

# Hydrological Study of Hydropower and Downstream Water Release

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## ABSTRACT

*Kihansi hydropower plant is located in south central Tanzania deriving its water from a catchment that has an approximate drainage area of 584km<sup>2</sup>. The availability of high head in a short stretch of the river and the reasonably favorable hydrology with a reliability of flows exceeding 7cumecs (95% of the time) makes the catchment an ideal source of water for the hydropower plant and the livelihoods of the species in the lower Kihansi gorge. A hydropower plant has been designed as a 180MW run-of-the-river type with provision for expansion to 300MW in the future making it a significant power source for the energy-strapped country. This research focuses on the hydrology of Kihansi river catchment and estimates the actual water release downstream for environmental mitigation purpose.*

*The study finds out that the catchment hydrological regime is characterized by a constant and reliable base flow and the percentage of time the average flow is equaled or exceeded ranges from 31% to 42%. Long term hydrologic data analysis indicated that water loss is high in the western and northern parts of the catchment. The landuse change such as the deforestation in the catchment is a potential threat for the availability of enough water to run the hydropower plant and sustain the downstream release required for endemic species, already in danger.*

*Average Annual Flow (AAF) was used to highlight the flow increase or decrease over the years. A general annual flow reduction was observed which is attributed to change in catchment landuse.*

*System types and lumped conceptual hydrologic models were applied to simulate the catchment hydrology. An Ordinary Least Square (OLS) method was used to estimate the unit hydrograph in the systems model application and two parametric Nash Gamma function model applied for the conceptual Soil Moisture Accounting and Routing (SMAR) model. The simulation results obtained were not satisfactory except for Linear Perturbation Model (LPM). Due to variations in catchment physiography and spatial hydrological input variables. The study recommends a distributed /semi distributed modeling approach to simulate the catchment hydrology.*

## 1 INTRODUCTION

In the Kihansi river catchment (that refers to the upper watershed area upstream the recently constructed Kihansi dam, the major threat of water resources management arises due to deforestation in search for further cultivated land and uncontrolled bottom valley cultivation (locally called 'Vinyungu' sing 'Kinyungu') as shown in Figure 1. Besides, there is heavy reliance on wood-based biomass which is potentially damaging much of the forest cover. Current agricultural settlements are carried out on steeply sloping hill sides without terracing or other soil conservation measures. These, together with losses of forest cover pose management challenges for the catchment because of increased sedimentation and irregular streamflow (World Bank, 2001).

Currently there are two water users in the catchment, the Kihansi hydropower company (designed for 180 MW with a possible extension to 300MW in the future) and the gorge eco-system, with particular interest to the Kihansi Spray Toad (*Nectophrynoides Asperginis*) which was discovered during the feasibility study of the Kihansi hydropower project. From the point of water use in the catchment, the water allocation issue seems simple, but the difficulty in sustaining the water use in the Kihansi catchment was well reported by Acreman *et al*, (undated). The major problem is that Kihansi power station provides a significant proportion of the electricity needs of Tanzania and any reduction in power output has far-reaching implications to the power supply of the country. With the high level of poverty within Tanzania, one might ask whether releasing water to conserve the minute Kihansi Spray Toad, in an inaccessible gorge can be afforded (Acreman *et al*, undated).

Various water allocation proposals and conservation measures have been suggested to avoid the reduction of power outputs and conserve the ecosystem which is under extinction (World Bank, 2001). The proposals were based on socio-economic approaches, which further needs to be strengthened by hydrological studies.

## 2 DESCRIPTION OF THE CATCHMENT

Kihansi catchment is part of the Eastern Arc Mountains (EAMs) in the south central Tanzania. The EAMs are a group of mountains which stretch from southeast Kenya through south central Tanzania and are situated between 3°20' and 8°45'S and 35°37' and 38°48'E. Kihansi catchment together with the hydrometric stations and its current catchment conditions are shown in Figure 1.

