Figure 7**). Then, broadleaved forests are expected to grow linearly, with Wundanyi's discharges increasing by about 3.3 m^3/s in the JJAS of 2030, a leap from the zero-discharge observed in 1970. In contrast, logarithmic plantation forest cover growth will result in a total discharge of 2.6 m^3/s by 2030.

Similar effects of forest cover change were also evident in OND discharges. From 1970 to 2010, a unit plantation forest expansion increased/decreased Wundanyi's OND discharges by 22.3% against a 0.5% discharge increase/decrease due to a unit change in broadleaved forests (**Table 8**). Discharges will be 3.75 m^3/s by 2030 under an assumption of a linear broadleaved forest expansion and 2.15 m^3/s under a logarithmic plantation forest expansion (**Figure 8**). These results emphasise the importance of natural forest protection and conservation for sustainable water ecosystem services in Wundanyi.

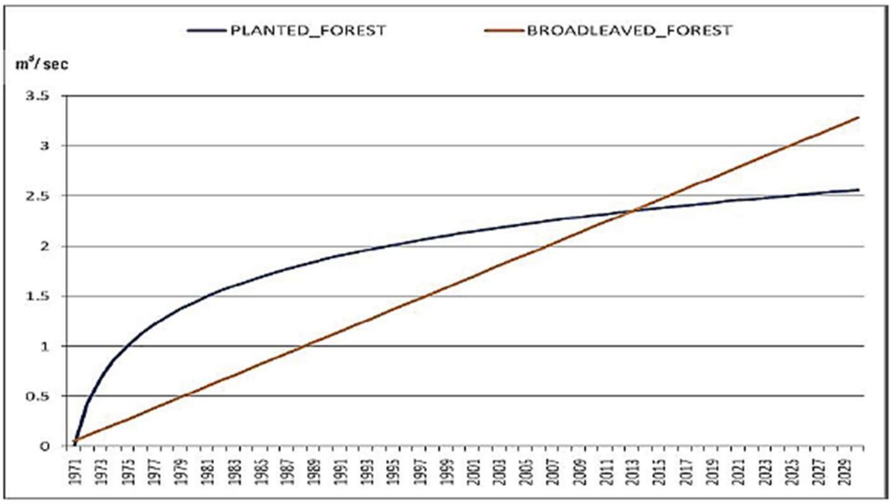

Figure 7. The impact of land cover change on JJAS discharge in Wundanyi (Source: Data analysis by authors).

Model design: $Q_j = \beta t$, where Q_j = JJAS_Discharge, t = time.

Table 8. The impact of forest cover change on OND discharge in Wundanyi (Source: Data analysis by authors).

Model	Adjusted R square	Factor/covariate	Unstandardized coefficients		Standardized coefficients	t	Sig.	F	Sig.
			B	Std. error	Beta				
Linear	0.570	Broadleaved_Forest	0.005	0.001	0.764	6.792	0.000	46.130	0.000
Logarithm (base e)	0.609	log(Planted_Forest)	0.223	0.030	0.788	7.341	0.000	53.889	0.000

Notes:
[a]Best fitting models estimated using univariate Weighted Least Squares (WLS) regression without a constant term (Weighting factor: River Distance_To_Forest).
[b]The Dependent variable is OND_Discharge for linear and exponential models and log(OND_Discharge) for logarithmic and power models.
[c]Model design: $Qo = bx$, where Qo = OND _Discharge, x = land cover area.

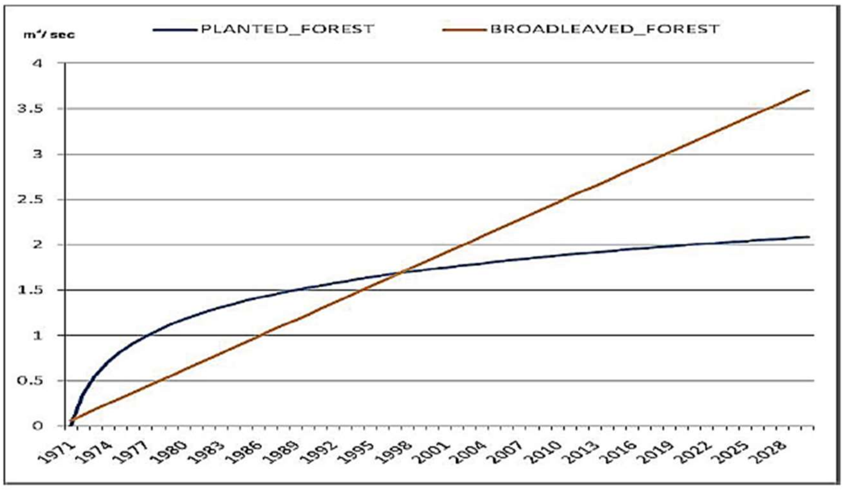

Figure 8. The impact of land cover change on OND discharge in Wundanyi (Source: Data analysis by authors).

