Assessment of Hydrokinetic Potential in the Umbeluzi Basin, Mozambique

Summary

Hydrokinetic turbines can play a pivotal role in providing electricity access to remote areas in Mozambique, as stand-alone isolated mini-grids. However, the suitable sites for application of Hydrokinetic Turbines throughout the country are not known, hence the need for this research. The study was done to evaluate electricity generation based on hydrokinetic turbines in the Umbeluzi basin. For this purpose, the following methods have been applied: 1) Frequency analysis using historical data of river stream velocity to generate velocity duration curves (VDC); 2) comparison of stream flow velocity to the design velocity of the hydrokinetic turbine and comparison of the rotor diameter of hydrokinetic turbine to the depth of the river to enable the evaluation of the feasibility of installation of the turbine in the basin. The results show that low flow velocities characterize the Umbeluzi River, hence no considerable potential sites for installations of hydrokinetic turbine. However, 444 W can be extracted in station 638 using dual axial turbine (Under Water Electric kit).

Key-words: **Hydrokinetic Turbines, Resources, Assessment**

1. Introduction

Mozambique has 27.2 million inhabitants and only about 20.2 % have access to electricity. Almost 97% of the total household energy needs are still met by traditional biomass fuels (wood and charcoal). Biomass meets 78% of the country's energy needs, followed by hydro (13%), oil products (7%) and 2% from other resources (IRENA, 2012; Mahumane, G. & Mulder, P., Nadaud, 2012). Total installed hydropower capacity is 2187 MW of which 2075 MW is from Cahora Bassa hydropower plant (IHA, 2015). Hydropower generation potential is estimated at 12,000 MW of which only 2,200 MW (Uamusse, Tsamba, Matsinhe, & Persson, 2015) has been exploited. The potential of small hydropower plants (<10 MW) is 1000 MW (Klunne, 2013) of which only 2.63 MW has been exploited. In fact, small hydropower compares well with other supply technologies; however, over 36 years large-scale hydropower projects dominated Mozambique's energy plans targeting neighboring countries market, especially South Africa.

Mozambique is a large country with widely dispersed; mostly rural population (70%) and no ambitious grid extension plans can reach the entire country in the short and medium term (IRENA, 2012).Other options such as small hydro therefore have to be explored to increase access to electricity. One of the options for harnessing kinetic energy from river currents is by using hydrokinetic turbines. However, the suitable sites for application of Hydrokinetic Turbines throughout the country are not known, hence the need for this research.

Hydrokinetic systems harness energy from natural water movement (kinetic energy) to generate electricity or provide mechanical power. The systems have been successfully powering rural communities such as 1.2 kW in Brazil (Els, 2008; Souza, j., Els & Diniz, J. & Wehrman, 2008); 5 kW in Ruby(Sornes, 2010), 200 W in Peru(Sornes, 2010)and pumping water for irrigation system in Sudan (M. J. Khan, Bhuyan, Iqbal, & Quaicoe, 2009). In Mozambique, the potential of hydrokinetic turbines is being studied at Eduardo Mondlane University (UEM) in partnership with University of Brasilia (UnB).

Traditionally, one way to validate water resources as adequate energy alternative is to evaluate its power potential available at the sites. For the case of hydrokinetic systems, the important parameter for this evaluation are: flow velocity and water depth of the rivers. This is the basic information required for system design and energy planning, especially to ensure that energy supply and demand decisions are compatible with overall goals for national sustainable development while diversifying energy resources.

1.1 Principle of Hydrokinetic Power

Through conservation of energy, the power existing at a point in the cross-sectional area of a stream of water flowing at a given speed can be obtained using Equation 1.