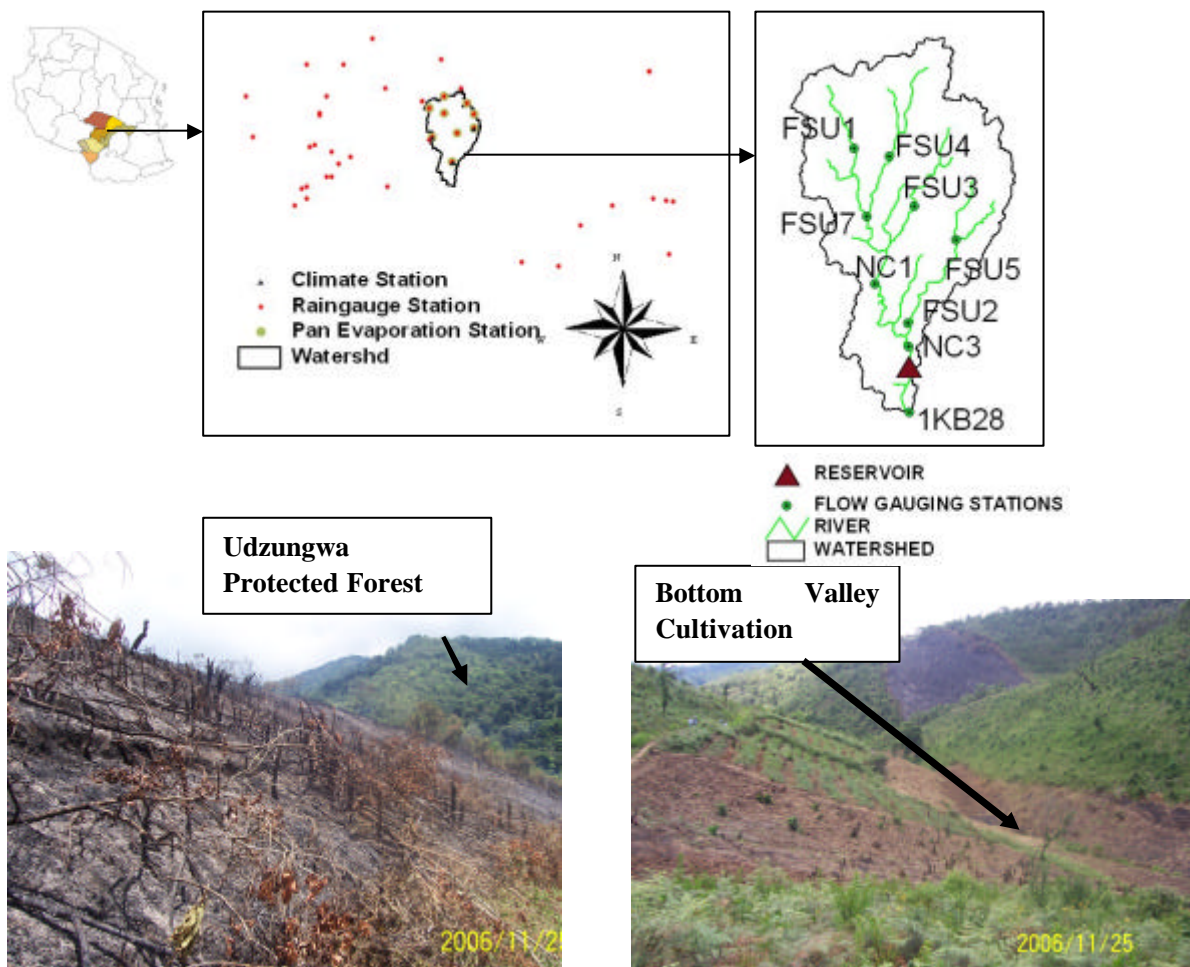


Fig. 1: Kihansi Catchment with hydro-climatic stations and current catchment conditions.

### 3 DATA ANALYSIS

Ultimately the success of a hydrological model depends critically on the data available to set it up and drive it. Basically, hydrology is limited as a science by data availability and measurement techniques (Beven, 2006). In this study hydro-climatic data were collected from Tanzania Electric Supply Corporation (TANESCO), Rufiji Basin Water office (RBWO) and Water Resources Engineering Department (WRED) and the quality of these data were assessed as indicated below.

#### 3.1 Pan Evaporation Data

There are nine records of pan evaporation data having record lengths from one year (station 0983501) to eleven years (station 0983509). The percentage missing varies from 7.4 percent to 46.69 percent. The daily pan evaporation estimates at four representative stations are shown in Figure 2.

