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IMPACTS OF RAINFALL AND FOREST COVER CHANGE ON RUNOFF IN SMALL CATCHMENTS: A CASE STUDY OF MULUNGUZI AND NAMADZI CATCHMENT AREAS IN SOUTHERN MALAWI

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ABSTRACT

The impacts of climate change on water resources have received much attention globally especially in the last 30 years. Rainfall, the main driver of the hydrological cycle, has been varying in parts of the world in various ways. The picture is more complicated if impacts of land cover changes on water resources are also taken into consideration. These two pose challenges which require an integrated approach to address. Not many of such studies have been conducted in Malawian catchments and other tropical regions. In this study, annual, seasonal and monthly series of rainfall and river discharge of the Mulunguzi and Namadzi River catchments, two small sub-catchments in the Lake Chilwa catchment area, were analysed for trends using the non parametric Mann-Kendall statistic and Sens slope estimator. Further, Linear regression and the RainRU model were applied to establish whether the relationship between rainfall and runoff in the two catchments has changed. Furthermore, linear regression was used to establish how increased forest cover has influenced river flows in the two catchments. The results suggest that rainfall in the Mulunguzi catchment has decreased significantly at all scales and this has also led to reduced river flows. Increased forest cover since the pre 1950s has also resulted in reduced flows but this is not as significant as the rainfall decrease. In the Namadzi catchment, the rainfall trends suggest a varying pattern with no obvious straight trends. At annual and some months timescale, the rainfall has increased significantly. The river flow on the other hand suggests an overall declining pattern. This pattern is well linked with significant forest area increments which have occurred since 1995. It is therefore important that more detailed studies should be conducted to gain further insight to these relations as both catchments are important socioeconomically.

Key words and phrases: Land use, land cover, river flow, rainfall, climate change.

1. INTRODUCTION

Many developing countries are experiencing extensive land use and land cover change (LUCC) including in river catchment areas. To a large extent, afforestation and deforestation are known major human activities responsible for these changes (Calder, 1992). The role of LUCC on hydrological processes has been of interest to many studies because of its crucial role on catchment water balance through interception and transpiration. Much effort has however been put into studying the potential impacts of a changing climate on hydrological processes (Bowling and Strzepek, 1997). Ward and Robinson (1990) proposed three theories to account for the role of forestry land cover on hydrological processes namely: the neutral hypothesis which assumes that interception losses are essentially evaporative and that, since only a certain amount of energy is available in any period of time, this will be used either to evaporate water from within the leaf, i.e. in transpiration, or to evaporate water from the surface of the leaf, i.e. interception loss; the negative hypothesis regards interception as a loss of precipitation that would otherwise have been available at the ground surface for direct evaporation, for infiltration through the surface or for overland flow. The third theory, the positive hypothesis, holds that in certain circumstances, the interaction of water loss and gain in vertical and horizontal interception respectively may result in a net gain in a catchment area. From the three hypotheses, Ward and Robinson (1990) observed that each of the cases is dependent on factors including climatology, altitude and geology of the area which varies.

Studies on the impacts of land use and land cover changes on hydrological processes indeed suggest that each of the three hypotheses by Ward and Robinson (1990) may apply in certain cases. In the Maying River catchment in China, Genxu et al (2006) established that extensive land use changes from woodland and grass land to cultivation have resulted in mean annual runoff decrease by as much as 28.12% since 1967, agreeing with the negative hypothesis. In Malawi, Calder et al (1995) modelled the impact of land use change on water resources on Lake Malawi level changes. The overall agreement be-

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tween predicted and observed levels indicated that variations in rainfall alone, without changes in either evaporative demand or in the hydraulic regime of the lake, are sufficient to explain lake level changes. Increased levels of the lake as a result of decreased cover in the catchment area were noted. Lane et al (2005) modeled the impact of plantation afforestation on the flow regime of rivers in 10 catchments from Australia, South Africa and New Zealand using the annual flow duration curve (FDC) analysis. Flow reductions were found in all catchments, suggesting agreement with the negative theory. Land cover changes from a natural landscape to an agricultural and urban mosaic system have been found to be partially responsible for an increase in the seasonal variability and the magnitude of the annual mean runoff and discharge in the late 20th century in the Mississippi catchment (Foley et al, 2004) in line with the positive hypothesis. Bowling and Strzepek (1997) studies in the South Platte Basin, Colorado River Basin agree with the positive theory where it was established that the land-use changes resulted in greater runoff and acted to mitigate negative effects and enhance positive impacts of climate change. In the Dreasam Basin in Germany, Ott and Ulenbrook (2004) modelled impacts of increasing urban area and changing a forest cover type. Changes in urbanisation did not result in significant change of the water balance while forest cover type change yielded significant changes in the runoff. Ranzi et al (2002) on the other hand found that increased forestry cover as a result of reduced fuel wood use in the Mella river catchment of the Italian Alps resulted in reduced flood peaks and volume, agreeing with the negative hypothesis. Most of

