Environmental Water Requirements Rapid Assessment (Downstream of the Hydropower Plant of Lower Kihansi)

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Abstract

The present study was carried out to assess the hydrological and hydraulic characteristics that control the flow dependent river ecosystem, necessary to maintain the adequacy of the Environmental Water Allocation downstream of the Kihansi Dam. The indicative parameters of Environmental Water Requirements were assessed using three independent methodologies namely, Hydrology-based, Hydraulic rating and Habitat simulation. The adopted approach was meant to ensure information sharing between the results of the three Environmental Flow Assessment (EFA) methods. This is partly because the data required for holistic methodology could not be obtained. The analysis of the research outputs showed that: the index of flow variability appears to be representative of frequency and magnitude of flood and low flow events at Q5 (42.6 m3/s for 1KB28 and 34.6 m3/s for NC3) and Q70 (11.8 m3/s for 1KB28 and 9.9 m3/s for NC3). The average hydraulic parameters are function of discharge and vary as the discharge increases, with a break point for the wetted perimeter beyond which the increase in the stream discharge causes minor increase of the considered hydraulic parameter. The break point varies at a discharge rate of 11.8 m3/s, 11.8 m3/s and 10 m3/s, respectively for the three cross sections. These values appear to be much higher than the three scenarios proposed by previous researchers for flow restoration downstream of the Kihansi Dam (Do nothing scenario, 1.83 m3/s and 7 m3/s). The habitat analysis was done using the Percent Average Annual Flow, which is a surrogate for habitat quality, through three physical stream parameters: depth, velocity and percent width. The values showed that the river contains 16-28% fewer depth than those prescribed by Tennant (1976) at the interval of 10 -200 % of AAF. However, the study was conducted using one flow sampling and it is required to undergo a complete sampling involving low, medium and high flows. An ecological database of the catchment is needed to set prescriptions for Environmental Water Requirements.

***Key words**:* EFA, Hydrology, Hydraulic rating, Habitat simulation, Lower Kihansi Hydropower

1. INTRODUCTION

The flow regime of a river can be altered from its natural conditions. Most of this the alteration results from water resources development projects that have a great implication on the local hydraulics and ecosystem function. The need to change the flow regime of a river (for the purposes of water resource development and management, while maintaining structural integrity of the ecosystem functioning) has provided the development of Environmental Flow Assessment (EFA) (Tharme, 1996).

Following the construction of a 25m high concrete gravity dam, at 1141 AMSL, the volume of the water was diverted from the dam to a power station near the foot of an escarpment at 310 AMSL. This diversion resulted in a large volume of water that no longer flows through the natural Kihansi River downstream of the dam. Reduced water flowing to the Kihansi Gorge ecosystems has resulted in negative impacts on aquatic biota of the area. The surrounding areas have dried and have experienced large ecological changes (Acremanen et al., 2005)

The studies that were carried out by the World Bank in close cooperation with Tanzanian government in July 2000 considered three options that are needed to mitigate the impacts of circumstances surrounding the Kihansi project. This is to maintain the status quo despite the very high risk of extinction of endemic species, to maintain a bypass flow between 1.51 and 1.89m3/s for carrying out further and more aggressive mitigation measures and to maintain a higher bypass flow of 7 m3/s per second (the historic minimum flow, and the level of flow provided for the provisional water right). The

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Review strongly recommended the second option. Since the river system requires a seasonal variability of flow regime, matching with low flow maintenance, drought maintenance, small and large flood maintenance to perform its function, this option still remains a daunting one.

The main objective of the present study is to assess stream flow parameters that control the adequacy of the environmental water allocation downstream Kihansi dam.

2. STUDY AREA

The Lower Kihansi Hydropower Plant (LKHP) is situated in the Rufiji Basin, a mountainous area in the South central Tanzania about 450 km South West of Dar es Salaam and 135 km South of Iringa town, figure 1.

