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Hydrological assessment of Makanya catchment in South Pare Mountains, semiarid northern Tanzania

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Abstract This paper focuses on a catchment in northern Tanzania, the Makanya catchment in the South Pare Mountains, where people have only recently started monitoring rainfall and runoff. The main interest of this research is to assess the hydrological situation in this widely ungauged catchment, both in the past and the present, and special attention is given to different scales. The largest scale is the Makanya catchment with an area of 320 km^2, and the smallest scale the Vudee sub-catchment with an area of 24 km^2. The ungauged history of the hydrology has been assessed through interviews and transect walks with local elders. Subsequently a timeline has been established of the hydrology and related driving forces. This has been compared to the meteorological data observed in a nearby catchment. A multiple linear regression (MLR) model for the Vudee sub-catchment based on the 2004–2005 data set was used to assess the current state of the hydrology.

Key words PUB; ungauged basin; conceptual model; historical runoff; rainfall trends

INTRODUCTION

Many river basins worldwide are not or poorly gauged. This is even more the case in Sub-Saharan Africa where countries lack the financial, human and technical resources for developing and maintaining monitoring networks (Mazvimavi, 2003). In poorly gauged catchments, conceptual hydrological models, requiring a limited amount of data, can be useful for a better understanding of the hydrology by quantifying the basic components of runoff generation including: net runoff coefficient, evaporation, catchment response, etc. Limitations and uncertainties associated with this approach are discussed extensively in the literature (e.g. Beven, 2001). Database approaches, as in this case multiple linear regressions between rainfall and runoff, can provide further insights into the thresholds above which storm flow is generated. Additionally the net runoff coefficient and response time of the catchment can be determined.

Indigenous knowledge has often been neglected in establishing the runoff characteristics of an ungauged catchment. In a rapidly changing environment indigenous knowledge is sometimes the only source of information about the runoff characteristics of a catchment under pristine conditions. The objective of this study is to gather information about the changes relevant for hydrology that have taken place under population pressure in a predominantly ungauged catchment, both through interviews and through the use of a conceptual model.

STUDY AREA

The study area is located in the South Pare Mountains in northern Tanzania and is a tributary to the River Pangani. The Makanya catchment, as it is called, covers an area of approximately 320 km^2 (Fig. 1). The altitude ranges between 500 and 2000 m. Four tributaries, Mwembe, Vudee, Chome and Tae, join the main stream in the Makanya catchment, which drains into the River Pangani only during exceptional flooding events (Vyagusa *et al.*, 2006).

The soils on the forested summit area and the scarp slopes of the Pare Mountains are red loamy clays; surface limestones occur sporadically. A series of northwest trending faults cuts the South Pare Mountains, but the nature and age of these faults is unknown. The general structure of the area has a foliation dipping east–north–east, at moderate angles up to 40% (Geological Survey of Tanzania, 1965).

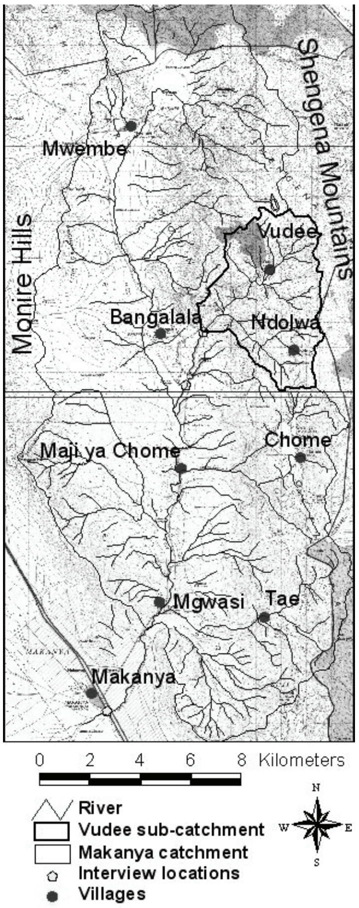

Fig. 1 Makanya catchment.