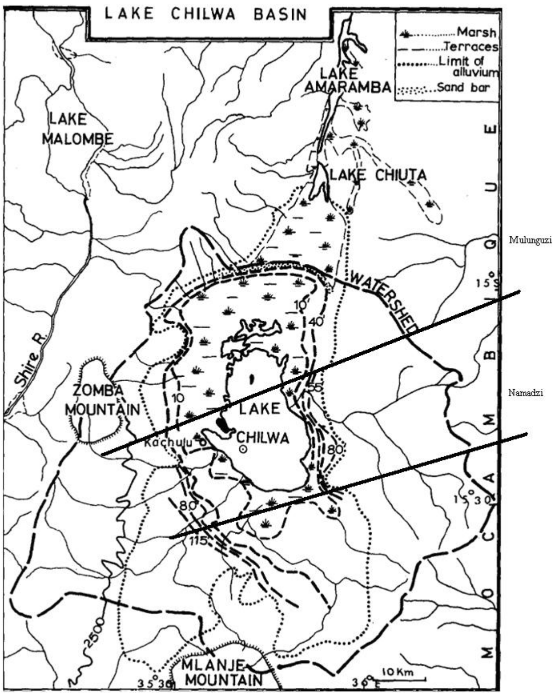

FIG. 1.— Map of Lake Chirwa Basin showing Mulunguzi and Namadzi Rivers (from Morgan and Kalk, 1970)

the studies on impacts of land use land cover change on hydrology have utilized various types of models to assess such impacts. Giertz and Diekkrger (2004) observed that while the bulk of investigations have been carried out in the temperate climate zones, only few field studies and very few model applications have been performed in the tropical environment mainly focusing on humid tropical regions like Amazonia. Notable among such studies in Malawi include that by Jamu et al (2005) who studied impacts of land use and cover changes in the Likangala catchment of the Lake Chilwa basin, Malawi with emphasis on implications for migration of fish species. This study therefore aims to assess the impacts of land cover change on two small catchment areas in a tropical climate setting, but with different characteristic using a simple rainfall runoff model. The study also analyses rainfall and observed river flow at monthly timescale for trends to establish if climate change and variability are affecting the hydrology of the small catchment.

2. STUDY AREA AND METHODS

The areas under study are shown in figure 1. They are part of the Lake Chilwa Catchment area in Zomba, Southern Malawi. The Lake Chilwa Wetland area was designated a Wetland of International Importance under the Ramsar Convention of 1971 and signed in 1997 by the Malawi Government.

The Mulunguzi River Catchment area at Mulunguzi river gauging station is entirely on Zomba Plateau and covers about 19.2 Km2. It is located in Zomba District, about 70 km from the City of Blantyre in Southern Malawi. A pine plantation covers three quarters of the Mulunguzi catchment. The Zomba Mountain pine plantations dates back to 1920 when the first *Pinus Patulla* trees were introduced. The plantation is also important in conserving both indigenous flora and fauna and contributes to biological diversity. Within the plantations, there are some patches of evergreen montane vegetation, scrub and glass woodlands. Apart from supplying water to the Municipality of Zomba, fishing, agricultural production and international research in water resources, biodiversity studies are a major activity in the area (Chavula, 1999). Average yearly rainfall is 1,894 mm/year for the period 1954 to 2003 with an annual minimum of 1,059 mm in 1991 and an annual maximum of 3,179 mm in 1978. Studies in the same catchment by Ngongondo (2004) showed significant reductions in the annual rainfall since 1954. Further studies established that the reductions in annual rainfall are having an impact on groundwater availability in the catchment Ngongondo (2006).