Model design: $Qo = \beta t$, where Qo = OND_Discharge, t = time.

Similar effects of forest cover change were also evident in OND discharges. From 1970 to 2010, a unit plantation forest expansion increased/decreased Wundanyi's

OND discharges by 22.3% against 0.5% for broadleaved forests (**Table 8**). Discharges will be 3.75 m^3/s by 2030 under a linear broadleaved forest expansion assumption and 2.15 m^3/s under a logarithmic plantation forest expansion assumption (**Figure 8**). These results emphasise the importance of natural forest protection and conservation for sustainable water ecosystem services in Wundanyi.

4. Discussion of the findings

4.1. Discussion on the changing LUC patterns predicted in Wundanyi (1970–2030)

The above analysis has established drastic increases in Wundanyi's afforestation and agro-forestry practices, while other LUC types, including cropland, have slightly decreased over the years. These shifts could be attributed to the conversion of broadleaved forests into plantation forests and the adoption of agroforestry practices in croplands in the catchment [9,29]. The increased forest cover may have positive long-run impacts on Wundanyi's micro-climate and hydrology [4,5].

Land-cover changes due to reforestation and forest plantation have resulted in increased forest cover in the Wundanyi catchment, thus reducing surface runoff and soil erosion. Consequently, the amount of soil organic carbon that could otherwise be lost to land clearance and cultivation is retained in the catchment to increase 'green water' flows [33,34]. Therefore, increased forest cover in the Wundanyi catchment will certainly have a positive impact on its micro-climate and hydrology in the long run. Water resource stakeholders need an integrated approach to acknowledge the interactions between water, forest, other land uses, and socio-economic factors in this complex catchment.

Enhanced knowledge on integrated management of water resources and the multi-functionality of forested watersheds in addressing water scarcity, water quality, and flood control in the light of a changing environment is inevitable. The upper catchment of this area is inhabited by subsistence farmers dependent on rain-fed agriculture for livelihoods, which results in increased surface runoff and enhanced soil erosion as they engage in poor farming practices. There are limited soil and water conservation measures to minimize water runoff and soil loss, maintain soil fertility, and improve land productivity in these hills.

Hydrological processes in a catchment are influenced by many factors, such as climate, human activities, and the physical characteristics of the catchment. Therefore, changes in any of these factors or their variables (rainfall and forest cover) are likely to affect surface runoff and stream flow, as evidenced in the results above. Forest cover modification due to harvesting or planting alters the water balance of the site and eventually the catchment hydrologic regime. Hence, a significant reduction in the forest cover is likely to alter the flow path of precipitation and cause an increase in surface runoff, erosion, and sedimentation of water bodies. This complex interaction between climate and human activities makes it very difficult to quantify individual effects on changes in runoff and stream flow [35].

Taita Hills comprises two main parts: the hilly one rising abruptly in a series of ridges with the highest peak of 2208 m.a.s.l. at Vuria; and the surrounding plains with an elevation of 600 to 900 m.a.s.l.mist and cloud precipitations occur almost throughout the year, while orographic rainfall plays an important role in this micro-climate change as most of the hills form the first significant barrier to marine moisture-laden air coming from the Indian Ocean, nearly 150 km away [24]. This annual precipitation, though highly variable by nature, is also greatly influenced by the movement of the Intertropical Convergence Zone, thus leading to a bimodal rainfall pattern, with long rains during March–May (MAM) and short rains in October–December (OND).

4.2. Discussion on the effects of LUCC on Wundanyi's hydrological processes

Studies in various parts of the world have shown that, in general, climate variability, slope gradient, and LUCC have a significant bearing on stream flow variations through interaction between urbanization, vegetation, soil, and rocks, upon which precipitation is being translated into surface runoff, stream flow, and groundwater recharge (baseflow) in larger basins (over 100,000 ha) and medium catchment areas between 5000 and 500,000 ha [2–4,10]. Changes in rainfall patterns associated with climate change and storm duration during rainy seasons may have a significant impact on runoff and soil erosion in larger catchments rather than smaller ones [33,34]. Hence, surface runoff and river discharges in smaller catchment areas (of less than 100 ha) may be altered by natural vegetation or the influence of man, such as significant forest cover removal and water abstractions upstream, rather than by significant effects of climate change. Furthermore, large coverage of natural vegetation dominated by large canopy forests prevents and/or decreases considerably runoff depth from high-risk areas [2]. Hence, in the short run, higher surface runoff and discharges are expected from deforested areas with high soil loss rates [8]. However, most forested areas may experience high evapotranspiration rates, leading to low groundwater generation and thus lower water tables, which in turn result in lower river discharges. In time, these dynamics change with high rates of soil erosion in deforested areas leading to the sedimentation of the river channels, while forest cover reduces soil erosion rate and, therefore, increases river discharges.