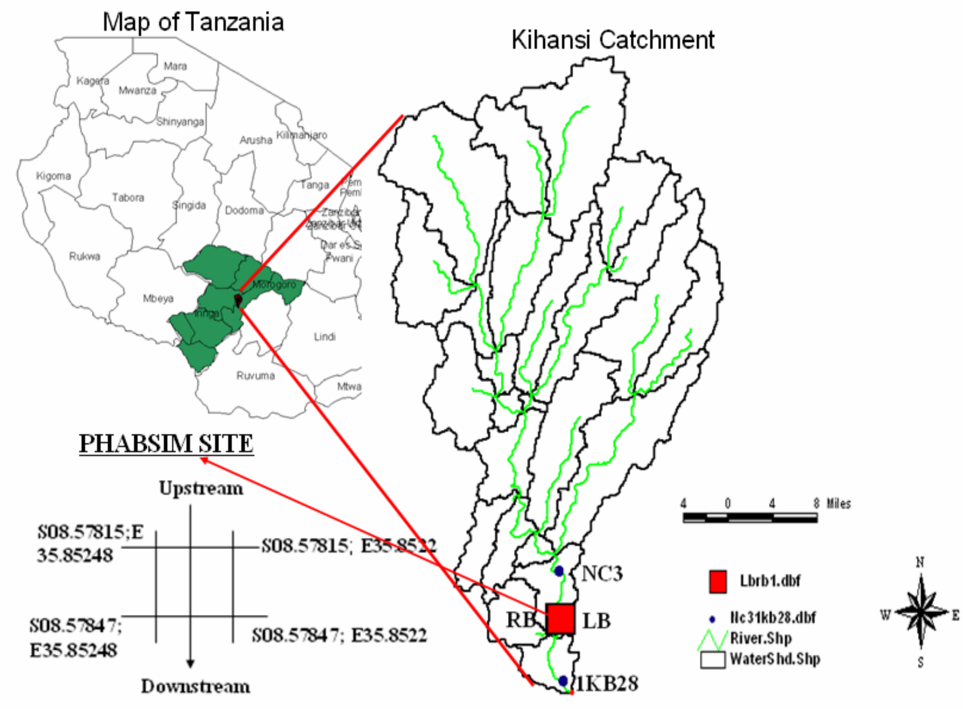

Figure 1 Study area on Tanzania map

The River Catchment is located between Longitudes of 35o44’22”E and 35o57’45”E, and Latitudes of 8o13’08”S to 8o37’12”S. The catchment has approximately a total area of about 590 km2 and lies between 1,200 m and 2200m above sea level.

3. HYDROLOGICAL ANALYSIS

The data used in this study are daily and monthly flow records of 21 years to two hydrometrical stations, NC3 for an area of 581 Km2 and 1KB28 covering 26 years of flow record over a total area of 618 Km2. The filling of missing data was done using seasonal mean approach.

Based on these flow data, the flow pattern of the river, at the site of interest, was analyzed using flow hydrograph, Mean monthly, and flow duration curves. The flow hydrographs for both 1KB28 and NC3 were plotted to examine the flow trend within the river from historical daily flow data. From an average flow, low flow and high flow periods were distinguished (Figures 2 and 3), which tend to establish the flow duration curves for both periods.