Monthly rainfall data for Zomba Plateaus stations (RGS 2BR2) which is located near the Ku Chawe Hotel for the period 1954 to 1993 was obtained from the Malawi National Meteorological Services. We assume that this station is representative of the catchment as it is roughly at the same altitude. Monthly River discharge data for the period from 1954 to 1993 for the Mulunguzi River at Mulunguzi station was used. This was obtained from the Ministry of Irrigation and Water Development, Hydrology section at daily timescale. The Zomba plateau pine tree cover and other forestry data were obtained from the Forestry Research Institute of Malawi.

The Namadzi River catchment is located in Chiradzulu and Zomba Districts, about 50 Km, from the City of Blantyre in Southern Malawi. The River marks the boundary of Zomba and Chiradzulu districts. The Namadzi catchment area at Namadzi river gauging station is about 26.7 km^2 (ha) (36,216 ha arable and 245 ha non-arable) (Thondwe EPA pers. comm) and Mbulumbuzi EPA has a total area of 13000 hactares (Mbulumbuzi EPA, Personal Communication). The river originates from Chikanguya Village in TA Mlumbe in Zomba and gets more water from Nambala aquifer in Chiradzulu district. The aquifer is located almost 800m from the Blantyre Zomba road and between latitude 16 degrees 31 south of the equator and 35 degrees 15 east of the Prime Meridian (GOM, 1987).

The monthly rainfall data for Namadzi catchment that was used in this study was for Makoka Research meteorological station and was collected from the Department of Meteorological Services in Blantyre for the period from 1958 to 2003. Average annual rainfall in Namadzi catchment for the station at Makoka for the period 1959 to 2003 is 997 mm/year. The Namadzi River discharge data used in the study was obtained from the Ministry of Irrigation and Water Development, Surface Water section. The record spans the period from 1952 to 1999 for Namadzi station number 20206. Both rainfall and discharge records were checked for consistency using double mass tests which they passed.

The Namadzi catchment tree cover data was obtained from the District Forestry Office in Zomba and was augmented with data from Amika, Nsamba, Gala, Nachambo, Kapalasa, New farm and Costa estates that boarder Namadzi River in its upper catchment. This data was in terms of total seedling that is planted in each year. This data was calculated into area planted with trees each year. The nonparametric Mann-Kendal test (S) was applied to monthy , seasonal and annual time series to detect the presence of a monotonic increasing or decreasing trend and the slope of a linear trend was estimated with the nonparametric Sens method (Gilbert, 1987).

Mann-Kendal test statistic S is calculated using:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(X_j - X_k) \qquad (1)$$

Where X_j and X_k are the annual values in years j and $k, j > k$, respectively, and

$$sgn(X_j - X_k) = \begin{cases} 1\,if & X_j - X_k > 0 \\ 0\,if & X_j - X_k = 0 \\ -1\,if & X_j - X_k < 0 \end{cases} \qquad (2)$$

Sens slope is calculated according to Sen (1948) as follows:

$$Q = \frac{X_j - X_k}{j - k} \qquad (3)$$

Where Q = slope between data points X_j and X_k; X_j = data measurement at time j; X_k = data measurement at time i and $k > j$. The slope Q can either be positive (upward) or negative (downwards). All the tests were done two sided at 90%, 95%, 99% and 99.9% confidence levels. The free spreadsheet based software MAKESENS developed by Sami et al (2002) of the Finnish Meteorological Institute was used to find the trends in the rainfall and runoff series. The spreadsheet has in built Mann-Kendal (S) test statistic and Sens Slope estimator functions. Details of the Mann-Kendal (S) test statistic and Sens Slope estimator methods and their applications can be found in Sen (1948), Kendal (1975), Gilbert (1987) and Sami et al (2002).