The Makanya catchment is practically ungauged, except for three rainfall stations located in the catchment and operated by individuals with records from the early 1990s. The nearest meteorological station with a long record (from 1957 onwards) is located in Same in a neighbouring catchment, approximately 10 km west of the catchment. In 2004, several raingauges were installed in the catchment, complemented by a compound weir installed on the River Vudee, one of the sub-catchments.

The hydrological year spans the period from 1 October to 30 September of the next year. The rainfall distribution in the catchment is bimodal with the short rainy season occurring in November–January (locally called “Vuli”) and the long rainy season in March–May (locally called “Masika”). The average annual rainfall is between 570 and 660 mm year^{-1} (Same and Tae, respectively). The potential evaporation in general exceeds 2000 mm year^{-1}.

HISTORICAL HYDROLOGICAL ASSESSMENT

Historical runoff in the catchment was assessed by using structured interviews with local elders; emphasis was put on establishing when the river used to be perennial (if at all), the current flow patterns and extreme events, both droughts and floods. These interviews were done at two locations in the catchment, Makanya and Bangalala (see Fig. 1). This was cross-checked with historical rainfall data (station in Same). This data set was used for trend analysis, using the Spearman rank test.

Vudee

The first catchment, the Vudee sub-catchment (24 km^2), was investigated at two locations. The first is where the River Vudee arrives at the main river valley, at Bangalala, while the second site is some 2 km downstream, just before the confluence with the main Makanya stream, downstream of two diversions for supplementary irrigation of 500 ha (Fig. 1). At the upstream site, flows are permanent, both in the past and present, with the exception of a few extremely dry events, which occurred in 1948, 1974, 1997 (before the El Niño rains) and early 2006. People observed that base flow has steadily decreased over the years since the 1950s. At the downstream site, the flow in the past reportedly resembled the flow of the upstream site. However, in the present situation flows only occur during the rainy season and then quickly recedes. This is mainly due to the increasing abstractions between these sites. Flood flows at both sites are not very different, indicating that the influence of the abstractions is mainly recognizable during the base flows. Flood flows have reportedly increased over the years, with the most extreme event during the El Niño year 1997, although in 1951 a heavy flood was also observed.

Makanya

In Makanya the flows at the outlet of the catchment have also been analysed through interviews. In Makanya, flows from the mountains are diverted in a spate irrigation scheme, established in the 1960s. From there they flow into a so-called seasonal wetland, occasionally linking the Makanya catchment with the River Pangani, 50 km downstream. The historical flow regime, both upstream and downstream of the spate irrigation, has been analysed. Upstream of the spate irrigation system, continuous flow was observed during the 1960s. At present the river bed is dry except after heavy rainfall events in the catchment, occurring on average five times a year, and flowing for at most a week at a time. During the El Niño season (1997–1998) a continuous flow reached Makanya from March until May. Downstream of the spate irrigation system, in the 1960s water regularly reached the River Pangani after heavy rains in the catchment, nowadays only extreme floods reach the River Pangani.

Most people in the two villages indicated that they feel that the rainfall has decreased over the years and that this is the main cause for the changes in the flow regime. Other causes mentioned by the locals were increased population and deforestation.

Rainfall trend analysis

The Same meteorological station is located near the western fringe of the Makanya catchment at the foot of the South Pare Mountains. A correlation analysis with the Tae station (1990–2000) within the Makanya catchment shows a good correlation (0.69 on a monthly basis), although the absolute values differ substantially (1990–2000), Tae (655 ± 250 mm year^{-1}), Same (500 ± 260 mm year^{-1}). Daily data from Same were used for trend analysis to represent the hydroclimatic situation in the Makanya catchment.

The meteorological data suggest that the rainfall in the area decreased during the period of observation (1957–2004) from an average of nearly 630 mm year^{-1} (1960s) to 500 mm year^{-1} (1990s) (Table 1). Enfors (personal communication) also indicated that changes in the rainfall pattern are mainly apparent in the larger occurrence of long dry spells (>21 days). Long dry spells have increased in occurrence significantly from 20% before the 1980s to 80% after the 1980s.

