Determination of design discharge and environmental flow in micro hydropower plants based on flow duration curve in small rivers: A Case Study of Hhaynu River - Mbulu,Tanzania

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Abstract: ***In designing micro hydropower plants capacity, the amount of water flow discharge determination is very essential in estimating the power output for the micro hydropower scheme due to the fact that in recent years there has been an increase in water demand due irrigation activities because of an increase in agriculture activities [1]. From the literature, there are several methods that are used to determine hydro turbine water flow discharge but the most widely used method is the hydrological method which is based on the formulation of flow duration curve or hydrograph for the respective river flow based on site historical and measured hydrological data.***

The hydrograph represents the amount of water flow in m^3/s that is available for a particular river or stream in percentage from the historical hydrological data which has been computed over a period of more than one year. From the study of Hhaynu River which is a small river in Tanzania, the computed flow results show that, 8% of the time the flow is at 2.3 m^3/s while at 50% of the time the river flow was at 1.86 m^3/s and at 100% of the time the water flow was at 0.60 m^3/s. When determining design discharge for run-of-river schemes, provision have to be considered for environmental flow on which for the Hhaynu River this has been analysed to be 0.2 m^3/s (33.3% of river base flow) which resulted to the hydro-turbine development design water flow discharge of 0.4 m^3/s from the computed flow duration curve with provision for environmental flow.

The usefulness of developing flow duration curve for rivers is to determine the available water flow in a particular small river and its suitability for micro hydropower development from estimates of the amount of water flow discharge.

Index Terms: Flow duration curve, River flow velocity, Discharge, Hydrograph, Time exceeded, Hhaynu, Mbulu

Note: *The authors declare that there is no conflict of interest regarding the publication of this paper.*

Figure 1.0: Location of the Hhaynu River – Mbulu, Tanzania

1. INTRODUCTION

1.1 Water availability

In today's trend, human activities which include agriculture, irrigation, deforestation, land use changes and increased water supply have impacted fresh water ecosystems through excessive usage of water from rivers and especially small rivers like Hhaynu [2]. Large population of people have been affected by water shortages in recent years due to climate change [3] and also lack of field data that highlights and analyse the problem. In this study I have analyse the water availability from a small river in Tanzania, called Hhaynu by using Hydrological method [4].

Based on the field study, total of 8,280 stage data were analysed from January 1985 to December 2007. These are the latest data available from this river. Based on measurement of discharge conducted during field work on June/July 2016, the stage of 50.25cm corresponds to a discharge of 0.90m^3/s. The site measurement was during the dry season and is close to the mean flow rate Q_{mean}(0.95 m^3/s) computed from the historical data and is typically in a range between $Q_{30\%}$ and $Q_{40\%}$ on the FDC for small rivers and streams and based on the used site data the value of Q_{mean} is around $Q_{39.3\%}$ which is typically for small rivers [5].

Table 1.1: Computed percentage of exceedance with river flow

% Time Exceeded	Flow rate [m^3/s]
8	2.3
17	1.59
25	1.22
33	1.02
42	0.92
50	0.86
58	0.79
67	0.74
75	0.69
83	0.65
92	0.62
100	0.60

The computed values of Table 1.1 above can be calculated in standard format of percentage from 10% to 100% and represented in discharge value (Q) as shown on Table 1.2 below;

II. METHOD

2.1 Materials and Methods

Flow analysis by means of Flow Duration Curve (FDC) was conducted to deduce the duration which certain flow magnitudes were exceeded within the period of analysis. The analysis (see Figure 1.1 below) reveal that a flow of approximately 0.60 m^3/s have a 100 percent of being exceeded, while that of approximate 2.14 m^3/s have a 10 percent of being exceed, in the specified period of analysis. Also from the analysis, a flow of approximately 0.86 m^3/s has a 50 percent chance of being exceeded and 0.63 m^3/s have a 90% of exceedance. The design discharge considered values taken for this research is exceeded for >95% of the year ($Q_{95\%}$) and considering the compensation flow this value have been taken as the characteristics value for minimum river flow [6] and this amount of river discharge that will be available for hydropower generation throughout the year round because there is no provision for water storage, only a small pondage. During the field work and site measurement in June/July 2016 the river flowrate reveal a discharge of 0.90m^3/s which is around 44.7 % of being exceed. See Figure 1.1 below;