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$$P_k = \frac{\rho}{2} A_c V^3 \quad \text{(eq. 1)}$$

Where P_k is available kinetic power, ρ is density of water (1000 kg/m^3), Ac is the cross-sectional area of the extraction and, V is the flow velocity (m/s). Hydrokinetic power is often reported as a power density, which is the power normalized to unit are:

$$\frac{P_k}{A_c} = \frac{\rho}{2} V^3 \quad \text{(eq. 2)}$$

Computation of the kinetic power depend on the cross-section area, which is either the river cross-sectional area for assessment of the total energy in then river, or the area of the device that will be used to extract the kinetic energy (NRC-CHC, 2010). For the purpose of this study, the cross-sectional area of the river is used to estimate power potential.

1.2 Extractable Hydrokinetic Power

When considering the use of a device to extract the available power, the cross-sectional area of the device that intersects the flow is taken as the area of interest and the total efficiency of the device and associated power system in converting the kinetic power into electrical power has to be considered. Thus, the generated power (Pg) given as:

$$P_g = Cp \frac{\rho}{2} A_s V^3 \quad \text{(eq. 3)}$$

Where Cp is power coefficient of the turbine and A_S is the swept rotor area of the turbine given as:

$$A_s = \pi \frac{D^2}{4} \quad \text{(eq. 4)}$$

Where D is the rotor diameter of the turbine, Л=3.14

Considering the Betz limits as the maximum turbine efficiency, the power extractable from a turbine is given as:

$$P_{g-Max} = 0.593 \frac{\rho}{2} A_s V^3 \quad \text{(eq. 5)}$$

1.3 Hydrokinetic technology and rural electrification

This section describes—in brief—the hydrokinetic turbines used for feasibility evaluation of hydrokinetic power with the river. Detailed technology review can be found in (Verdant Power Canada, 2006), (M. J. Khan et al., 2009)and (Lago, Ponta, & Chen, 2010).

The Amazon aquacharger shown in figure 1 has ability to charge up to five 12 V or 24 V batteries simultaneously (Anyi & Kirke, 2010). The EnCurrent turbine shown in Figure 2 is a vertical axis Darrieus cross-axis turbine available in both ducted and non-ducted. The non-ducted configuration uses a 1.6 m diameter and 0.8 m tall turbine, it requires a minimum water velocity of 2 m/s to provide effective power output. However, as stated by (J. Khan, 2006), the turbine has ability to generate 0.4 kW power output at 0.9 m/s. In their website, (New Energy Corporation, 2014)), announce the use of Encurrrent turbine in powering rural community in Ruby at central Alaska.

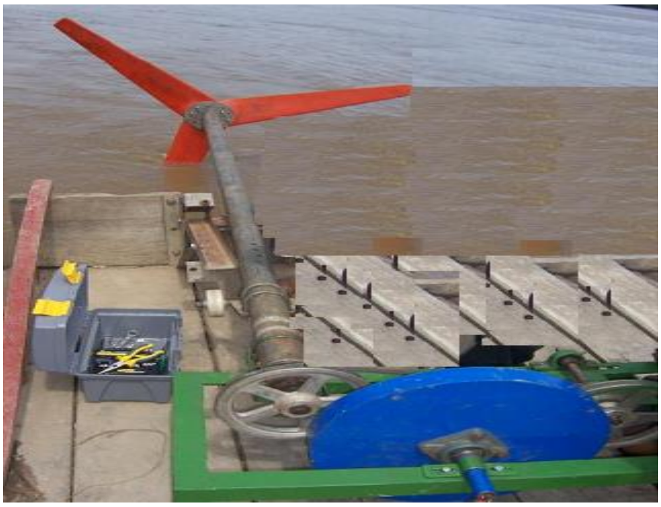

Figure 1: Amazon AquaCharger

Figure 2: EnCurrent HydroTurbine

The Axial flow turbine (figure 3) was designed by University of Brasilia to attend specific rural electrification projects with installed capacity from 300W up to 2000W(Els, R. & Junior, 2015) and was installed in Suriname village. The system provide power to school, health centre and hybrid solar dryer (Els, 2008). Under Water Electric Kit shown in figure 4, is designed to operate in river, tidal and ocean currents. The turbine with rotor ranging from 2 to 5 m operates in extremely low velocities of 0.20 m/s or less (Verdant Power Canada, 2006). However, Anyi & Kirke(2010) discuss that the axial flow turbine with diameter ranging from 0.8 – 2.7 m can be used to generate a practical amount of electrical power from water between 0.5 - 2 m/s up to 100 kW.

