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Dynamics of Land Cover and Impact on Stream flow in the Modder River Basin of South Africa: Case Study of a Quaternary Catchment

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Abstract: Understanding how dynamics in individual land use types influence changes in streamflow is vital. Most hydrological studies are based on paired catchment and modelling approaches. These are data intensive and require a long period of monitoring. To determine the hydrological effects of tropical vegetation conversion over large areas, it is manageable to study the same basin over different time periods. The study analysed changes in historical stream flow patterns with reference to dynamics in land cover in C52A quaternary catchment of South Africa. Landsat images for years 1993, 2004 and 2013 were used for the development of land cover maps. Subsequently, step-change (median point change, Mann-Whitney and Kruskall Willis) and trend detection tests (Spearman's rho and Kindall's tau) were applied to average annual discharge and rainfall data for the catchment between 1984 and 2013.Tukey's honestly significant difference (HSD) test was also used to compare the means. Results revealed that huge land cover changes coincided with significant ($p<0.05$) changes in streamflow although rainfall remained homogenous over the same period. This suggests that land cover change is intricately coupled to increases in streamflow. In addition, increased runoff is usually accompanied by increased rates of erosion and siltation. To ensure sustainable management of the catchment, therefore, soil and water conservation measures are critical within the broader context of integrated water resources management.

Keywords: Change Detection, Land Cover Classification, Landsat Image, Streamflow, Rainfall

1. Introduction

Scarcity and misuse of freshwater resources pose serious and growing threats to sustainable development and protection of the environment [1]. The quality and quantity of water heavily impact ecosystem services and human health. River flows are essential for the health of aquatic ecosystems and water supply [2]. Streamflow is also crucial for both ground and surface water resources. Rainfall-runoff relationships within a watershed are the result of the interplay of many factors, but are driven primarily by the interaction of climate, land cover, and soils [3]. Man as a keystone species has been modifying the environment for his own selfish needs. Increasing population necessitates further vegetation clearance to accommodate the farming and settlement needs of the communities which have significantly altered the magnitude and timing of river flows [4, 5, 6, 7].As a result, the health of aquatic ecosystems has declined and some water supplies have become stressed [8, 9, 10]. Therefore, it is imperative to understand the coupling between land use change and the generation of streamflow in a catchment as this influences water balance.

Land use and land cover play a crucial role in driving hydrological processes within watersheds[11].These include changes in water demands e.g. irrigation and urbanization, changes in water supply from altered hydrological processes of infiltration, groundwater recharge and runoff, and changes in water quality from agricultural runoff and suburban development [12]. Sound water resource management is central to the achievement of sustainable development. South Africa has adopted a total catchment approach to the management of water resources. As such the country has been divided into water management areas [13]. Land cover change is a primary concern in watershed management as it may also lead to increased flooding, soil degradation and decreased recharge of aquifers. Some studies have suggested that the consequences of land cover change may outweigh those from climate change [14, 8].Understanding the consequences of land-use change for hydrologic processes, and integrating this understanding into the emerging focus on land-change science are major needs for the future [15]. Woyessa et al., focused on the possible impacts on streamflow of scaling up rainwater harvesting techniques by farmers in the C52A catchment of South Africa [16]. However, for a complete understanding of the flow regimes of the system, it is prudent to look at a whole range of land use activities that could possibly pose impacts.

Studies on the effect of land cover changes on streamflow have yielded different and contrasting results [17, 18, 19, 20]. Bewket and Sterk noted that such contrasting findings suggest that the impacts of land cover changes on water resource systems vary from place to place depending on site-specific factors [21]. In addition, [22] believe that changes in a series of hydrological data can occur either gradually or abruptly or in a more complex form. Investigating stream flow patterns with respect to land cover dynamics enables assessment of sustainability of land use systems, because the stream flows are reflections of the ecological state of the entire watershed [21].This may also form a basis for forecasting the likely effects of any potential changes in land cover on water resource systems within this catchment. Therefore, this study analysed changes in annual historical stream flow and rainfall patterns with reference to dynamics in land cover in the C52A catchment in South Africa. The study findings are important in the development of responsive decisions and policy implementations with respect to catchment utilization in South Africa.