The situation may be different for medium catchments (between 5000 and 500,000 ha). Studies have shown that during the dry seasons (JF or JJAS), a decrease of forest cover in such catchments results in an increase of surface runoff with decreasing infiltration rates, thus leading to lower baseflow and stream flow downstream of between 50% and 75%. This situation is explained by the removal of organic matter (humus), which serves as a sponge in the soil and enhances soil porosity. Once removed, soil absorption capacity will decrease along with infiltration, percolation, and groundwater recharge. The latter results in decreasing baseflow and river discharge and increasing surface runoff. During the rainy seasons (OND or MAM), high rainfall inputs result in higher surface runoff, as well as discharge in forested areas rather than on cropland and deforested areas.

A different scenario would be experienced in areas with large forest cover (over 100,000 ha) during the dry seasons. High rainfall inputs do not result in significant changes in the water balance in vegetated areas, except in areas where almost all forest cover has been cleared. Also, sharp surface runoff and discharges are experienced in areas where half of cropland has been removed. Consequently, surface runoff and stream flow in large forest areas are affected by both climate and vegetation cover. In either case, researchers concur that changes in surface runoff and river discharges occur within specific types of vegetation cover cut and/or replaced [36,37]. Therefore, crop selection and management are vital for maintaining stream flow and reducing runoff in Taita Hills.

The rainfall fluctuations coupled with LUCC over time may lead to decreased stream flow in the river basin [9,38]. Thus, the hydrological benefits could be threatened by land use/cover changes and climate variability. Land use/cover changes in the catchment impact water quality and quantity in streams [38]. It is postulated that the rapidly increasing population in the upper parts of the catchment has influenced changes that result in an increased inflow of sediments and nutrients in the river basin. For instance, a decreased water infiltration rate in a catchment may influence runoff and soil erosion patterns as observed.

5. Conclusion

The study assessed the effects of LUCC on Wundanyi's hydrological processes, focusing on surface runoff and streamflow. The findings show that Wundanyi has a highly fragmented LUC landscape. A spatial LUCC modelling of three-epoch satellite images (1990, 2000, and 2010) generated 12 LUCC categories within Wundanyi based on FAO's classification. The catchment's LUC landscape has undergone sustained modifications, which will continue up to 2030. Plantation forest has overtaken cropland as the largest LUC category; the former's share is increasing, while the proportion of the catchment's area under crops is declining, suggesting that part of the area previously used for crops is being converted to forest plantations. Significant LUC changes will occur in the future as the areas under grassland, plantation forests, and thickets increase tremendously, while woodland, broadleaved forests, shrubland, and cropland will reduce by up to half their area in 1970 by 2030. Wundanyi's LUCC has significant specific impacts on its surface runoff and streamflow, and different LUC types have had varied effects on the catchment's hydrological processes.

6. Recommendations

As a recommendation, the government and other stakeholders should implement interventions with direct and/or indirect relevance to climate change adaptation and mitigation. The interventions could cover several sectors, including agriculture, water, energy, and infrastructure. In the agriculture sector, for example, the government should promote irrigated and conservation agriculture and value addition to agricultural products. In the energy sector, the government could promote alternative energy, including geothermal, wind, solar, and mini hydropower generation, to minimize reliance on wood for fuel. The government should implement or enforce policies encouraging intensified afforestation, agroforestry-based alternative livelihood systems, alternative energy sources, community forest management, REDD+ initiatives, and reduced mono-species plantation stands. Such strategies may help reduce Wundanyi's LUCC and the associated impacts on the catchment's hydrology.

Author contributions: Conceptualization, RAA and CNL; methodology, JAO; software, CNL and RAA; validation, RAA, JAO and CNL; formal analysis, RAA; investigation, RAA; resources, RAA; data curation, CNL; writing—original draft preparation, RAA; writing—review and editing, JAO; visualization, CNL; supervision, JAO and CNL; project administration, RAA; funding acquisition, RAA. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest: The authors declare no conflict of interest.

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