The Garlov-Darrieus Helical Turbine, shown in Figure 5 consists of a rotor with 2 to 4 blades, whose extremities are fixed to disks, forming only one set that rotates together with generator. The turbine is available in several diameters: 1.25 m, 1.5m, 2.5 m, 3.0 m, and 6.0 m. The smallest turbine developed by Alternative Hydro Solutions is 1.25 m diameter and 0.5 m height (Verdant Power Canada, 2006). The turbine starts producing power at approximately 0.60 m/s, according to studies done in 2004 (Sornes, 2010; Verdant Power Canada, 2006).

Figure 3: Axial Cross flow –UnB (Viana, 2014)

Figure 4: Under Water Electric

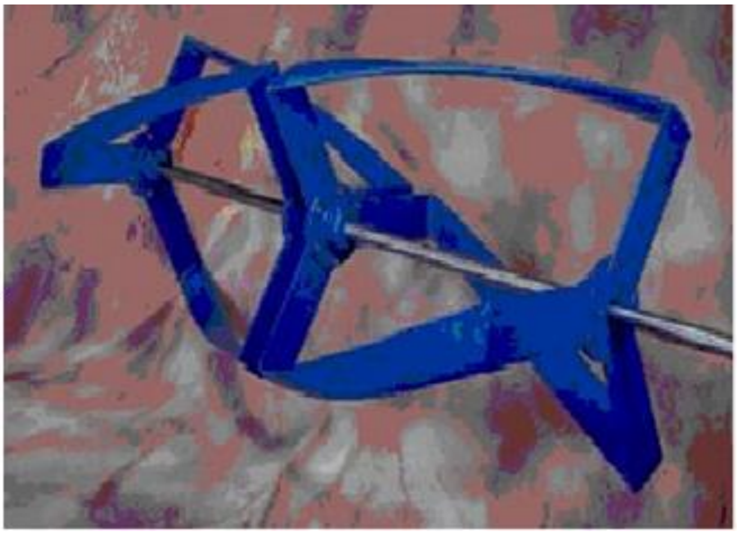

Figure 5: Garlov Helical Turbine

Turbines specification and their operation requirement are shown in table 1.

Table 1: Output Power of Axial and Cross-Flow Hydrokinetic Turbines

Device	Minimum River Depth requirement (m)	Stream Flow Velocity requirement range (m/s)	Rotor diameter (m)	Power Output Capacity
Amazon Aquacharger turbine	1.75	0.45- 1.5	1.8	500 W at 1.5 m/s
Under Water Electric Kit Turbine(twin unit)	2	0.20	2 - 5	100 kW
Garlov Helical Turbine	2.5	0.6-1.3		0.7 kW at 1.3 m/s
EnCurrent Hydro Turbine	0.8	1.5-2.5	1.6	10 kW at 1.5 m/s
Axial-Flow (UnB) Turbine	1	1.5	0.8	20 kW

2. Methodology

This study was based on frequency analysis of historical data, survey on hydrokinetic technologies for river application, hydrokinetic resources studies approaches and field survey. Preliminary data for desk analysis were collected from Department of Water Resources under National Directorate of Water in Mozambique.

2.1 Area of study

Umbeluzi is an international river shared by Swaziland, Mozambique and South Africa; it originates in Swaziland close to the border with Mozambique. It covers a total area of 5,400 km^2, of which 40% in Mozambican, 58% in Swaziland and the remaining 2% in South Africa (Joel das Neves Tembe and Aristides Baloi, 2001). The basin and Umbeluzi river main course are shown in Figure 6.