Table 1.2: Standardised percentage of exceedance with river flow

% Time Exceeded	Flow rate [m^3/s]
Q_{10}	2.14
Q_{20}	1.45
Q_{30}	1.10
Q_{40}	0.94
Q_{50}	0.86
Q_{60}	0.78
Q_{70}	0.72
Q_{75}	0.69
Q_{80}	0.67
Q_{90}	0.63
Q_{95}	0.61
Q_{100}	0.60
Q_{mean} = $Q_{39.3\%}$	0.95

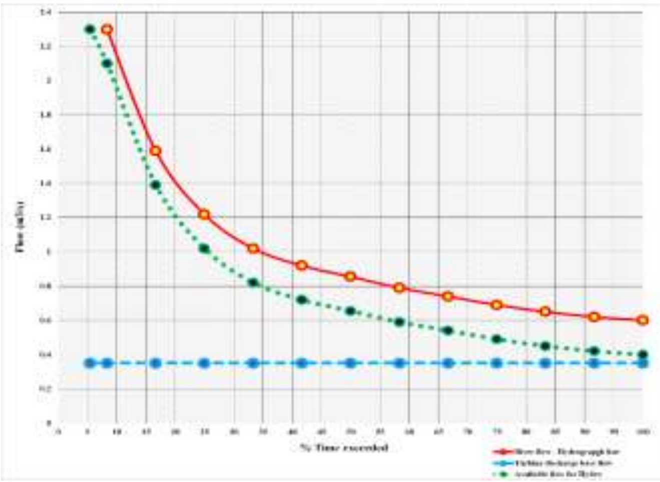

Figure 1.1: Flow duration for Hhaynu river (Period of analysis is between 1985 - 2007)

From the Figure 1.1 above, the minimum flow at 10%, 50% and 95% of the time are found to be 2.14 m^3/s, 0.86 m^3/s and 0.61 m^3/s respectively. On the other hand, the flow at 100% of time is found to be 0.60m^3 /s (0.4m^3/s when considering compensation flow) and this is the characteristic value for minimum river flow that could be available during the dry seasons. Since the discharge data for the water availability studies in this micro hydropower have been available for more than 10 years then its FDC will be drawn from the river flow value >90% time of exceeded for the system design and energy estimation [7]. The basic assumptions of the analysis are that the river flow condition is quasi-steady to steady and the river bed at the recording location is free from any sort of serious erosion and siltation.

2.2 Flow duration curve with available flow for Micro Hydropower

From the above river flow duration curve Figure 1.1 with the historical data and take into account the compensation flow based on the 0.2 m3/s minimum environmental flow, the flow duration curve with the available flow for hydro can be derived as shown on Table 1.3 below;

Table 1.3: Percentage of exceedance with available flowfor hydropower

Percentage of Exceedence (%)	Available flow for hydro [m^3/s]
5	2.3
8	2.1
17	1.39
25	1.02
33	0.82
42	0.72
50	0.655
58	0.59
67	0.54
75	0.49
83	0.45
92	0.42
100	0.4

Similarly, the above values can be standardised to represent the flowrate values from 10% to 100 % as shown on Table 1.4 below;

Table 1.4: Standardised % of exceedance with available flow for hydro flow for hydro

Standardised % Time Exceeded	Flow rate [m^3/s]
Q_{10}	1.79
Q_{20}	1.25
Q_{30}	0.90
Q_{40}	0.74
Q_{50}	0.66
Q_{60}	0.58
Q_{70}	0.52
Q_{75}	0.49
Q_{80}	0.47
Q_{90}	0.43
Q_{95}	0.41
Q_{100}	0.40
$Q_{mean} = Q_{42\%}$	0.72