2. Material and Methods

2.1. Study Site

The study site lies between 26º 01`5 0 E and 27 º 0 0` 0 E and 29º 0` 0 S and 29 º 45` 0 S. The Modder river originates from the eastern hills of the quaternary catchment C52Abetween Dewetsdorp town and Rustfontein dam located at the outlet of the catchment C52A. The C52A catchment covers about 937km^{2}and lies in the semi-arid central South Africa (Figure 1). The soil texture sandy clay loam to sandy clay and is susceptible to crusting. The quaternary catchment C52A is located in the undulating and high altitude part of the basin between altitudes of 1400 and 1500 m above sea level. Mean annual rainfall for the last 30 years was 542mm and the maximum mean daily temperature is 29^{0}C. Vegetation physiognomic type is predominantly savanna grassland.

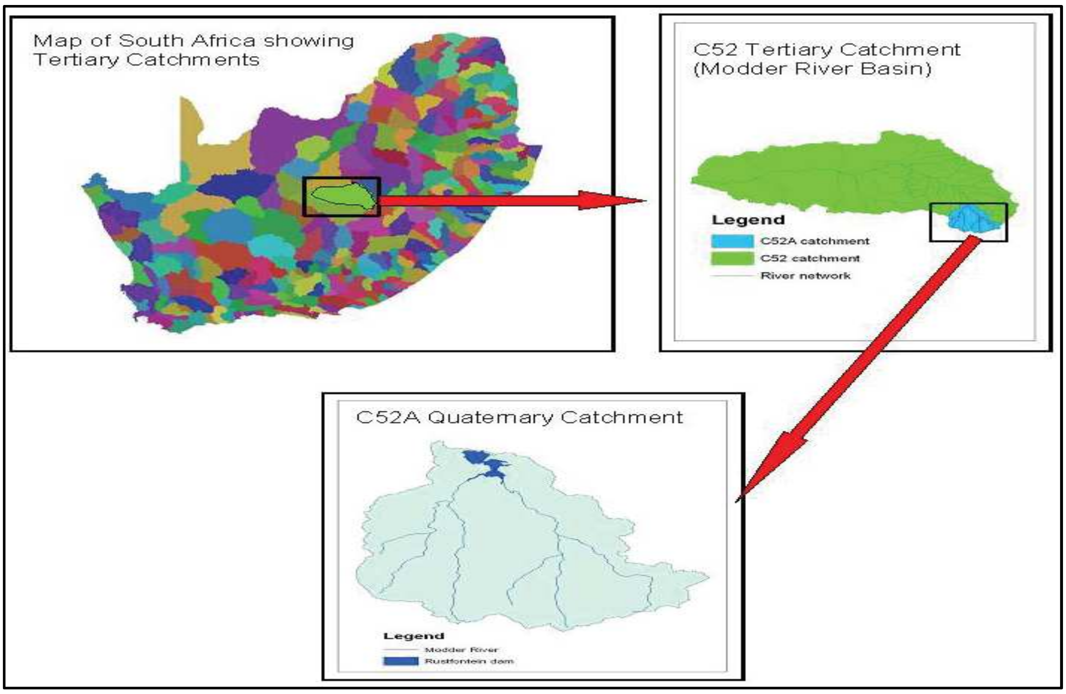


Figure 1. Location of the study area.

2.2. Method of Analysis

It has been observed that it is more manageable to study the same basin over different time periods of time rather than adopt a paired catchment approach when determining hydrological effects of tropical vegetation over large areas [23]. Unlike the conventional methods of the paired-catchment and modelling approaches which require a long period of monitoring and are data intensive, this study linked breaks or changes in streamflow to land cover dynamics in the catchment to ascertain the coupling between the two. To achieve this, dynamics in land cover between 1993 and 2013 were assessed using landsat images. Furthermore, average annual streamflow and rainfall data from 1984 to 2013 were subjected to a number of shift and trend detection methods. To this end, classified land cover maps for 1993, 2004 and 2013 were generated for the catchment. Throughout the text, significant difference means that $p < 0.05$ for means comparison.