The relationship between any two variables was investigated using simple linear regression. Runoff series in the two catchments were generated using the Curve Number method which is also called the Hydrologic Soil Cover Complex Method (Colombo, 1997; Regis, 2000). The method is based on the integration of various land use types and soil in a catchment. A dimensionless curve number of between 0 and 100 is then generated. In this study, the curve numbers were found to be 77 for Mulunguzi and 79 for the Namadzi. The RainRu model, a spreadsheet based model, was used to investigate if there are any changes in the rainfall- runoff relationship for the two areas. The RainRu model is based on the equation as follows:

$$\begin{aligned} R_t = & b_1 Max(P_t - T, 0) + b_2 Max(P_{t-1} - T, 0) \\ & + b_3 Max(P_{t-2} - T, 0) \end{aligned} \qquad (4)$$

Where the runoff R_t in time step t is a function of rainfall P in the current time step and the previous time steps. In the $Max(P_t - T, 0)$, T represents the interception losses and part of the transpiration. As long as the rainfall P is less than T, all the rainfall is evaporated, without becoming surface runoff first. The T represents interception and evapotranspiration threshold and the average pan evaporation measurements of 46 mm and 60 mm for the Namadzi and Mulunguzi respectively were used. The partial runoff coefficients b_i are found through multiple stepwise backward regression. The bs are defined for the best fit with a least square error method. It also provides the error by which one can see which time memory of the system gives the best result. The total amount of months taken into account should not exceed 6 months because of the fictive correlation as a result of seasonality (de Groen, 2002). In excel, this operation is performed by using the LINEST Function. The simulated runoff was compared with the observed runoff to find out if there are any changes in the rainfall and runoff relationship for the two catchments.

3. RESULTS AND DISCUSSIONS

3.1. *Rainfall and Discharge Trends*

Tables 1 and 2 show trends in the rainfall and discharge series of the Mulunguzi and Namadzi catchments at monthly, annual and seasonal scales. From table 1, decreasing rainfall trends at monthly, annual and seasonal scale in the Mulunguzi catchment are evident with the exception of June, August and November where slight positive but statistically insignificant trends are suggested. However, only the March, September and October series have significant trends at 95%, 99% and 95% respectively. These results are also supported by the Sens Slope estimator. The annual rainfall declining trend agrees with the results from a previous study on the annual rainfall and discharge series by Ngongondo (2004).

From table 1 as well, all the river discharge series are showing stronger negative trends than the rainfall trends for the period under consideration. But there is overall agreement in that both rainfall and discharge series have negative trends at all scales. The results are also supported by the Sens slope estimator where all the median

TABLE 1
Mulunguzi monthly, seasonal and annual rainfall and river flow trends.

Series	Rainfall			Discharge		
	Test S	Significance	Sen Q	Test Z	Significance	Sen Q
Nov	0.61		-0.008	-1.33		-0.001
Dec	-0.31		-0.009	-2.31	*	-0.005
Jan	-0.62		-0.012	-3.27	**	-0.017
Feb	-0.1		0.000	-4	***	-0.026
March	-2.08	*	0.000	-4.78	***	-0.021
April	-1.12		0.000	-3.72	***	-0.026
May	-0.75		0.000	-2.72	**	-0.010
June	0.79		0.001	-2.11	*	-0.004
July	-1.17		0.001	-2.41	*	-0.003
August	0.34		0.001	-2.8	**	-0.003
Sept	-2.92	**	0.002	-3.9	***	-0.003
Oct	-2.4	*	0.000	-2.7	**	-0.001
Annual	-1.22		-0.003	-3.51	***	-0.117
Wet	-1.07		-0.006	-4.37	***	-0.018
Dry	-1.27		0.000	-2.85	**	-0.004

*** If trend at $\alpha = 0.001$ level of significance; ** if trend at $\alpha = 0.01$ level of significance; * If trend at $\alpha = 0.05$ level of significance; + if trend at $\alpha = 0.1$ level of significance.

slopes are negative. A strong dependence of the river discharge on the rainfall is therefore suggested. For the Namadzi catchment series in table 2, decreasing rainfall trends are suggested in May, June, July, Sept, November, December and the dry season with January, February, March, April, August and October suggesting upward trends. The May and Dry season flows are the only ones with significant downward trends at 90%. The results are also supported by the Sens Slope estimator.

TABLE 2
Namadzi monthly, seasonal and annual rainfall and river flow trends.