Spearman rank tests were performed on annual totals, Vuli and Masika seasons and for the dry season. The test for annual totals showed a visible but not significant trend (test statistic $t = -1.48$ within the interval –2 and 2; Voogt, 2005), although Fig. 2 shows that since 1990 a period with clearly below average rainfall predominates, with the exception of the 1997–1998 El Niño season.

The tests for Vuli and Masika also showed no significant trend (t = –0.46 and –0.96 respectively; Voogt, 2005), although in Fig. 2 it can be seen that the Masika season has a clear visible trend, whereas Vuli rainfall shows no visible trend. The variations in Vuli are higher, with an average rainfall of 220 mm season^{-1} and standard deviation of 150 mm season^{-1}, than in Masika, with an average rainfall of 320 mm season^{-1} and a standard deviation of 130 mm season^{-1}.

Table 1 Average rainfall and standard deviation of the rainfall, Same station.

	Annual (mm season^{-1})		Vuli (mm season^{-1})		Masika (mm season^{-1})	
	Average	Stdev	Average	Stdev	Average	Stdev
1960s	627	193	263	185	330	175
1970s	615	250	241	162	339	135
1980s	587	140	216	90	343	105
1990s	499	276	213	240	264	66

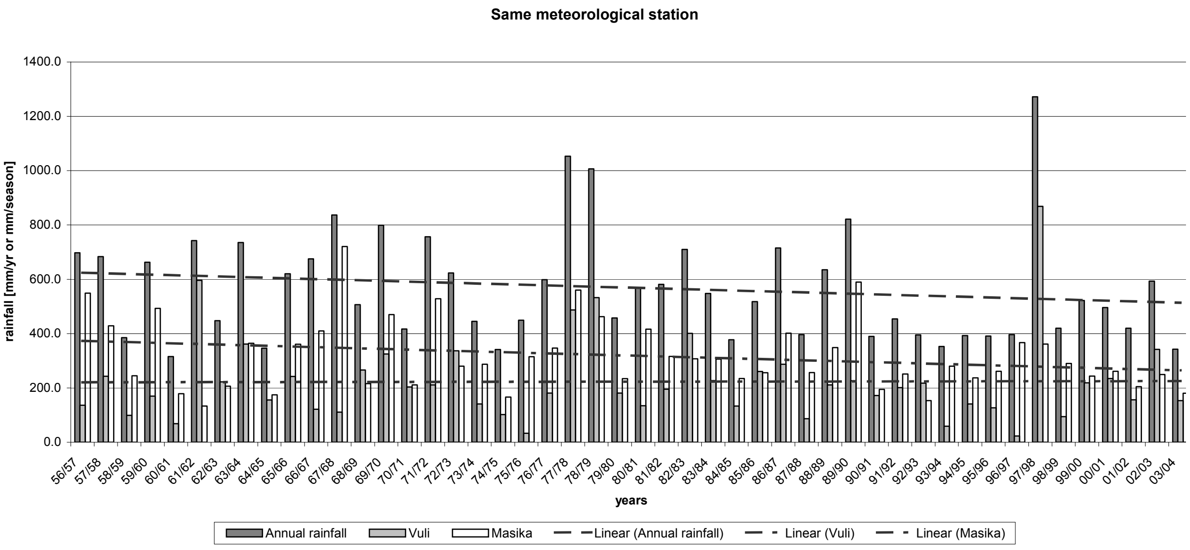

Fig. 2 Annual, Masika and Vuli rainfall Same station with trend lines (mm year^{-1}or mm season^{-1}).

The previous analysis is consistent with the study performed by Valimba (2004) indicating that in northern Tanzania changes in rainfall patterns cannot be found in annual totals, however occurrences of low intensity rainfall (<10 mm day^{-1}) have significantly decreased, whereas high intensity rainfall has increased. This trend is particularly apparent during the Masika season.