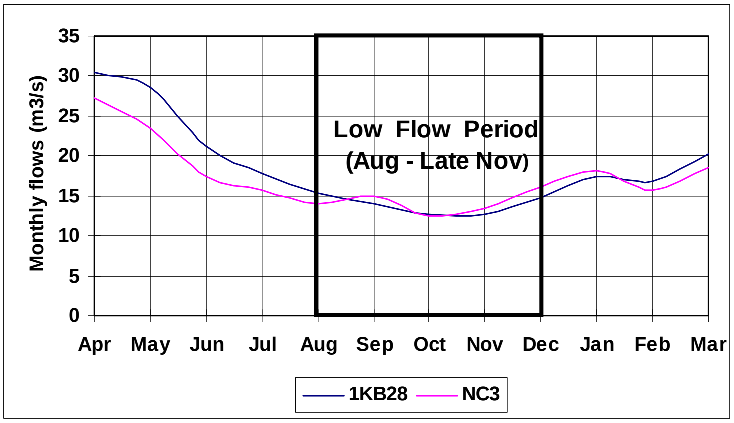

Figure 2 Low Flow Periods for LKHP

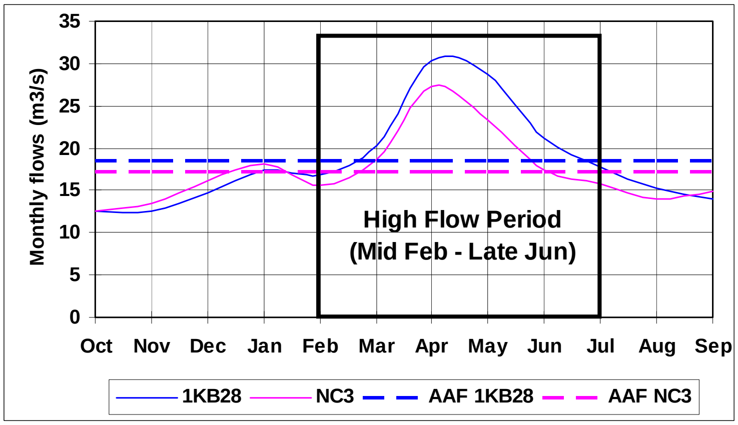

Figure 3 Low flow period for LKHP

From the monthly long term average flows, the high flow period (Mid February to late May) and Low Flow period (August to late November), and the Flow Duration Curves (FDCs) were established for the LKHP. The FDCs were split into seasons to represent the possible related variations for ecological changes. From this, the high and low flows indices of flow were calculated and were matched with the flow hydrograph in order to select the representative indices of flow regime (Qx) in the catchment. The area under the threshold of the median flow (Q50) of the FDC may approximate the total annual base flow that occurs under the natural conditions (Smakhtin, 2001). It is thus logic to use Q50 as a measure of LFR for the top conservation status: natural ecosystems.

4. HYDRAULIC AND HABITAT SIMULATIONS

In order to interpolate or extrapolate hydraulic parameters other than the measured ones, a hydraulic model is necessary. The choice of the Physical Habitat Simulation System (PHABSIM) was meant to generate various hydraulic parameters that usually serve the link with habitat components. PHABSIM is part of a broad conceptual and analytical framework for addressing stream flow management issues called the Instream Flow Incremental Methodology (IFIM) (Stalnaker et al. 1994) that provides a problem-solving outline for water resource issues in streams and rivers. The structure addresses the hydraulic and habitat simulations of a stream reach utilizing defined hydraulic parameters and habitat suitability criteria. The latter constituted a major challenge to this study as the ecological database for the species in the catchment was not provided. Application of the PHABSIM requires geometric dataset of the river cross section, measured discharge data and model simulation (Bovee, 1997).

4.1 The Geometric Data

Geometric survey involved activities that focused on the bed elevation, cross section and hydraulic control. The data obtained in this study are summarized in Table 1.

Table1 Summary of geometric data

Transect	**Distance**	**Sounded**	**Average**	**Thalweg**
1	0	0.61	1197.902	1197.398
2	94	0.71	1197.939	1197.122
3	152	0.93	1198.823	1197.606
Mean		0.75	1198.221	1197.3753
STD		0.16	0.52	0.24

Note: WSL is Water Surface Elevation; Thalweg is the lowest point in the stream channel

The physical and morphological characteristics of the selected site resulting from reconnaissance survey are illustrated on figure 4.