Series	Rainfall			Discharge		
	Test S	Significance	Sen Q	Test Z	Significance	Sen Q
Jan	0.86		1.100	-2.63	**	-0.008
Feb	0.98		-0.373	-1.91	+	-0.009
March	0.40		-0.957	-3.06	**	-0.012
April	0.27		-0.200	-0.22		0.000
May	-1.71	+	-0.700	0.08		0.000
June	-0.87		-0.229	-0.44		0.000
July	-0.64		-0.067	-0.02		0.000
August	0.64		0.053	0.96		0.001
Sept	-1.37		-0.042	2.00	*	0.001
Oct	0.29		0.077	1.15		0.001
Nov	-1.60		-2.218	2.67	**	0.002
Dec	-0.64		-3.280	-0.42		0.000
Annual	0.13		-6.271	-2.46	*	-0.003
Wet	0.67		-4.333	-2.53	*	-0.006
Dry	-1.96	+	-0.893	0.12		0.000

From table 2, significant trends are evident in the Namadzi discharge series for January (decrease at 99%), February (decrease at 90%), March (decrease at 99%), September (increase at 90%), November (increase at 99%), annual and wet season (decrease at 90%). Comparing the rainfall and discharge of the catchment in table 2, there is no strong correlation between the rainfall and discharge trends.

More significant downward trends are however suggested in the discharge. Secondly there is even negative correlation between the rainfall and both the May and Dry season flows with the rainfall showing negative significant trends while the discharge series have positive non- significant trends. In addition, January, February, march and April rainfall are all positive but not significant while January, February, march and April flows are all negative with the January, February, March series being significant at 99%, 90% and 99% respectively. Annual and wet season flows all have negative trends at 95% while the rainfall series are all positive but not significant. Overall, the picture seems to be that of negative correlation between the two series, which could be an indication that that rainfall trends in the catchment are not having a significant direct impact on the river flows.

3.2. *Rainfall -Runoff - Forest cover change relationships*

From the results in the preceding section, there is a contrast between the two catchments on the rainfall and river discharge trends. The Mulunguzi catchment flows show more dependence on rainfall as evidenced by similar trends of rainfall and discharge while the Namadzi Catchment flows show more independence from rainfall. As discussed earlier, afforestation and deforestation are known major human activities responsible for altering river flows behavior in many catchments (Calder, 1992). The Mulunguzi catchment is under pine forest introduced in 1921 while the Namadzi is under various forest cover with pine and eucalyptus dominating. In both catchments, planted tree cover area has been on the increase as shown in figures 2 and 3 where we trace cumulative forest cover change since 1960 for the Namadzi catchment and 1950 for the Mulunguzi catchment. The Namadzi catchment has obviously experienced the larger land cover change with a big jump of forest planted after the 1990s.

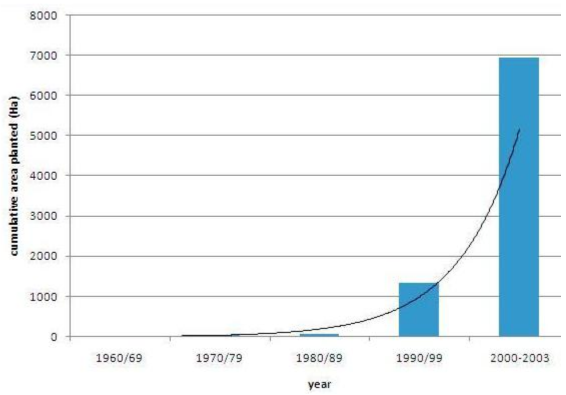

Fig. 2.— Namadzi catchment forested area

Figures 4 and 5 show linear regression results of a com-

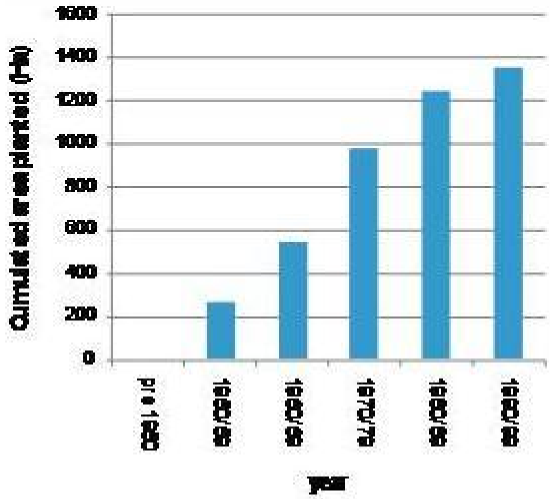

FIG. 3.— Mulunguzi catchment forested area

parison between forest cover as an independent variable and discharge as the dependent variable. In both cases, it is evident that as the area is increasing, there are corresponding flow reductions. The slope for the Namadzi however is much higher than that of the Mulunguzi despite the fact that it is the Mulunguzi catchment which has experienced more land cover changes. In both catchments, the rainfall-runoff relationships have not changed with time as shown in figures 6 and 7 and as rainfall increases, so does runoff. This is further confirmed by the comparisons of the simulated and observed flows of RainRu based on the rainfall input at 10 year intervals shown in figures 8 and 9. The figures show that that there is not much difference between the observed and calculated flows both in the Mulunguzi and Namadzi catchments.