CURRENT STATE OF THE HYDROLOGY IN VUDEE SUB-CATCHMENT

Multiple linear regression model

The assessment of the current state of the hydrology has been done with the data gathered from the Makanya catchment during the rainy season of 2004/2005. Data was collected from one operating rainfall station in the upper catchment, which was used for the rainfall input and a gauging station where the River Vudee enters the valley. A multiple linear regression (MLR) model for rainfall–runoff (RAINRU) was developed by Savenije (1997), where rainfall in the previous time steps is linked with the runoff in the present time step. A threshold value is used in the model before runoff is generated. On a monthly time step this threshold value converges to the interception value. Since runoff in a particular month depends not only on the rainfall for that month, but through storage also on the rainfall in the preceding months, a linear transfer function is used (Savenije, 1997):

$$Q(t) = \sum_{i=1}^{n} b_i * \mathrm{Max}\left(P(t-i) - D, 0\right)$$

where $i \in [0, 1, 2, \ldots n]$ is the counter backward time step from the start of the rainfall at time step t. The parameters Q, P and D are expressed in mm (time step)$^{-1}$. The coefficients b_i are determined through multiple linear stepwise regression. The coefficients generated by the regression model give information on runoff response to rainfall, and how long a rainfall event impacts on the runoff. Finally it gives a quantification of the percentage of the net rainfall that comes to runoff (net runoff coefficient). This study uses the concept of RAINRU and applies it to daily and weekly rainfall and runoff data as done by Woltering (2005) for a catchment in Zimbabwe.

Daily linear regression

Initially the threshold value was set to 3 mm day^{-1} corresponding to a realistic daily interception value. The net runoff coefficient (percentage of net rainfall ($P - D$) coming to runoff) is 6.3%. The results for the Vuli 2004 season are shown in Fig. 3. Basically 80% of the runoff is generated in the first three days, with subsequent days generating less than 5% of the total runoff. Increasing the number of days beyond 5 days did not enhance the simulation regarding the peaks; in general the model also could not simulate the base flow. The model accuracy, r^2 is 0.62, when considering

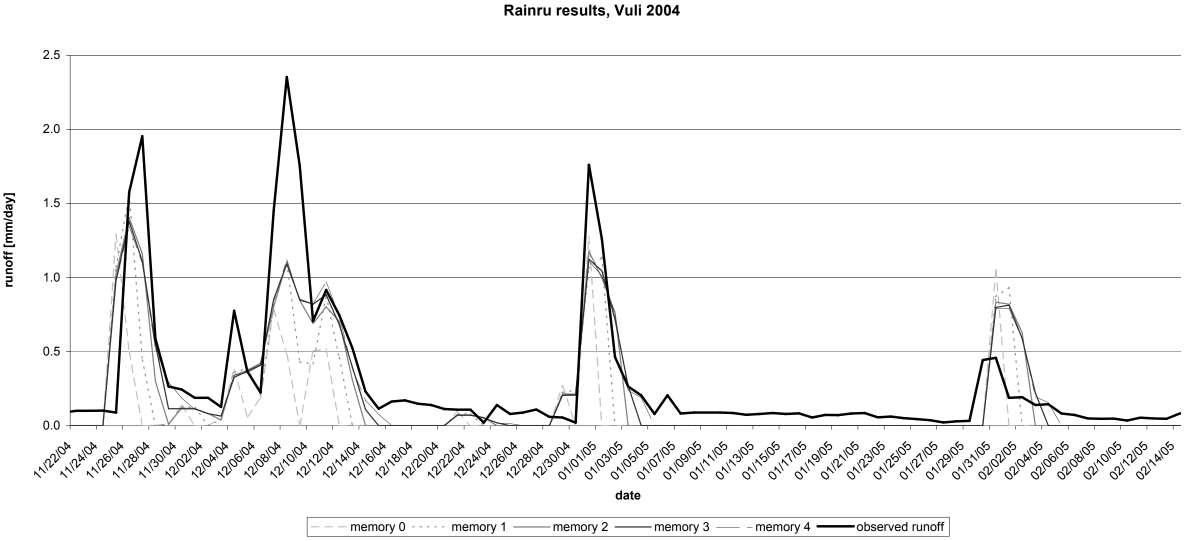

Fig. 3 Results for Rainru on a daily basis with threshold of 3 mm day^{-1}, Vuli season 2004.