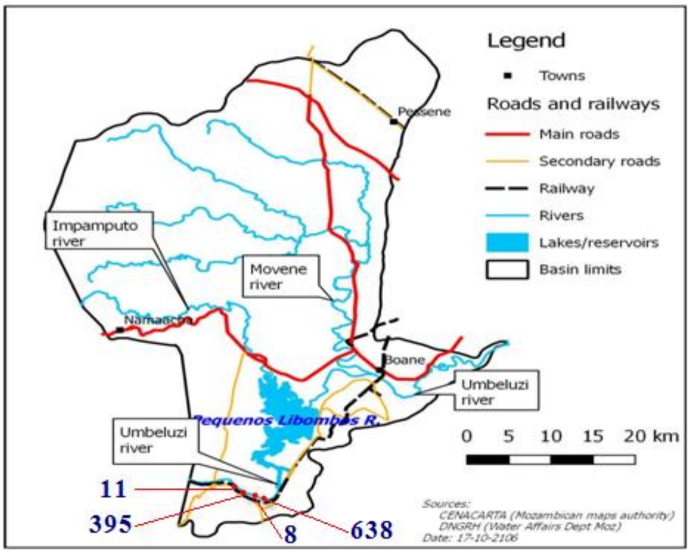

Figure 6: Umbeluzi Basin and its tributaries rivers. Source: CENACARTA (2016)

The main course of the Umbeluzi River runs in the East direction and discharges into Indian Ocean through Espirito Santo estuary at the southern Maputo bay. The main course consists of two tributaries, Mbuluzane River in Swaziland and Movene River in Mozambique (Juizo, D.,Liden, 2008). The table below indicates the sites (stations) were the study took place.

Table 2: Stations studied

Station number	Latitude	Longitude	Altitude
8	26:5:41 S	32:19:30 E	3
11	26:11:46 S	32:7:17 E	63
395	26:5:15 S	32:14:32 E	17
638	26:2:11 S	32:23:1 E	99

2.2 Stream Flow Velocity flow Characterization of the Main Maputo's Hydrological Basins

The study has used Frequency Analysis using historical data of velocity of river streams to generate velocity duration curves (VDC). VDC are graphical plot of stream velocity against the corresponding percent of time that the stream velocity is same or is exceeded. It describes the variability of the stream velocity. VDC were generated arranging velocity data in descending order and the percentage probability, Pp, of any magnitude, V, being exceeded calculated using Equation 6.

$$Pp = \frac{m}{N+1} \times 100\% \qquad \text{(eq. 6)}$$

Where P_P is percentage probability (%), m is number of the velocity (rank), N is number of the data in the list.

2.3 Evaluation of the feasibility for Installation of hydrokinetic turbines in the Umbeluzi main course

The evaluations of the feasibility for installation of hydrokinetic turbine in the Umbeluzi basin was done through comparison of the velocity of the stream versus the design velocity of the hydrokinetic turbines, and comparing the rotor diameter of the hydrokinetic turbines to the depth of the river, then evaluate the feasibility for installation of hydrokinetic turbines in the Umbeluzi River.

2.4 Hydrokinetic and Extractable Power

Assuming hydrokinetic turbines maximum efficiency 0.593 stated by Betz limit, extractable power was computed using Equation 5. However, this was done for stream section which equally had the minimum water depth matched with the specific turbine requirement, such as station number 638. The turbines used for energy evaluation at these stream sections are respectively Under Water Electric kit (UEK), the ducted cross-axis by UnB and EnCurrent.

The energy evaluation was based on the stream flow velocities which is more than 90% of time available throughout the year.

2.5 Field Measurements and Equipment

River depth and flow velocity through main Umbeluzi channel was carried out at Goba and Mafavuca communities. The flow velocity of the river was directly measured using Gurley 572771 current meter shaft. Area of each sub-section was determined by directly measuring width and depth and computed using Equation 7.

$$A_i = W_i \times D_i \quad \text{(eq. 7)}$$

Where A_i is sub-sectional area, W_i, D_i area the correspondent width and depth of each subsection. The flow velocity in each sub-section was estimated at selected vertical locations in the water column.