Statistical shift detection methods applied

Test for step change

Rainfall and streamflow data were divided into three periods (1984-1993, 1994-2003 and 2004-2013), taking into consideration the availability of land cover maps The Median change, Kruskal-Wallisand the Mann -Whitney tests were used to detect any changes in the distribution of discharge and rainfall over the years. It is important to use more than one change detection method when dealing with hydrological data in order to ascertain the change [22].The median test compares medians across groups. These are essentially rank-based non parametric tests [23,22].

Test for trend

The Kindall's tauand Spearman's rhotests were applied to establish the presence of any trend in the data. These are non-parametric tests and particularly useful for eliminating influence of extreme or "outlier" values in hydrological data as well as for avoiding the requirements of normal distribution [24]. It should be noted that outliers are common in most hydrological data series. Two tailed test of significance for the correlation between time and hydrological data (discharge and rainfall) was performed.

Analysis of Variance (ANOVA)

Finally, ANOVA was computed to confirm changes in streamflow and rainfall patterns. As such to test for the homogeneity of variances, Levene's test was used. Subsequently, equal variances were assumed and post hoc Tukey's HSD test was applied to enable multiple comparisons of means across sub periods.

2.3. Land Cover Data and Image Analysis

The materials used in the study include Landsat TM, ETM and Landsat 8 satellite images for 1993, and 2004 and 2013. GIS and remote sensing software that were used include ArcGIS version® 10, ArcView® 3.2 and ENVI® 4.3 All the data were downloaded into the workstation for analysis using the GIS software. Image analysis was done using ENVI® 4.3 software as shown in Figure 2.

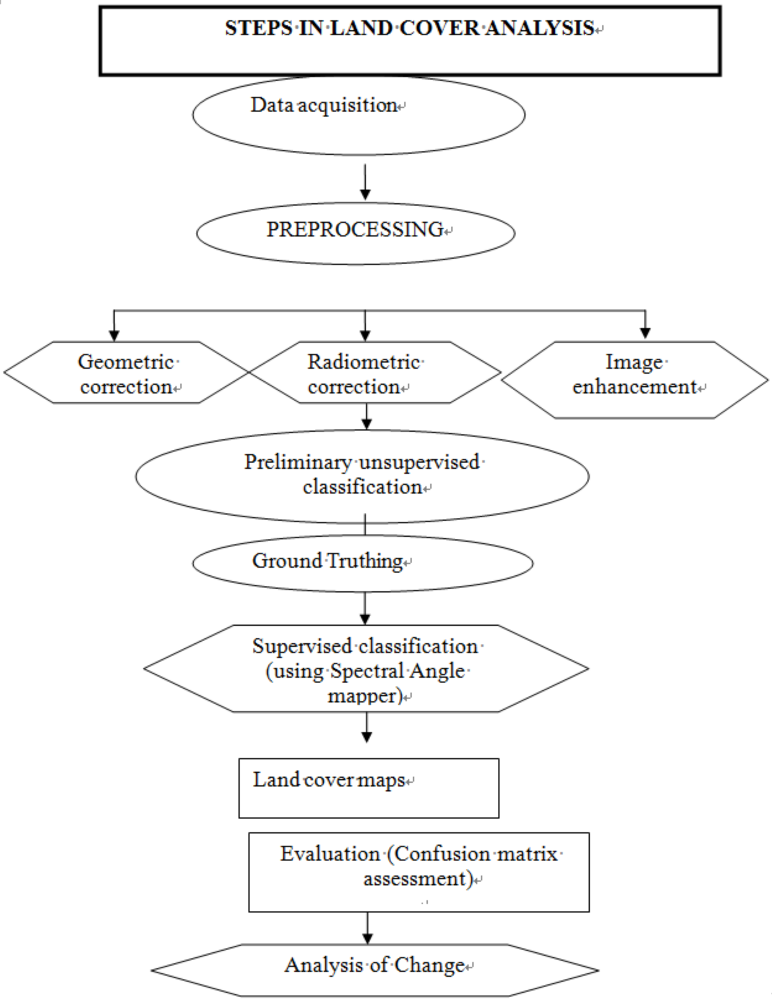


Figure 2. *Steps in vegetation analysis.*

2.3.1. Image Acquisition

A series of Landsat TM/ETM+ and Landsat 8 images (path 170 row 080) covering the watershed were acquired from NASA portal (GLOVIS). The images were selected for cloud free days during April, May, and June for the years 1993-03-18, 2004-06-04, and 2013-04-26. The acquired images were georeferenced and co-registered to one another to allow time line analysis.