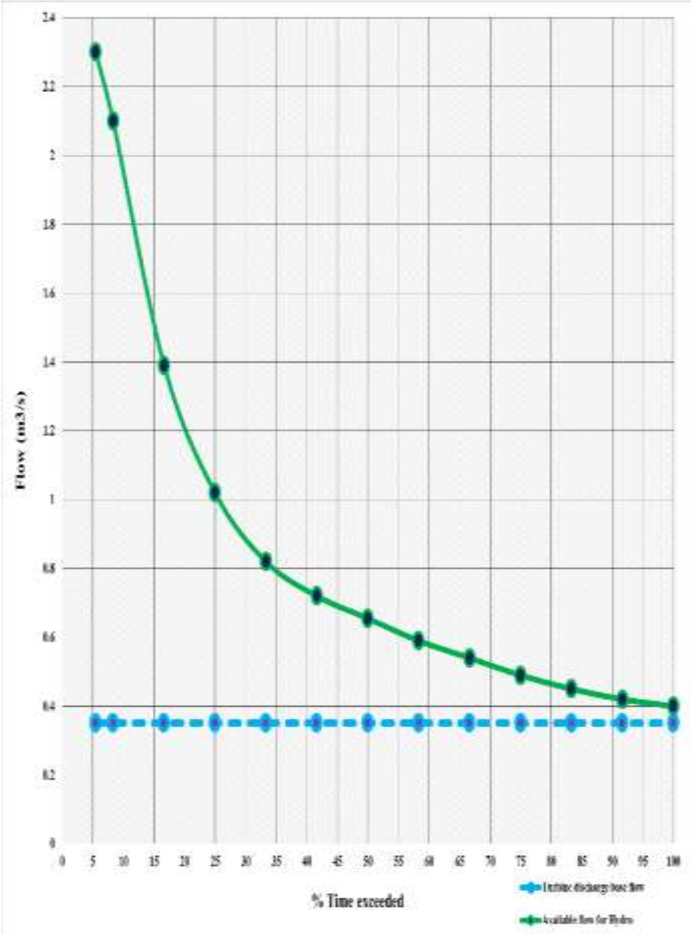

Figure 1.2: Available flow duration curve for hydropower (Period of analysis is between 1985 - 2007)

From the above Figure 1.2 the available river flow for hydropower at $Q_{95\%}$ is found to be 0.41 m^3/s and that of the Q_{mean} is at $Q_{42\%}$ which is 0.72 m^3/s. From literature and in relation to FDC, mean flow are typically in a range between Q_{30} and Q_{40} [4]. The Q_{mean} value is above Q_{40} due the very high base flow for the river (Q_{95}/Q_{mean}> 0.4). The value taken for the base flow is 0.35 m^3/s at > $Q_{100\%}$ as shown on Figure 1.2 and this indicate a high base flow value for the scheme which is characterised by most of the run-of-river schemes [8].

2.3 River Discharge

The monthly average discharge data for Hhaynu River was measured for a period of one year, from September 2015 to August 2016. Also, managed to obtain the historical river flow discharge data which is the record of water flow for the river for the past years. These data were obtained from the local water basin authority and represent the volumetric flow rate for the river for many years from 1985 to 2007. The values have been computed to obtain the monthly average and compared with the site measured discharge values. See Table 1.5 below;

Table 1.5: Historical and Site measured flow data

Month	Site measurement river flow average (Sept.2015 - Aug.2016) [m^3/s]	Historical average river flow (1985-2007) [m^3/s]	Design base flow Q_D [m3/s]	Difference in flow (Site measured – Historical) [m^3/s]
January	0.84	0.89	0.35	-0.05
February	0.83	0.82	0.35	0.01
March	1.22	1.14	0.35	0.08
April	2.30	2.66	0.35	-0.36
May	1.59	1.63	0.35	-0.04
June	0.90	0.96	0.35	-0.06
July	0.74	0.76	0.35	-0.02
August	0.66	0.68	0.35	-0.02
September	0.62	0.64	0.35	-0.02
October	0.60	0.60	0.35	0
November	1.05	0.98	0.35	0.07
December	1.01	0.92	0.35	0.09
Average	1.030	1.057	0.35	

Note:
The negative values are the ones below minimum flow value and positive values are the ones above minimum flow value.