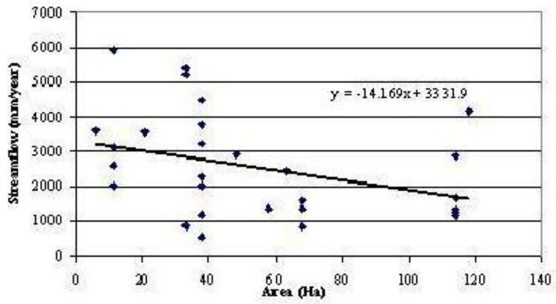

FIG. 4.— Steam flow Relationship between Area Planted with Trees and Stream Flow in Namadzi catchment (1968-1999)

From the preceding sections, it is noted that rainfall in the Mulunguzi catchment area has reduced significantly at all scales and these reductions are well reflected in the river flows as well. Further, there is some influence of catchment land use change activities on the river flows in addition to the rainfall reduction impacts. For the Namadzi catchment area, rainfall and discharge trends are not in agreement at most of the scales. Significant flow reductions are however evident at most of the scales in the observed river flows. There is some indication

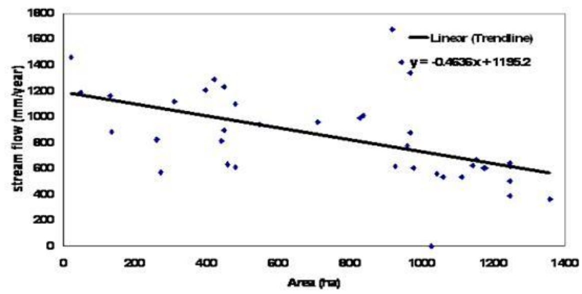

FIG. 5.— Relationship between area cultivated with pine trees and stream flow in Mulunguzi.

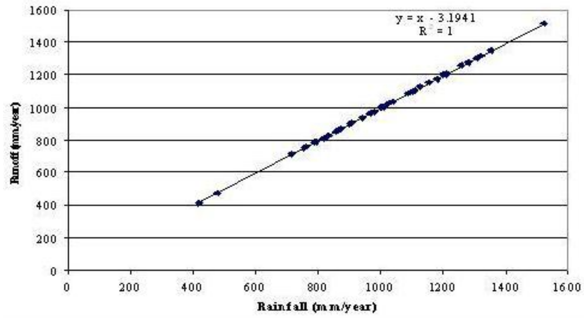

FIG. 6.— Rainfall runoff relation in Namadzi Cachment

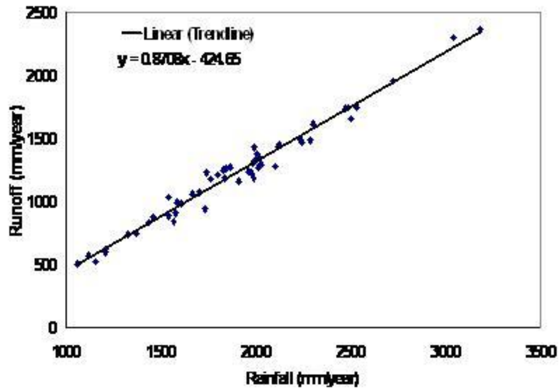

FIG. 7.— Rainfall Runoff Relation in Mulunguzi

that the flow reductions could be a result of land cover change and this is supported by simple linear regression results of flow and cumulative area planted with forest cover at annual scale. The Mann-Kendall statistics and Sens Slope estimator of the annual rainfall and flows also show significant reduction in flows but increased rainfall. Over time, RainRu model results in both catchments show that the rainfall runoff relations have not changed in both catchments.