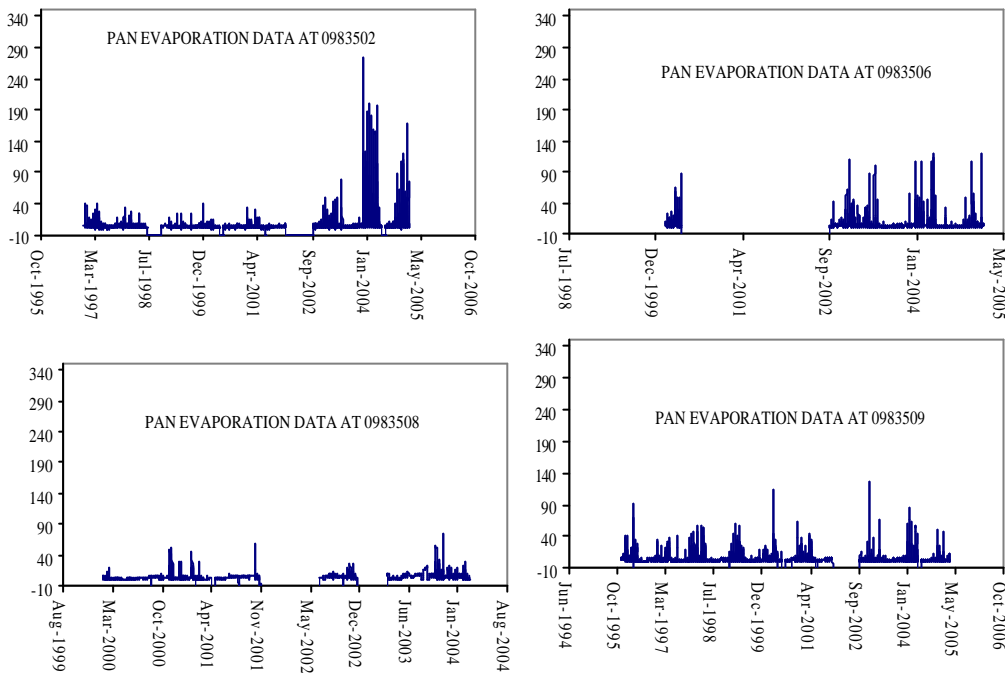


Fig. 2: Pan Evaporation data for Kihansi River catchment. The vertical axis is Pan Evaporation (mm/day) and the horizontal axis is days.

According to Figure 2, pan evaporation data records are exceeding 10mm/day in almost all gauging stations. A standard methodology as shown in equation (1) was used to compute evaporation from the pan (Norplan, 2003).

$$Evaporation(mm / day) = 0.5xCUPS_{in} + RAINFALL - 0.5XCUPS_{out} \quad (1)$$

Where  $CUPS_{in}$  and  $CUPS_{out}$  are the number of cups in and cups out respectively and  $RAINFALL$  is the daily rain fall in mm. The factor 0.5 reflects that 1 cup=0.5mm.

Pan evaporation data was overestimated in some periods of record and the possible errors of over estimation arises due to negligence of recording particularly during rainy seasons. During heavy rains it is possible that there is pan overflow and the component  $0.5xCUPS_{out}$  of equation (1) was missing making the evaporation volume to be large (Norplan, 2003). Thus, the authors of this research suggest pan data collected from Kihansi River catchment is unrealistic and should be avoided.

### 3.2 Temperature, Wind Speed, Solar Radiation and Humidity Data

There are three automatic weather stations (SEBA) in the Kihansi River catchment that recorded humidity, solar radiation, temperature, and wind speed. These stations are located in Ruaha catchment (983506), NC1 catchment (983508) and closer to NC3 gauging station (983509). It was identified that these gauging stations recorded data from the year 2000 to 2002 and currently they are not operational due to incompatibility with the weather condition or due to lack of proper maintenance (Personal communication). The climatic data records are shown in Figure 3.

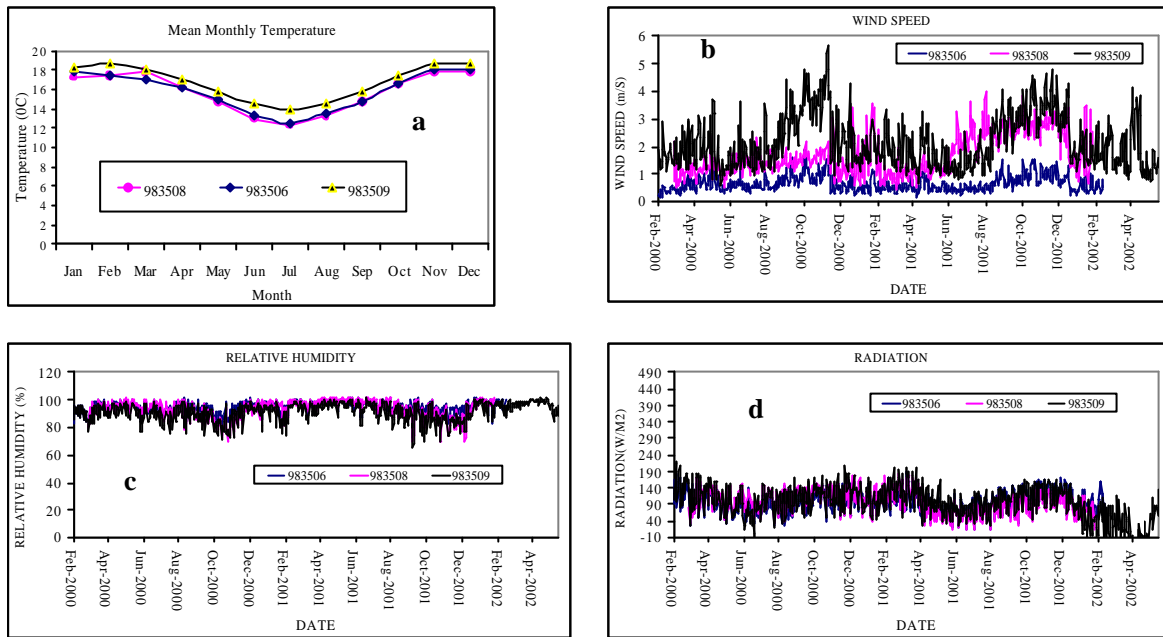


Fig. 3: Climatic data Kihansi River catchment (a) Mean Monthly Temperature, (b) Wind speed (c) Radiation and (d) Relative Humidity

According to Figure 3; spatially, higher temperature was observed for Uhafiwa climatic station, whereas, mean monthly temperature for Udzungwa and Mapanda are nearly identical. In all climatic stations lower temperatures were recorded in the months of May, June, July, August and September. The mean monthly temperature ranges from 13.5°C to 18.4°C. Higher wind speed data was observed at Uhafiwa climatic station, and Mapanda wind speed data in between. Relatively low records of wind speed were recorded in Udzungwa climatic stations, which can be explained by the forest in the ‘Udzungwa forest reserve’ which reduces the exposure to wind. Average wind speed ranges from 1.1m/s to 3.1m/s. The month of March has low and October has high average wind speeds respectively.