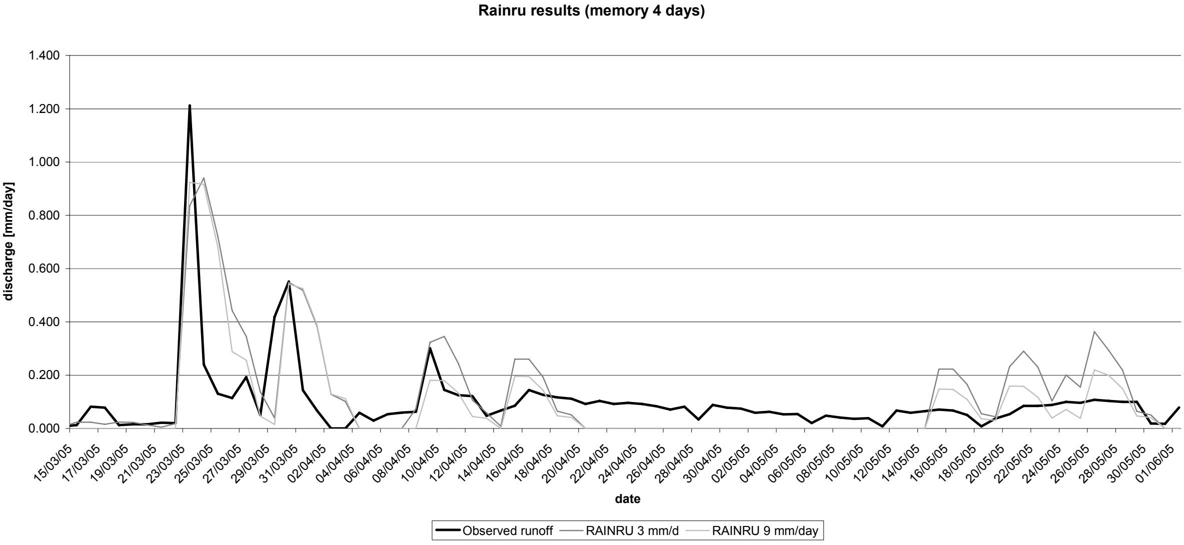

Fig. 4 Results for RAINRU on a daily basis with threshold of 3 and 9 mm day^{-1} memory of 4 days, Masika season 2005.

more than 2 days in the computation. The MLR model could not account for the base flow that is observed almost continuously. Currently the base flow rises to a steady 25 L s^{-1} during the rainy season and decreases to 5 l s^{-1} during the dry season. The failure of the model to predict this base flow indicates that a different system is responsible for the generation of this flow.

In the model run (Fig. 4) it shows that during the Masika rains in May hardly any increase in flow was observed. This indicated that the threshold value of 3 mm day^{-1} did not adequately address the threshold behaviour of the system. Rainfall in this period ranged from 11–17 mm day^{-1} and did not generate a substantial increase in runoff. A threshold value of 9 mm day^{-1} was then used, reducing the overshoot of the runoff simulation (Fig. 4). The net runoff coefficient also increased because of the increasing threshold value (net precipitation decreases) to 5.9%. The performance of the model remained the same (r^2 = 0.62), whereas increasing the threshold value to a higher value affected the performance negatively. The need for a threshold value higher than 3 mm day^{-1} to increase overall performance indicates that the threshold on a daily basis is more then interception.