4. CONCLUSION

This paper has looked at how small catchments located in the same climate setting may respond to climate change and land use changes using the Mulunguzi and Namadzi catchments of Southern Malawi. Significant rainfall reductions at monthly, seasonal and annual scales have resulted in corresponding flow reductions in

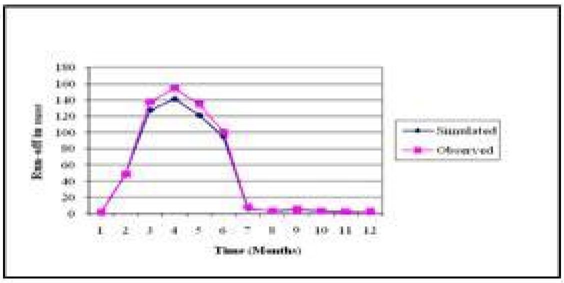

Figure 8a Namadzi Simulated and Observed Discharge for period 1958 to 1968

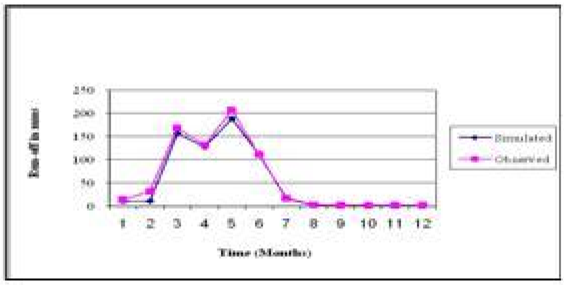

Figure 8c. Namadzi Observed and Simulated Run-off for Period 1979-1988

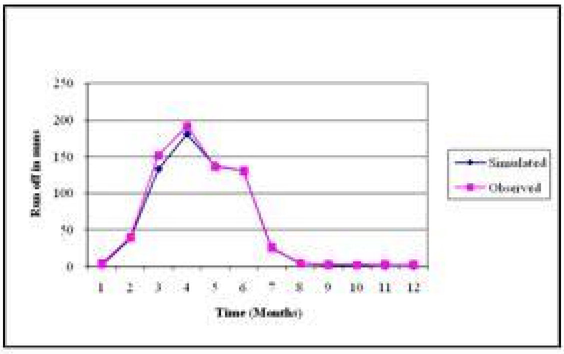

Figure 8b. Namadzi Observed and Simulated Run-off for Period 1969-1978

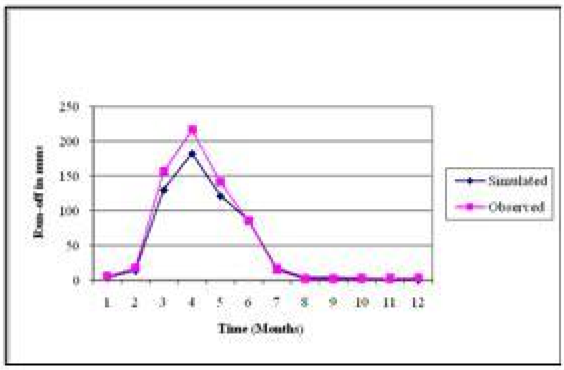

Figure 8d Namadzi Observed and Simulated Run-off for period 1989-1998

FIG. 8.— Observed and Simulated results

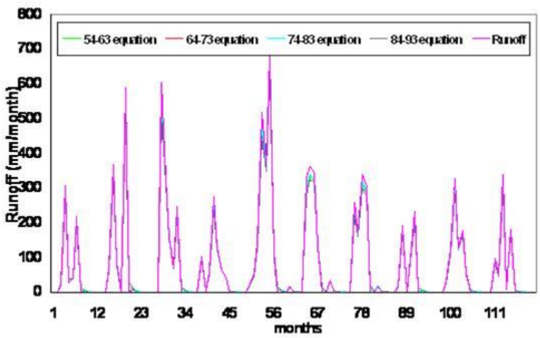

FIG. 9.— Simulated and Observed discharge in the Mulunguzi catchment

the Mulunguzi area. Although there could be some influence of land cover changes on the river flows, these are mostly minor. We can therefore conclude that rainfall is the main driver of runoff in the Mulunguzi catchment as opposed to land cover changes.

On the other hand, river flows in the Namadzi river catchment have reduced mainly due to land use changes as the rainfall trends at monthly, seasonal and annual scales were not totally in agreement with the flows and there was strong correlation with the land use change trends. Although there is no change in the rainfall-runoff relationship, there is significant reductions in the river discharge which can be attributed to the land cover changes.

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