The historical data have been used to validate the site measured data and the general trend shows that both data display similar patterns with high discharge in March, April and May due to a lot of rains in the area and low discharge in September and October due to dry weather in the area. The historical data has a bit of high discharge values in many months due to the fact that there were a lot of volumetric water flow to the river in the area due to the fact that there were less environmental degradation eg. Deforestation, farming near the river banks, irrigation activities, which reduce the water volume significantly. Now days these activities are practised in the villages in most rural areas which affect significantly the river flow pattern due the effect on rainfall and runoff.

From the theoretical design point of view the high water volume during the rain months could be stored in a reservoir and used during the dry months to produce additional energy required from the demand. But in many micro scale schemes this idea may not be viable options due to the fact that it requires additional facilities for the reservoir which in turn will increase the project cost due to the acquisition of land and compensations. The maximum value difference between the site measured data and historical data range between 0.36 m^3/s below the minimum value (negative) to 0.09 m^3/s above the minimum value (positive).

In this research project, the minimum flow discharge value considered for system design is around 0.40 m^3/s which is the discharge value that is available for both measured data and historical data when considering compensation flow. Thus, in this case the minimum residual flow is around 0.20 m^3/s based on the fact that there is no depleted reach on the river flow throughout the year as shown on Figure 1.3 below;

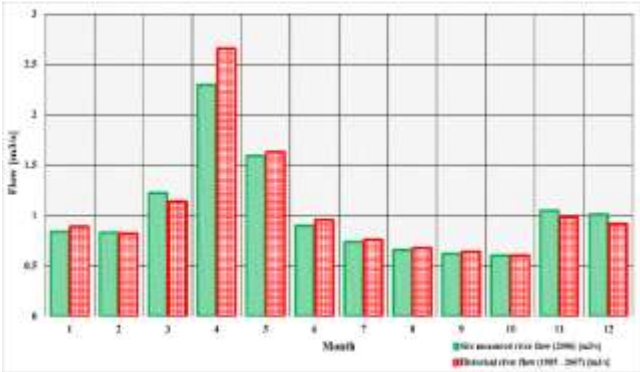

Figure 1.3: Flow comparison between the measured data and historical data

The minimum discharge amount that may be available throughout the year for both sites in measured data and historical data when not considering a pondage for small water storage is around 0.6m^3/s. In consideration of the residual flow the value of 0.4m^3/s will be used on the initial system design as the discharge design base flow from the river. See Figure 1.4 below for details of the annual river hydrograph;

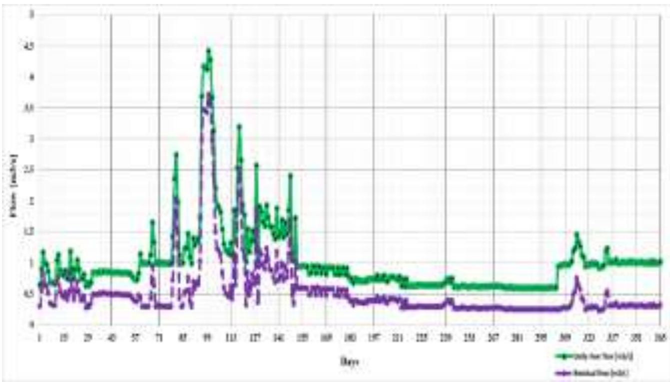

Figure 1.4: Annual river hydrograph

More discharge is available in the months of March, April and May because of much rain in the area as these are the main rain months in the year. The rain increases the water run-off from the catchment area and hence increase the river flow downstream. In the other months of October, November and December there is also a small amount of rain in the area but the quantity is not as many as in the main rain season. The area is characterised by tropical climate on which there is only two seasons. Rain seasons with major rain in March, April and May and minor rain in October, November and December with dry season in July, August and September.