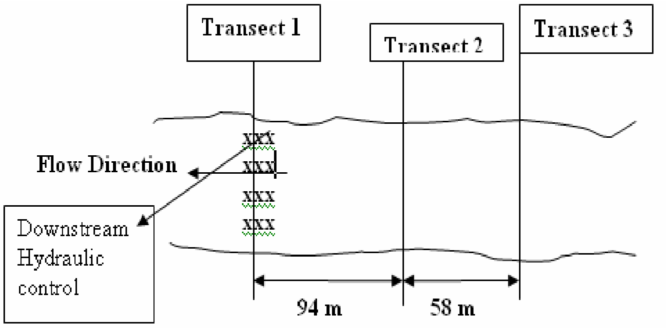

Figure 4 Schematic representation of the study site

4.2 The Discharge Data

The mean-section method was used to calculate the discharge from current meter measurements. The method is based on the given formula.

$$Q = \sum (a_i * v_i) \tag{1}$$

Where Q = the discharge, a_i = the cross-sectional area of an individual partial section (equivalent to a cell in PHABSIM terminology), and v_i = the average velocity normal to the partial area.

Table 2 Discharge measurements at the study site

Transect	Cross section	Mean velocity	Discharge
1	29	0.699	10.085
2	32	0.479	8.705
3	29	0.481	9.082
Mean	30	0.553	9.29
STD	1.73	0.13	0.71

4.3 Calibration of the Model

The usual application of the physical habitat simulation system requires a set of WSL, discharge and velocity to calibrate the model. The data used for the model calibration are summarized below for each cross section.

Table 3 Calibration data as simulated from PHABSIM

Calibration parameters	**C/S ID 0.0**	**C/S ID 94**	**C/S ID 152**
Chainage (m)	0.0	94	152
Calibration stage (m)	1198.067	1198.089	1198.696
Cross sectional area (m^2)	6.32	11.04	7.22
Average depth (m)	0.3	0.6	0.55
Thalweg (m)	1197.4	1196.99	1197.61
Stage of zero flow (m)	1197.4	1197.4	1197.4
Calibration discharge (m^3/s)	10	10	10
Hydraulic radius (m)	0.29	0.56	0.25
Maximum depth (m)	0.67	1.1	1.09
Observed discharge (m^3/s)	10.085	8.705	9.082
Estimated slope (%)	0.388	0.388	0.388

Note: C/S ID i is Cross Section Identity at Chainage i

4.4 Modelling the Stage-Discharge Relationship Using Manning's Equation – The MANSQ Model

The MANSQ programme uses an imperialized Manning's equation (Equations 2 and 3) to calculate water surface elevations on a cross section by cross section basis and therefore treats each cross section independently (Waddle, 2001).

$$Q = \left[\frac{1.49}{n} * S^{\frac{1}{2}} \right] * A * R^{\frac{2}{3}} \tag{2}$$

Where Q is the discharge, n is the roughness, R is the hydraulic radius, A is the cross section area, and S is the energy slope. And it may be simplified to:

$$Q = KAR^{\frac{2}{3}} \tag{3}$$

The value of K is determined from one set of measured discharge and water surface elevation pairs and measured channel geometry at a cross section. Model calibration is accomplished by a trial and error procedure to select a β coefficient (selected by the user) that minimizes the error between observed and simulated water surface elevations at all measured discharges. The program then uses additional calibration data sets (discharges and water surface elevations) to solve one of the following three equations:

$$K = K_o \left[\frac{Q}{Q_o} \right]^{\beta} \tag{4}$$

$$K = K_o \left[\frac{R}{R_o} \right]^{\beta} \tag{5}$$

$$K = K_0 \left[\frac{R_0}{R} \right]^{\frac{5}{3}} * \log \left[2.42 * \frac{R}{D\,50} \left[\log \left[2.42 * \frac{R_0}{D\,50} \right] \right]^{-1} \right] \tag{6}$$

Where: subscript "o" denotes the calibration values, exponent β represents a coefficient supplied for each transect, and D50 is the median particle size on the stream bed.