2.3.2. Image Enhancement

Image enhancement techniques used were contrast stretching at 2.5%, and false colour composites to facilitate the identification of features. The near infrared composite was combined with visible bands (band combination NIR, Red, Green) to produce a false colour composite. Vegetation in the Near Infra-red (NIR) band was highly reflective due to chlorophyll pigment and false colour composite vividly showed vegetation in various shades of red . Built up areas were displayed in blue in the false colour composites while soil colours varied from dark to light brown. Deep red hues indicated broad leaf healthier vegetation while lighter reds signified grasslands or sparse vegetation. Water appeared dark and black depending on depth and clarity, due to absorption of energy in the visible red and NIR bands. False colour composites helped in differentiating water, soil and vegetated areas.

2.3.3. Normalization

Most sensors including LANDSAT record reflected electromagnetic radiation by earth features in the form of Digital Numbers (DN). These pose difficulties when comparing multi-temporal images because of differences in sun angle, sensor angle and flight height among other reasons. This problem was circumvented by changing DN values to radiance and then radiance to reflectance, a process called normalization. The following formula was used:

Digital Numbers to Radiance

$$\text{rad} = \frac{\text{LMAX}-\text{LMIN}}{255*\text{DN}+\text{LMIN}} \quad (1)$$

Radiance to reflectance:

$$\rho\text{p} = \frac{\pi*\text{L}\lambda*\text{d2}}{\text{ESUN}\lambda*\ \text{COS}\ (\Theta\text{s})} \quad (2)$$

where:

ρp = planetary reflectance,

L_λ=spectral radiance at sensor's aperture,

$ESUN_\lambda$ = band dependant mean solar exo-atmospheric irradiance,

Θs = solar zenith angle, and

d = earth-sun distance, in astronomical units

2.4. Image Analysis

The images were classified based on four techniques, namely unsupervised K-means, supervised Spectral Angle Mapper (SAM) and visual interpretation.

2.4.1 K-Means

K-means is a form of unsupervised classification technique which calculates initial class means evenly distributed in the data space. It then iteratively clusters the pixels into the nearest class using a minimum distance technique. All pixels were classified to the nearest class. It generated a general view of the area, creating a classified image with many clusters that aided in training site selection.

2.4.2. Spectral Angle Mapper (SAM)

The Spectral Angle Mapper (SAM) is a physically-based spectral classification that uses an n-dimensional angle to match pixels to reference spectra. It worked by determining the spectral similarity between two spectra, calculating the angle between the spectra, treating them as vectors in a space with dimensionality equal to the number of bands [25]. This technique was used on calibrated reflectance data and was more effective because it was relatively insensitive to illumination and albedo effects compared to other methods like maximum likelihood and minimum distance methods. The end member spectra were collected from false colour images through Region of Interest (ROI) average spectra. The spectra for different land cover classes were compared to typical spectra of known land features for the purpose of separating ambiguity features.

2.4.3. Visual Analysis

After the SAM analysis, visual aids were employed for further feature identity based on the features' site, location, arrangement and their shape. Land cover maps were produced for all the satellite image dates and the earlier date image was compared against the later date image in order to establish percentage changes. Image subtraction was done for each class to assess whether there were positive or negative changes on identified corresponding land cover classes.

2.4.4. Accuracy Assessment of Supervised Classification

The standard method of Confusion Matrix was used to assess classification accuracy for each image date by comparing classification results with ground truth region of interest (ROIs). The methods of accuracy assessment used included the Kappa statistic and Google Earth. The Kappa statistic is a statistical method of assessing the accuracy that took into account the chance of random agreement. Average accuracy of classification was 78%, 80 and 93% for 1993, 2004 and 2013 images respectively.