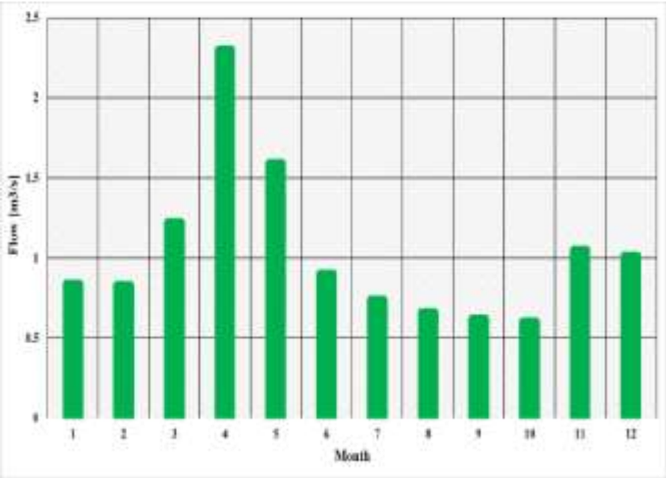

Figure 1.5: Site measured monthly average flow

Hydrograph for hydropower development can be further represented in detail for 90 days continuous river discharge as shown on Figure 1.6 below;

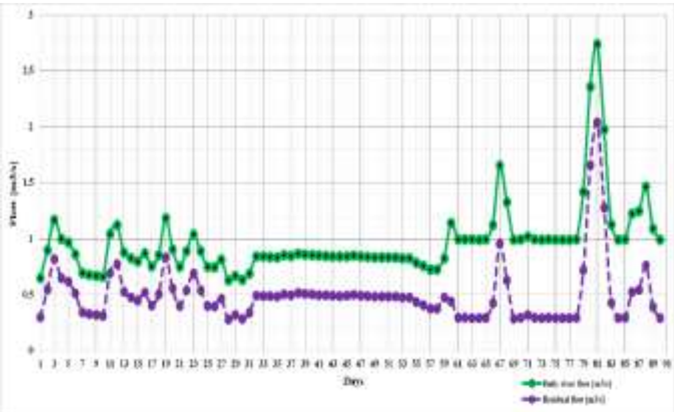

Figure 1.6: 90 days site measured river flow

From the hydrograph and flow duration curve, it is noted that the minimum river discharge at any given day is around 0.6 m^3/s. So, in considering residual flow, the minimum water availability for hydropower generation from the river is <= 0.4 m^3/s and this value is the feasible discharge that is reliable and available throughout the years, thus why it is taken as a design discharge for the hydropower system in this research project.

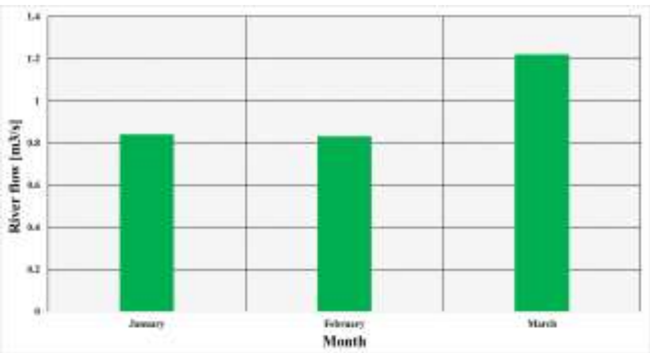

Figure 1.7: Three months average site measured river flow

2.4 Validation of the Hydrological method and Limitations of the study

The performance of the study using hydrological method in calculating environmental flow was validated against the locally calculated environmental regimes using the efficiency coefficient R^2 [9]. The validation method was based on the maximum and minimum river flows during the rain and dry seasons. The choice of determining the environmental flow was limited by using hydrological methods because of lack of detailed eco-hydrological data on river ecosystem responses to flow alterations for most small river basins in Tanzania

III. CONCLUSION

In determination of run-of-river flow suitable for micro hydropower plants design discharge, provisions have to be considered for environmental flow which is the water that must be allowed to flow downstream on the river at the length of the penstock. Based on the study data, the available water flow discharge from the Hhaynu river which is suitable for micro hydropower plant and available throughout the year is around 0.4 m^3/s ($Q_{100\%}$). From the base flow without considering water for the hydropower, the flow at $Q_{100\%}$ is 0.6m^3/s on which the provision of environmental flow accounted for is 33.3% of the original base flow. So whenever applicable in small rivers, the minimum provision for environmental flow may be accounted for at least 30% [10] of the river flow in most small rivers with similar flow pattern like Hhaynu in order to keep ecosystem in a fair ecological condition.

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