The radiation records in the Kihansi river catchment at the three climatic stations are nearly identical as shown in Figure 3 (c). The mean monthly radiation ranges from 58.7 to 109.4MJm<sup>-2</sup>d<sup>-1</sup>. Udzungwa has the lowest monthly mean radiation and the trend is just like that of temperature. The mean monthly relative humidity in the Kihansi river catchment ranges from 86% to 97%. Higher relative humidity records were observed at Udzungwa (95%) climatic station, and relative humidity at Uhafiwa (87%) is the smallest as shown in Figure 3(d). The months of April and October have maximum and minimum mean monthly relative humidity values.

The higher wind speed, higher temperature and relatively lower records of relative humidity at Uhafiwa favors higher potential evapotranspiration than Udzungwa (Ruaha catchment) and Mapanda (NC1 catchment). And potential evaporation was estimated from climatic data using Penman combination method as shown in equation 2. The Penman combination method is suited for application for small catchments areas with detailed Climatological data. The data required are daily net radiation, relative humidity, wind speed, air pressure and temperature. The Penman combination is given as

$$E = \frac{\Delta}{\Delta + g} E_r + \frac{g}{\Delta + g} E_a \tag{2}$$

Where E is evapotranspiration (mm/day),  $\Delta$  is gradient of saturated vapor pressure curve at air temperature  $T_a$ ,  $\gamma$  is psychometric constant,  $E_r$  is radiation term and  $E_a$  is aerodynamic term.

### 3.3 Flow Data

There are nine flow gauging stations in the Kihansi river catchment whose record varies from five years (for the station FSU7) to 21 years (for the station NC3). The percentage missing varies from zero percent to 11.94 percent. The analysis of Flow Duration Curves (FDCs) at three gauging stations indicated that the percentage of time the average flow was equalled or exceeded ranges from 31 % (for the station FSU2) to 42 % (for the station NC1) as shown in Figure 4.

The statistics of the Average Daily Flow (ADF) at the three gauging stations indicate the ADF ranges from 5.26 cumecs to 14.94 cumecs, and there are no zero flows recorded in the catchment indicating Kihansi river is perennial. And the median daily flow, i.e. the 50% daily flow ranges from 3.77 cumecs (for the station FSU2) to 12.43cumecs (for the station NC3)

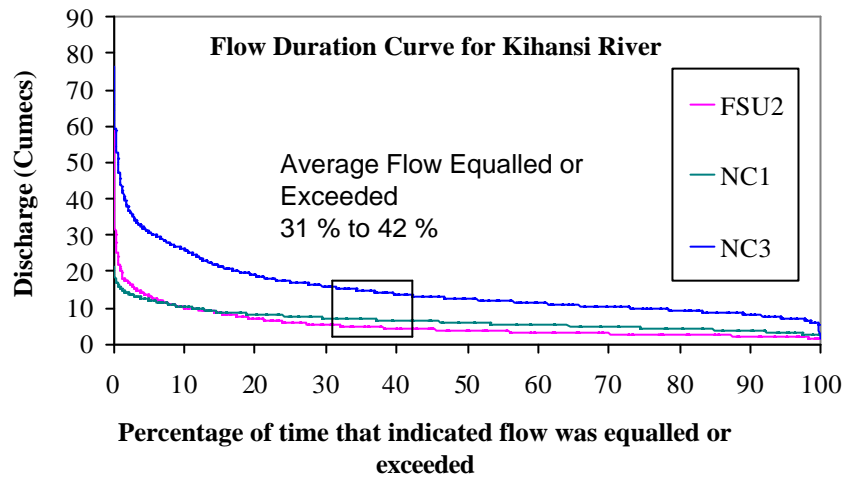


Fig. 4: Flow duration curves for three gauging stations in Kihansi river catchment.

Daily stream flow with an exceedence probability of 5% (Q5) has an environmental threat in flooding of human properties and disturbance of the eco-systems by floods. The Q5 and Q95 at NC3 and for other sub-basins is presented in Table 1. Thus, according to the flow duration analysis there is 7.23cumecs of flow 95% of the time from the Kihansi river catchment.

Table 1 Summary statistics for stream flow stations in the Kihansi catchment.