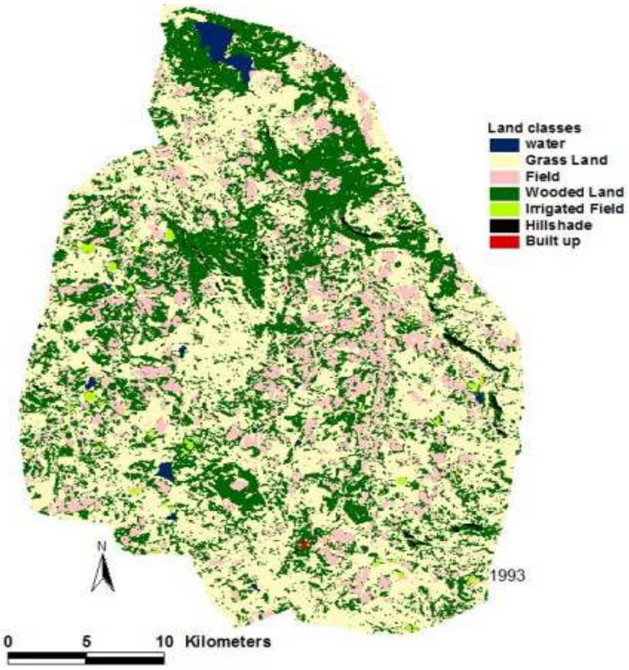
2.5. Streamflow and Rainfall Data

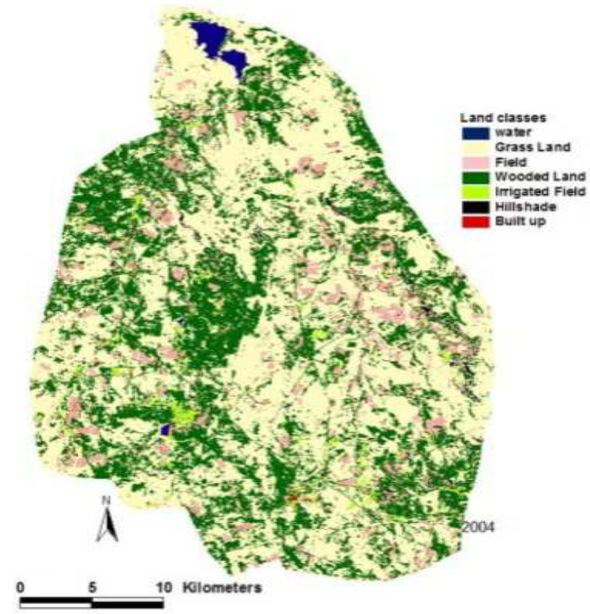
Stream flow data was obtained from the Department of Water Affairs and rainfall data was obtained from the South Africa Weather Services websites.

3. Results and Discussion

3.1. Land Cover Changes

Great land transformations have taken place within the catchment during the selected period. Figure 3 and Table 1 show results of land cover classification of C52A quaternary catchment for 1993, 2004 and 2013.





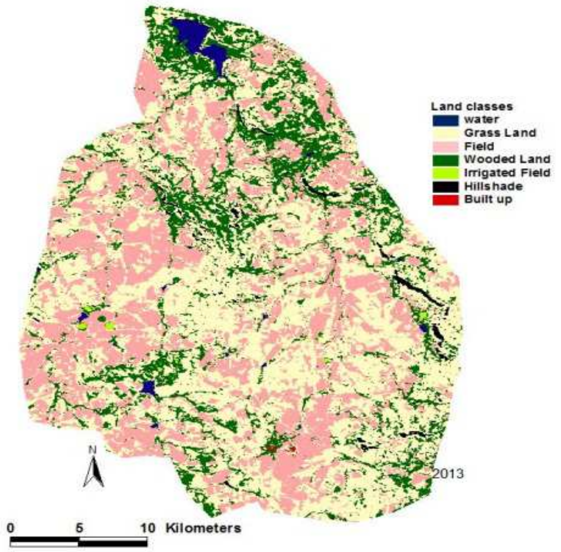


Figure 3. *Land cover maps of C52A quaternary catchment for 1993, 2004 and 2013.*