4.5 Velocity Modelling

This study was conducted using a set of velocities that were measured at one flow calibration. In this case the velocity simulation was based on an initial solution of Manning's equation to obtain an estimated Manning's 'n' at each vertical along a cross section. This approach treats the observed velocity profile as a template for describing velocities for other discharges. Since slope, water surface, and observed velocity are given as part of the calibration data, Manning's equation can be solved for 'n_i'at each vertical.

$$n_i = [1.486 * Se^{1/2} * d_i^{2/3}]/v_i \tag{7}$$

Where:
n_i = estimated Manning's n value at vertical i,
S_e = energy slope for transect
d_i = depth at vertical i, and
v_i = measured velocity at vertical i.

In this equation, depth d_i at the vertical has been substituted for the hydraulic radius and is computed from the difference between specified water surface elevation and bed elevation at each vertical. The measured velocity (v_i) at each vertical is obtained from the input data. Having obtained individual Manning's n values at each vertical, individual cell velocities can be computed at any alternative discharge by solving Manning's equation for velocity and using the initial Manning's n value derived from the calibration velocity set:

$$v_i = [1.486/ni] * d_i^{2/3} * S_e^{1/2} \tag{8}$$

n values for each cell were determined on stream bed sampling using the channel index criteria provided by Bovee and Cochnaur (1987).

5. RESULTS AND DISCUSSIONS

5.1 Hydrological Parameters of Environmental Water Requirements

The particular flow components or statistics, used to define flow requirements in different parts of the world, necessarily vary to some degree, depending upon regional differences in annual hydrological patterns. On the basis of ecosystem flow requirements, a wise choice of the variability indices is determinant and can be specified as numerical ranges within which the flow component is to be maintained or can be expressed as threshold limits for specific flow characteristics that should not be crossed.

The analysis of the daily hydrograph, figures 5 and 6, demonstrates that Q1 is appearing at 47.2 m3/s and 53.2 m3/s for the stations 1KB28 and NC3, respectively and the magnitude of the covered peak flows, in this range, is less than those covered at the range of flows within Q5.

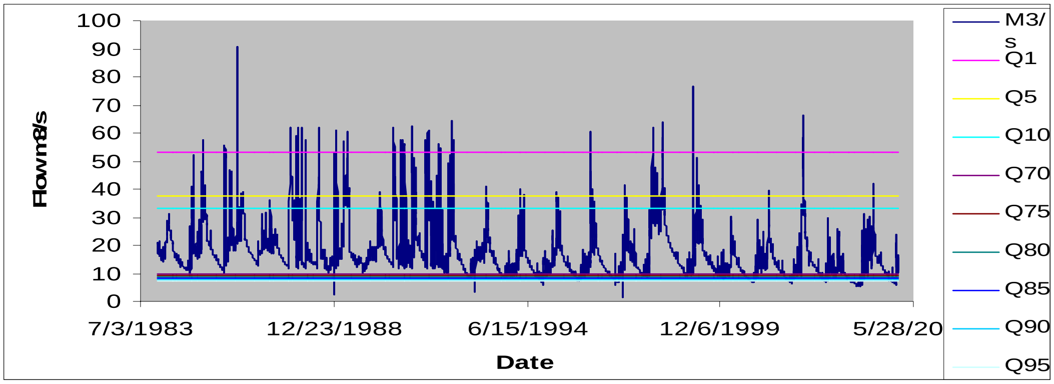

Figure 5 Flow hydrograph and the corresponding indices of flow variability for NC3