Gauging Station	Mean Daily Flow(cumecs)	% of time average flow is equalled or exceeded	Q5 (cumecs)	Q50 (cumecs)	Q95 (cumecs)
FSU2	5.26	30.85	13.19	3.77	2.01
NC1	6.55	42.10	12.00	5.80	3.20
NC3	14.94	34.43	30.06	12.43	7.23

#### 3.3.1 Seasonal Streamflow Variations

Seasonal discharges were computed for the hydrologic year (November to October) and shown in Figure 5. With regards to seasonal flow, flows are expected to increase during rainy seasons in a catchment, the

phenomenon which was predominantly seen at FSU2 gauging station. The flow pattern at NC1 indicates a stable flow throughout the season except in April where the flow is greater than 50mm /Area.

NC3 flow, which is a cumulative flow from sub-catchments of FSU2 and NC1 and a catchment downstream of FSU2 and NC1 gauging stations (87.2km<sup>2</sup>), shows seasonal flow variation more pronounced than NC1, with peak flow in the month of April equal to 105mm. As shown in Figure 5, flow contribution from the eastern escarpment gauged at FSU2 has greater effect on the seasonal behavior of Kihansi River at NC3.

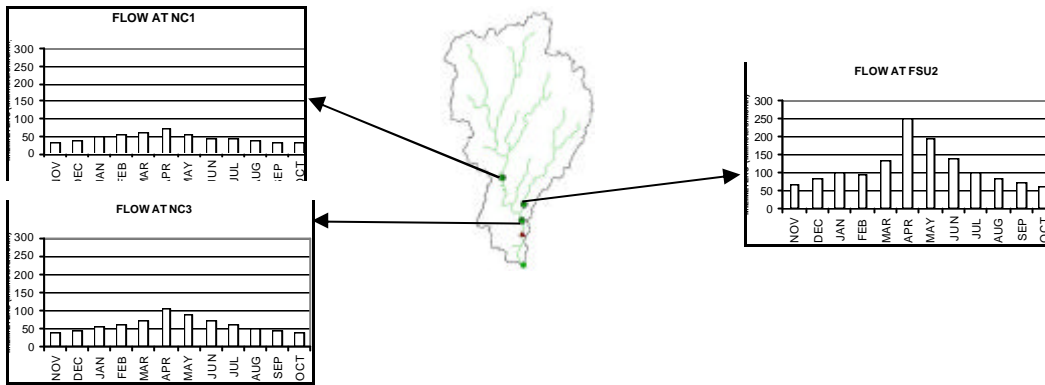


Fig. 5: Seasonal flow pattern, the vertical axis is Millimeters /Area

Average annual flow was used to highlight the flow increase or decrease over the years in response of rainfall. And a general annual flow reduction was observed as shown in Figure 6 and Figure 7.

Further, trend analysis of rainfall and flow was conducted using Mann-Kendall’s tau (Kendall and Stuart, 1968) to test a trend in rainfall and flow, and to identify whether any change in flow series is associated with rainfall changes. The study uses a Z statistics and the significance of the slope of a trend (Z) was assessed at 5% level of significance and values of Z outside the limits at a given significance level were considered statistically significant. The trend analysis was performed for four seasons and annual time scales based on the principles documented in Mtaló *et al.*, (2005). They include the two main rainy seasons, the October-November-December (OND) short and March-April-May (MAM) long rains, the intermediate January-February (JF) season and the “dry” June-July-August-September (JJAS) season. The appropriateness of these seasons for analyses in Tanzania were reported by BICO, 2005 which referred the works of Valimba (2005) from the patterns associated with rainfall variations and results of inter-annual variations of stream flows.

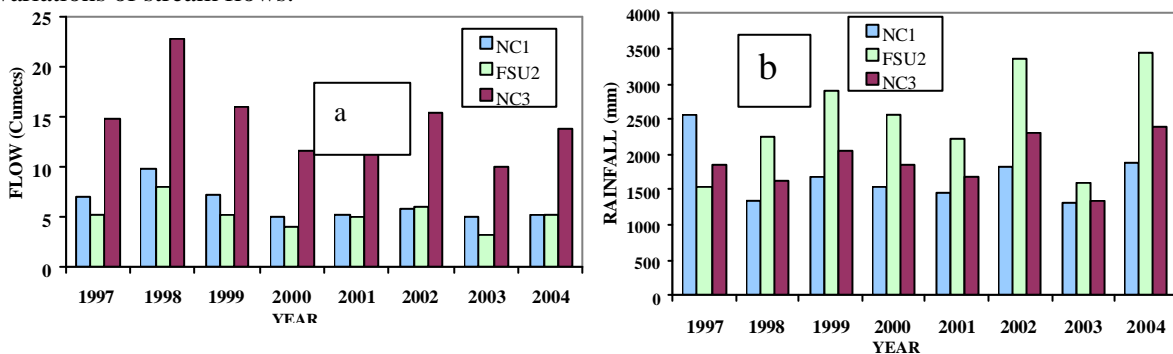


Fig. 6: Average Annual Flow (a) and Annual Rainfall (b) at three gauging stations.