Table 1. *Land cover changes between 1993 and 2013 in C52A quaternary catchment.*

Land cover	%age cover	%age cover	%age cover	%age changes	%age change
	1993	2004	2013	1993-2004	2004-2013
Water	0.95	0.89	0.99	-6.7	12
Grassland	57	54.6	49.3	-4.3	-9.8
Cultivated area	15	16.6	31.8	14.9	92
Irrigated field	0.6	1.8	0.18	202	-89
Wooded land	25.8	25.4	16.5	-1.6	-35
Hill shade	0.5	0.3	0.9	-40	200
Built up	0.2	0.4	0.6	100	47
Total	100	100	100		

In 1993 most of the land was occupied by grasslands (57%), wooded land (26%) and cultivated area covered about 15 % of the total area. The irrigated land, built up area and water surface contributed 0.6%, 0.2% and 1% respectively to the total land cover. Between 1993 and 2004, water and grassland covers decreased by about 6.7% and 4.3% respectively. Wooded land slightly decreased by 1.6% owing to human encroachment. The area occupied by irrigated fields increased by 202% and the built up area increased by 100% (Table 1). The cultivated area also increased by about

15%. The decrease in grassland cover suggests that other land use options such as cultivation were encroaching into grasslands. By 2004 grassland continued to dominate land cover at 55% of the total area and declined by about 10% to contribute 49% of total catchment coverage in 2013. The wooded area covered about 25% in 2004, declining by about 35% in 2013. The cultivated area occupied about 32% of the total watershed in 2004 and declined by 92% to contribute15% of total area of the catchment in 2013.

3.2. Change Detection

3.2.1. Step-Change Detection

The results from the Median change point test/ Pettit's test for change reveal that the medians of discharge are not the same across the categories (p = 0.006).This suggests a shift in stream flow between 1984 and 2013. Mann-Whitney test revealed that streamflow was not significantly different between the first period (1984-1993) and the second period (1994-2003); but statistically different (p = 0.004) between the second period and the third period (2004-2013). The stream flow pattern was also significantly different (p = 0.003) when the first and third periods were compared. The Kruskal-Wallis test also confirmed that the distribution of streamflow across these three sub-periods was not the same (p = 0.003) and the mean has been increasing over the selected periods (Figure 4). The three tests above were also applied to rainfall data over the same periods and the differences were statistically insignificant.