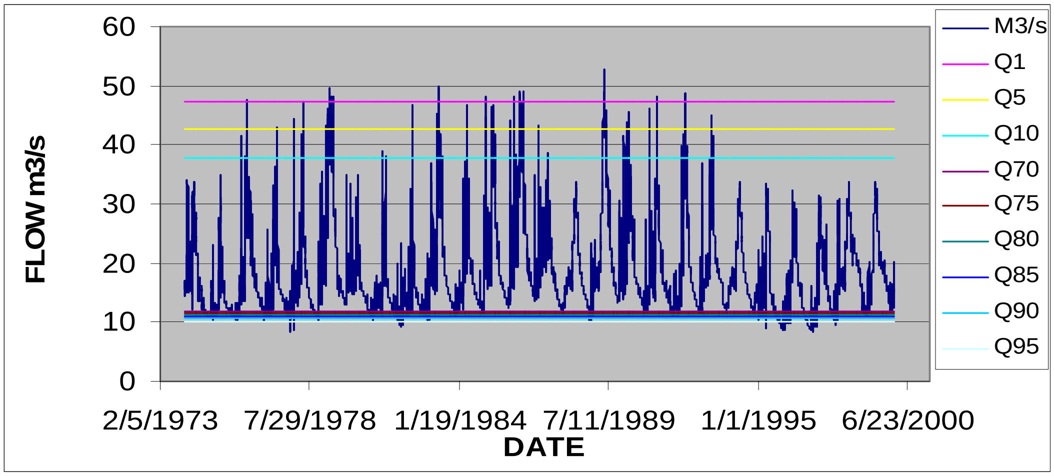

Figure 6 Flow hydrograph and the corresponding indices of flow variability for 1KB28

Taking into account the magnitude of peak flows at the range of Q5, which determines high flow discharges of 42.6m3/s and 37.8 m3/s for 1KB28 and NC3, respectively, it can be seen that the best index of flow variability in this site is represented at Q5.

Considering the indices of low flow for both stations, it appears that Q70 and Q75 are depicting a better representation of magnitude of flow than those represented at other indices of low flow (Q90, Q95, Q99) for both stations. Smakhtin and Toulouse (1998) stipulated that, to keep an ecosystem in natural condition, the Low Flow Requirements (LFR) volume shall not be less than Q50. Their LFR is represented by the flow, which exceeds 75 percent of the time (Q75). This characteristic may be simply interpreted as the discharge that is exceeded 9 months. Smakhtin and Toulouse showed that for a variety of perennial flow regime, Q75 constitutes approximately 65 to 80 percent of the total annual base flow. Therefore, setting a LFR at the level of Q75 implies that a significant proportion of annual flow will be allocated to ecosystem. On the basis of the aforementioned, the stream flow requirements, depending upon the variability of flow indices of the Kihansi, depict the magnitude of flow needed to sustain the river ecosystems in natural, good or fair conditions, Table 4.

Table 4 Stream flow requirements

Percentile	Requirements(in m^3/s)			
	NC3 Dry	NC3 Wet	1KB28 Dry	1KB28 Wet
5th	34.6	37.8	18.9	42.6
50th	11.7	18.6	13.1	20.8
70th	9.9	15.7	11.8	17.2
75th	9.4	14.7	11.6	16.5
90th	8	11.8	10.6	13.9
95th	7.2	10.4	10.11	12.3

5.2 Hydraulic Parameters of Environmental Water Requirements

Local hydraulics and channel morphology are the primary determinants of the availability of physical habitat which is a major determinant of ecosystem function (King et al., 2000). The product of the hydraulic components in this study comprises a series of relationships between discharge and other flow parameters necessary for Environmental Flow Recommendations. They include water depth, flow velocity, wetted perimeter, and water surface width and Froude number, Tables 5, 6, and 7.

A comparison of the average hydraulic parameters (water surface elevation, average velocity, hydraulic depth, hydraulic radius, wetted width, and wetted perimeter and Froude number) at reach scale showed the following observations. The average hydraulic parameters are function of discharge and vary as the discharge increases from low to high values. This forms a linear relationship between the discharge and hydraulic parameters. However, a non linear relationship is observed for parameters such as wetted width and wetted perimeter. This non linear relationship presents an inflection point, beyond which additional flow results in only minor increases in wetted perimeter.