Figure 6 indicates a general flow decrease from the catchment, though the decrease is not statistically significant except for annual flow of FSU2 for the period 1997 to 2000 and seasonal (Jun-Sept of the years 2001 to 2004) as shown in Table 2.

From the results of seasonal and inter annual trend analysis (Table 2 and Table 3) it was understood that the annual flow decrease in the three gauging stations was not attributed to rainfall, as rainfall was not

decreasing for the periods considered. Besides, 31 days of moving average of the flow data at the outlet of Kihansi river catchment (NC3) from 1984 to 2004 was computed by splitting the years of record and the analysis shows a continuous reduction of flow from 1984 to 2004.

Table 2 Results of Trend Analysis (Trend Slopes) for Flow

Gauging Station	Period	SEASON				
		Jan-Feb	Mar-Mai	Jun-Sep	Oct-Dec	Annual
FSU2	1997-2000	0.71	-0.71	-0.71	-0.71	-2.12
	2001-2004	0.71	0.00	-2.12	0.71	0.00
	1997-2004	1.89	-0.51	-1.54	-0.51	-0.86
	Z(95%)	1.96	1.96	1.96	1.96	1.96
NC1	1997-2000	-0.71	-0.71	-0.71	-3.54	-0.71
	2001-2004	0.00	0.00	-0.71	-0.71	-0.71
	1997-2004	-0.86	-2.57	-2.23	-2.57	-1.89
	Z(95%)	1.96	1.96	1.96	1.96	1.96
NC3	1997-2000	0.00	-0.71	-0.71	-3.54	-0.71
	2001-2004	0.71	0.00	-0.71	2.12	0.00
	1997-2004	0.86	-1.20	-1.89	-2.23	-1.54
	Z(95%)	1.96	1.96	1.96	1.96	1.96

Table 3 Results of Trend Analysis (Trend Slopes) for Rainfall

Gauging Station	Period	SEASON				
		Jan-Feb	Mar-Mai	Jun-Sep	Oct-Dec	Annual
FSU2	1997-2000	0.00	0.71	0.71	0.00	0.71
	2001-2004	0.71	0.00	0.00	2.12	0.71
	1997-2004	1.54	0.51	-0.17	0.17	0.51
	Z(95%)	1.96	1.96	1.96	1.96	1.96
NC1	1997-2000	0.71	0.71	0	0	0.71
	2001-2004	-0.71	-2.12	0	2.12	0.71
	1997-2004	1.2	-1.2	-0.17	1.2	0.86
	Z(95%)	1.96	1.96	1.96	1.96	1.96
NC3	1997-2000	0	0.71	0	0	0.71
	2001-2004	0.71	-0.71	0	2.12	0.71
	1997-2004	1.54	-0.17	-0.86	0.86	0.86
	Z(95%)	1.96	1.96	1.96	1.96	1.96

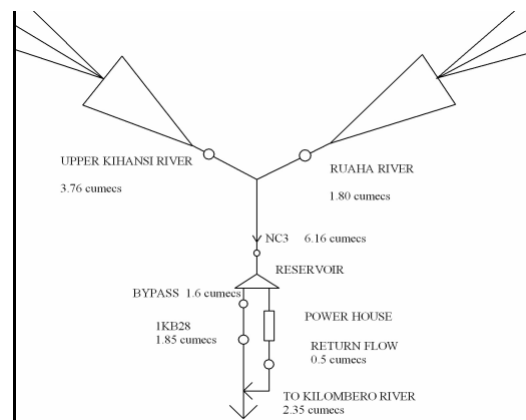
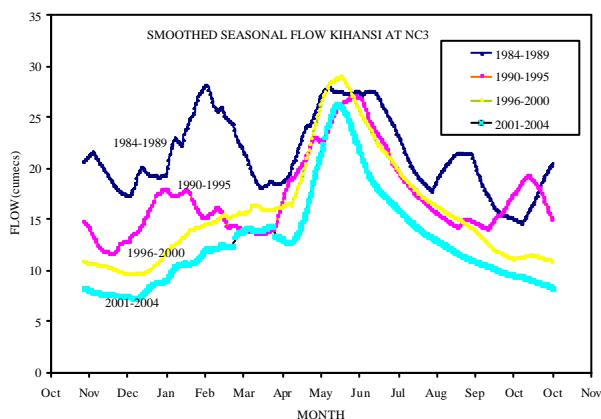


Fig.7: Smoothed seasonal flow for Kihansi river catchment Fig. 8: Spot Discharge Measurements

### 3.3.2 Flow Monitoring and Water Resources Assessment

In this study five flow gauging stations (two before the reservoir and three after the reservoir) as shown in Figure 8 were used to monitor inflow into the reservoir, bypass release from the reservoir, and downstream flow.