Weekly linear regression

The daily MLR model clearly had a deficiency in predicting base flow. An attempt was made to model this by increasing the time step of the model to a week. The threshold value was tested. An

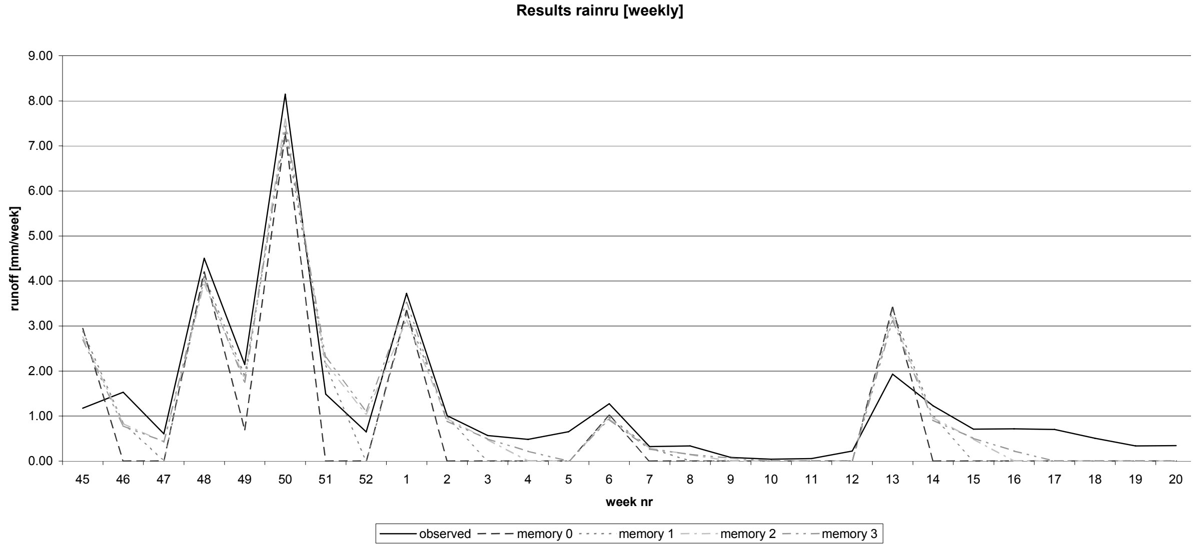

Fig. 5 Results for Rainru on a weekly basis with threshold of 35 mm week^{-1} Vuli 2004 and Masika 2005 season.

optimum of the model performance was obtained with a threshold value of 35 mm week^{-1}. The model performance is better on a weekly basis than on a daily basis (r^2 amounts to 0.90 compared to 0.62), with a better prediction of base flow. As the previous model indicated, most runoff is generated in the first three days. This model shows similar response, with 90% of the total runoff generated in the first week (Fig. 5).

CONCLUSIONS

The interviews suggest that the River Makanya at the railroad bridge (320 km^2) changed from a perennial river in the 1950s to an intermittent river in the 1990s. The flow from the River Makanya into the River Pangani ceased and the seasonal wetland turned into a steppe terrain. On the sub-catchment scale, flows from the mountains have reportedly dried up and the base flow decreased significantly. Decreasing rainfall amounts were predominantly mentioned as the main causes of the changes, although this could not be substantiated with a rainfall trend analysis with data from a nearby station.

The rainfall–runoff data collected for the Vudee sub-catchment (24 km^2) suggest that no more than 6% of the net rainfall forms runoff. It also shows that there are two flow paths, one very slow, contributing to long-lasting base flow from the mountains to the villages at the foot of the mountains (between 5 and 25 L s^{-1}, at the end of the dry season and during the wet season, respectively). The other flow path is fast runoff, with the peak reaching the foot of the mountain within one day with 80% of the runoff generated in the first 3 days after the rainfall.

Even with a limited amount of data, a good initial hydrological picture could be established for a widely ungauged catchment through the MLR model. Interviews with locals and a comparison with a nearby meteorological station established an historical overview of the runoff regime and its variability.

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