Table 5 Average hydraulic parameters of first cross section

Hydraulic parameters	Hydraulic parameters at simulated discharges					
	1.9 m^3/s	7.0m^3/s	10.0 m^3/s	11.8 m^3/s	15.0 m^3/s	42.6 m^3/s
WSL	1197.744	1197.968	1198.067	1198.105	1198.172	1198.482
Average velocity	1.097	1.552	1.583	1.649	1.702	2.442
Hydraulic depth	0.18	0.292	0.298	0.316	0.327	0.611
Hydraulic radius	0.178	0.287	0.292	0.31	0.321	0.599
Wetted width	9.62	15.44	21.19	22.67	26.96	28.56
Wetted perimeter	9.75	15.72	21.6	23.12	27.47	29.1
Froude number	0.825	0.916	0.926	0.937	0.95	0.997

Table 6 Average hydraulic parameters of second cross section.

Hydraulic parameters	Hydraulic parameters at simulated discharges					
	1.9 m^3/s	7.0 m^3/s	10.0 m^3/s	11.8 m^3/s	15.0 m^3/s	42.6 m^3/s
WSL	1197.637	1197.959	1198.089	1198.171	1198.302	1198.885
Average velocity	0.521	0.803	0.906	0.936	0.967	1.342
Hydraulic depth	0.271	0.504	0.598	0.624	0.646	1.019
Hydraulic radius	0.257	0.472	0.559	0.584	0.609	0.966
Wetted width	13.45	17.31	18.45	20.19	23.98	31.15
Wetted perimeter	14.19	18.49	19.76	21.57	25.47	32.86
Froude number	0.32	0.361	0.374	0.378	0.384	0.424

Table 7 Average hydraulic parameters of third cross section

Hydraulic parameters	**Hydraulic parameters at simulated discharges**					
	1.9m3/s	7.0 m3/s	10.0	11.8	15.0	42.6
WSL	1198.503	1198.828	1198.912	1198.957	1199.03	1199.479
Average velocity	1.65	1.696	1.869	1.953	2.082	2.765
Hydraulic depth	0.247	0.294	0.356	0.389	0.442	0.779
Hydraulic radius	0.238	0.286	0.345	0.376	0.425	0.73
Wetted width	4.67	14.06	15.02	15.53	16.29	19.78
Wetted perimeter	4.84	14.41	15.49	16.08	16.96	21.1
Froude number	1.06	0.999	1	1	1	1

Within the cross sections, hydraulic depth-hydraulic radius and wetted width-wetted perimeter appear to be much close to each other. Generally the two terms (hydraulic depth and hydraulic radius) give values that are similar when the top-width-to-depth ratio for the flow area of any channel is greater than approximately 5.

The average velocity is much higher at the third cross section, Table 7, followed by the first cross section (riffle), Table 5. The average velocity at the second cross section is almost half the velocity of the first cross section. This traduces the effect of flow regime which is sub critical at the second cross section: $v = \sqrt{gD}$ (v=velocity, g=acceleration, D=depth).

This is also the case for the Froude number which is below 0.5 in the cross section of a pool habitat, between 0.5 and 0.9 in the riffle habitat, and 1 in the run habitat (Third cross section). Therefore, the pattern of non uniform flows at this site can be distinguished which determines the mesohabitat characteristics.

In the contrary, the hydraulic depth, hydraulic radius, wetted width, wetted perimeter is kept at higher values in the second cross section than others. This traduces the difference in term of biotic abundance that increases with the channel wetted width and depth.

5.3 Aquatic Habitat Analysis

In a study of 58 cross sections, Tennant (1975) cited that Mann (2006) defined the percent average annual flow, which is a surrogate for habitat quality, through three physical stream parameters: depth, velocity and percent width. These physical parameters along with biological and recreational considerations were used to determine the percentage of the average annual flow (AAF) that correspond to Tennant's perception of fish habitat quality. The data in this study provides evidence that the percent of width are very close to Tennant widths as shown on figure 7.