The flow at NC3 on the 25th of Nov. 2006, (6.16 cumecs) is a cumulative of flow from Kihansi at Uhafiwa (3.76 cumecs) and Ruaha at Uhafiwa (1.80 cumecs) and partly from the catchment below these gauging stations (which has a drainage area 87.18 km<sup>2</sup>). The bypass release from the dam for environmental flow regulation was 1.60 cumecs on day 26<sup>th</sup> Nov. 2006. This flow together with small streams around the Kihansi gorge contributes a flow of 1.85 cumecs at 1KB28 gauging station. The measured discharge from the tail race on the same day was 0.50. Thus, downstream of Kihansi at Lugoda (confluence of Kihansi and the tail race) there was 2.35 cumecs flow on the day 26<sup>th</sup> of Nov. 2006.

## 4 APPLICATION OF SYSTEM AND CONCEPTUAL MODELS

A Linear Perturbation Modelling, LPM (Nash and Barsi, 1983) with a non parametric pulse response function and parametric function were used to check the evidence of time variance (seasonality) of the hydrological inputs in the catchment. An Ordinary Least Square (OLS) was used for the estimation of the pulse response in the non parametric modeling and a type of Linear Transfer Function (LTF) was used in the parametric modeling. The LPM assumes that in any year in which the input followed exactly the seasonal expectation the output would, similarly, follow its seasonal expectation, and in other years the departure from seasonal expectations occurring in the two series would be linearly related (Kachroo, 1992).

The version of SMAR used in this study has nine parameters, five of which control the overall operation of the water- budget component, while the remaining four parameters (including a weighing parameter which determines the amount of generated ‘ground water runoff’) control the operation of the routing component. In the water budget component the rainfall and evaporation interact to produce runoff and a linear routing component transforms the generated runoff in to discharge. In this study five years of calibration (1997-2001) and three years of verification (2002-2004) were used and a Nash and Sutcliffe (1970) efficiency criterion was used to test the modeling performance.

## 5 RESULTS AND DISCUSSIONS

The modeling performance of both systems type (LPM) and conceptual type (SMAR) are shown in Table 5. and indicates better modeling performance of LPM than SMAR. The hydrograph pattern as shown in Figure 8 also shows a close agreement between the estimated and observed flow using LPM modeling except for some peak records of flow. In this case, LPM was not capable of simulating the peak flows. The better performance of LPM indicates an evidence of time variance (seasonality) between the residuals and independent input and output functions.

Table 5 Modelling Efficiencies, Nash and Sutcliff (1970) for NPLPM, PLPM, and SMAR

Subcatchment	NPLPM		PLPM		SMAR	
	CALIB(%)	VERIF(%)	CALIB(%)	VERIF(%)	CALIB(%)	VERIF(%)
FSU1	45.95	-11.86	45.12	-8.14	28.72	-144.24
FSU2	84.87	71.19	83.71	70.55	83.63	67.34
FSU3	75.04	36.05	73.98	35.97	-656.03	-275.73
FSU4	53.85	-18.47	53.72	-16.93	9..89	-453.3
FSU5	84.03	36.95	78.99	12.28	52.54	38.13
FSU7	73.08	33.28	64.43	39.08	-0.13	-62.71
NC1	83.19	60.47	80.59	62.05	58.98	-280.43
NC3	87.22	63.27	86.17	63.5	82.58	-36.27

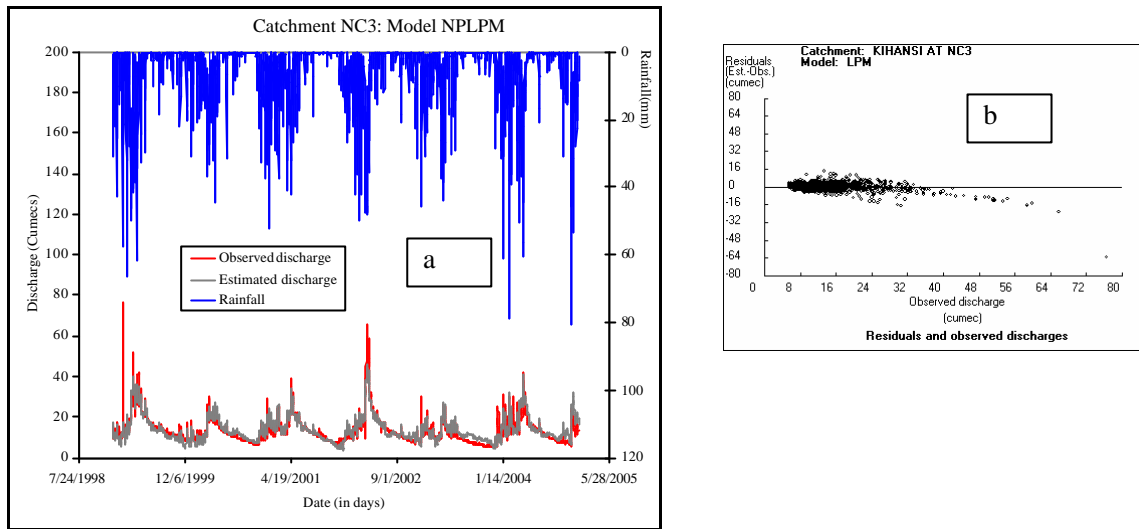


Fig.8: Results of NPLPM (a) and Residuals (b)

Figure 9 shows the hydrograph of the observed and simulated discharge at NC3 using SMAR model. It indicates, peak flows are not captured properly and predicted flow was underestimated particularly after June 2003.