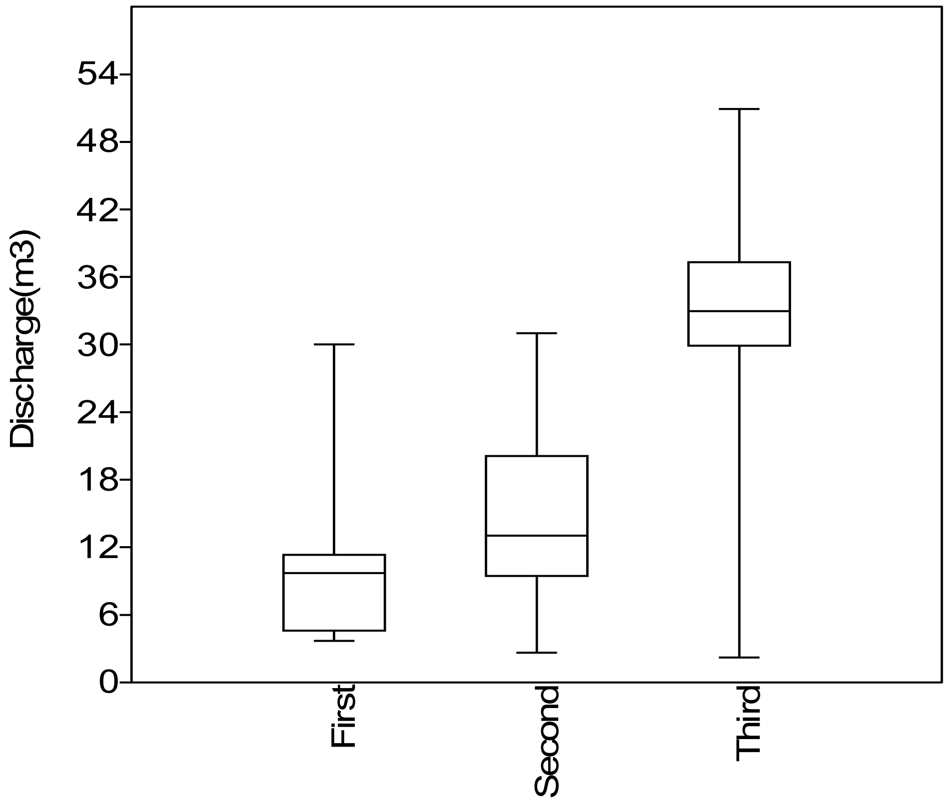


Figure 4. *Box plot showing changes in discharge over the first (1984-1993, second (1994-2003) and third periods (2004-2013).*

3.2.2. Trend Detection

Two trend detection tests in the form of the f Spearman's rho and Kendall's tau were applied to both discharge and rainfall data. The null hypothesis that there is no change in the mean of the data overtime is rejected since results revealed that there was a significant difference (p = 0.000001), suggesting that streamflow is either increasing or decreasing. Figure 4 confirms that mean discharge has been increasing progressively. However, the null hypothesis with respect to rainfall was accepted suggesting that the rainfall was homogenous over these time period.

The Levene test of the homogeneity of variance revealed that the variances were homogenous. Subsequently, the post hoc Tukey's HSD test was performed assuming equal variances.. Results confirmed that the means of the first and second periods were not significantly different (p = 0.74) while those of the first and third were significantly different (p = 0.00001). The second and third were also significantly different (p = 0.002).

3.3. Impacts of Land Use Change on Hydrologic Response

Results suggest that land use has greatly changed in the catchment and rainfall has remained essentially homogenous over the selected period. The observed changes in streamflow are to a large extent, not related to climate variability or climate change. The changes in land use coincided with shifts in streamflow patterns. For example during the first period, statistical tests could not detect significant changes in streamflow probably due to smaller land transformations that took place. During this period, cultivated area increased by 14.9% while grasslands and woodlands decreased by 4.3 and 1.6% respectively. These land use changes did not result in significant changes in streamflow and this was not surprising because, paired catchment experiments have shown that changes in annual water yield from forest cover reductions of less than 30% of the catchment could not be detected by streamflow measurement [26]. However, between the second and third period, statistical tests highlighted significant changes and these were accompanied by huge land cover changes. Cultivation increased by about 92% while wooded land decreased by about 35% and the grasslands decreased by about 9.8%. Therefore, the increase in streamflow is consistent with common knowledge on the prospective role of tropical forests, that reducing forest cover in forested catchments increases the water yield from the catchment with the majority of the increase occurring in the base flow component [21]. It is also consistent with results from paired catcthment studies[27, 17, 28, 29, 30, 31] that reduction in forest cover increased water yield.Also the area covered by the built up area grew by about 47% providing ample opportunities for runoff generation because of hard surfaces.

4. Conclusions

The contribution of land cover change to streamflow was evaluated by analyzing historical land cover dynamics with reference to streamflow and rainfall patterns. Results suggest that land cover change is one of the major factors influencing streamflow in the C52A catchment. Increase in streamflow coincided with dramatic changes in land cover within the catchment. Management of land use change will be vital for streamflow generation. Future decisions on land use in the catchment will be vital in determining the flow regime and ultimately the water balance in the catchment. Water balance at a catchment level is important since it informs water resource allocation for different user groups including the environment. The increase in streamflow over time suggests that there is increased runoff, usually accompanied by increased rates of erosion and siltation. It can also be discerned from the results that long-term monitoring of land use changes is important for determining trends in hydrology. This information is also important for the development of decision support tools for catchment farmers and managers and to inform policy. In order to ensure sustainable management of the catchment, soil and water conservation measures will be critical within the broader context of integrated water resources management.

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