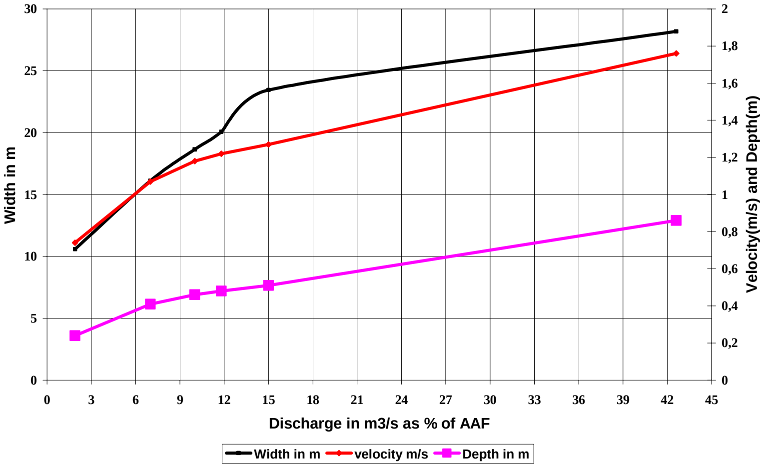

Figure 7 Habitat quality parameters

The average depth depicts few differences from those provided by Tennant showing that the river contains fewer habitats in terms of river depth than those predicted by Tennant. This difference ranged between 16 and 28 %(Tennant Depths: 0.3m, 0.5m, 0.6m and 0.9m at 10, 30, 100 and 200 % of AAF, respectively). However, in a similar study carried out using 151 cross sections from seventy river segments in Western United State of America, Mann (2006) stipulates, from depths only, that Tennant's flow recommendations are not conservative for typical mountain stream types, which is the case for Kihansi catchment situated above 1000m AMSL in Udzungwa Mountain. In her study, Mann (2006) found out that at 30% AAF the difference between the observed depth and Tennant's data remains about 25 percent, 1.12 ft and 1.50 ft respectively. At 100% AAF the difference between the mean of the study data and Tennant's estimate are closer to each other. Tennant's estimate is only 14 percent higher than the study data set, 2.00 ft and 1.72 ft, respectively. The difference returns to 25 percent higher for the 200% AAF category where the data shows a depth of 2.24 ft and Tennant states 3.00 ft. Therefore, it can be seen that the study carried out by Mann (2006) gives the flow parameters that are very close to those observed in the current study for the Kihansi. Considering velocity, the current study shows the observed values which are overestimated in regards to those provided by Tennant (1975) in Mann (2006). This would require further investigations to find out the reasons for deviations.

6. CONCLUSIONS

Several studies have been conducted aiming at determining a minimum flow with regards to aquatic biodiversity protection of the LKHP; yet this was only a drop of water in a huge and complex process of EFA. Other studies were conducted depicting the socio economic components of the river ecosystem, but the link with environmental flow determination was missing. The approach used in this study was specific site based and was meant to ensure information sharing between the results of the three Environmental Flow Assessment (EFA) methods. An aquatic habitat is a composite element of stream velocity, depth, stream width, and channel index. These variables change with changes in stream flow. These changes can be temporary hydraulic changes that are reversed when flows increase, or semi permanent morphological changes that alter the hydraulic conditions for the entire flow regime as the channel geometry changes.

Similar studies using the same approaches should be conducted to verify the accuracy and applicability of the methods in the catchment. The current study was conducted using one flow sampling (Overspill+ Bypass releases= 10.0 m3/s as best discharge, Q). For modeling purposes and assessment of data, for verification, three flow samplings are needed (low, medium and high Flow). Reach representation is not adequate; River segments and Seasons need to be given attention (time, financial and human resources). Dry period needs to be considered for the geometric survey to capture hydraulic controls that represent the reach. There is, also, a need to an ecological database to the catchment with regards to the Wetted Usable Area for species of interest and more biophysical input for the applicability of the reserve determination decision support system.

7. ACKNOWLEDGMENTS

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