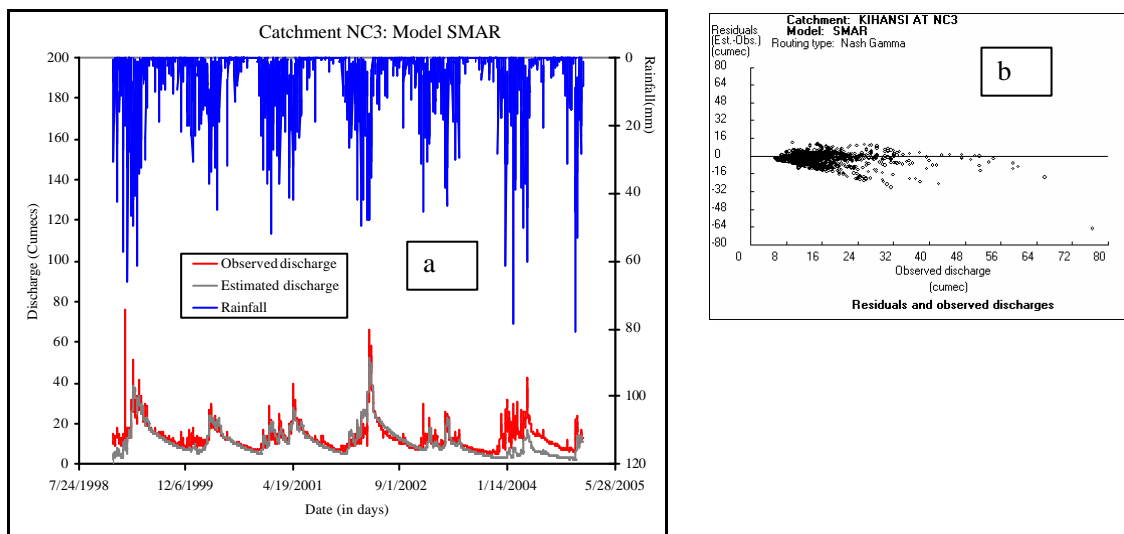


Fig. 9: Rainfall, and Observed and Estimated discharges for Kihansi at NC3 using SMAR (a) and Residuals (b)

The performance of the conceptual SMAR model as shown in Table 5 is worse than LPM and it couldn't appropriately describe the soil moisture zone of the Kihansi catchment. Increasing the complexity of model structure and optimized parameters for model calibration and verification didn't work in this case. This is possibly because of the inability of the SMAR model to adequately represent the lumped characteristics defined by the parameters of the model structure. Besides Figure 8 (b) and Figure 9(b) indicates the residuals are higher for higher flows, indicating both LPM and SMAR could not simulate peak flows appropriately. The Kihansi catchment at a gauging station NC3 (having a drainage area of 584km<sup>2</sup>) has wide variability in physiographic and hydro-meteorological conditions. This wide variability was lumped together for the conceptual modeling using SMAR. But, independent modeling of the subcatchments with smaller drainage area also didn't produce good results either, except for two subcatchments in the eastern part (FSU2 and FSU5).

## 6 CONCLUSIONS AND RECOMMENDATIONS

Spot discharge measurement in the dry season indicated that 6.16 cumecs of flow was available to flow to the Kihansi reservoir, 1.6 cumecs of flow was released from the dam for the Kihansi gorge ecosystem and 2.35 cumecs was available downstream in the Kilombero valley.

Hydrological data analysis indicated that flow from Kihansi river catchment is decreasing, however no significant high flow changes with-in the years responding to the wet and dry seasons were observed. Which in particular is attributed to an increasing depletion of vegetation cover for fire wood and most notably cultivation whose effect on streamflow quantities, and on the over all hydrology of the catchment needs to be established using a GIS based hydrologic models.

Both system types and lumped conceptual models applied, being lumped in their structure couldn't reflect the physiographic variation of the Kihansi catchment. The consideration of the average areal hydrological input variables in the catchment was probably one of the reasons for the poor performance of the hydrological models applied particularly in the western part of the catchment.

Subcatchments with higher runoff coefficients (FSU2 and FSU5) showed better rainfall runoff transformations using the applied models. This implies that apart from variation in hydrological input variables catchment characteristics like: slope, slope length, lateral flow travel time, ground water delay, wetness of the catchment and catchment cover play a significant role in transforming rainfall into runoff.

Inline with the above conclusions, there is a need to have a model that provides a physically sound description of the hydrological processes in the catchment. In this case, vegetation cover and landuse are expected to be important factors contributing to the water balance in the catchment by influencing the total porosity of soil for holding water.

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