3. Results and Discussion

3.1 Characterization of Umbeluzi River Flow Velocity

Umbeluzi basin consists of 37 hydrometric stations most of them built in 1950s. For the purpose of this study, four Gauging Stations have been used to characterize Umbeluzi River flow velocity. Figure 7 up to Figure 14 show Umbeluzi River Flow Velocity hydrographs and velocity duration curves from Goba Village (where the river enters Mozambique from) up to Boane Village.

The observations of stream flow of Umbeluzi at Station 11, downstream Goba Village is shown in figure7. The curve was plotted using monthly averaged values of 5 years (1981-1985).

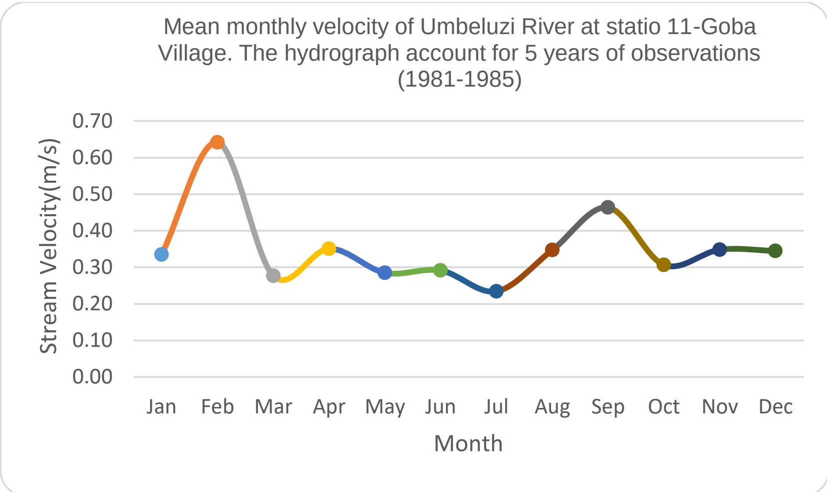

Figure 7: Umbeluzi Mean Monthly Velocity-Station 11 at Goba Village

From the hydrograph (mean monthly flow velocity variation) in figure 7, it can be noted that the maximum flow velocity of 0.64 m/s is reached in February. The minimum stream flow is 0.23 m/s observed in July However, with the exception of February, the stream flow velocity of Umbeluzi at this site is in the range of 0.23 m/s to 0.4 m/s. Figure 8 shows the time each stream flow is available throughout the year.

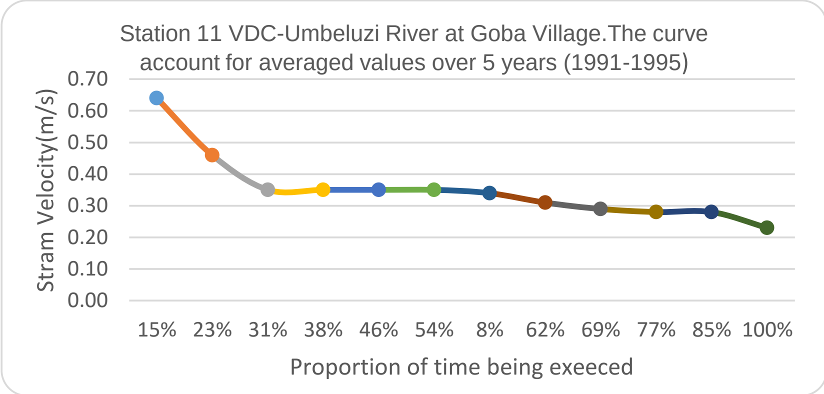

Figure 8: Umbeluzi Velocity Duration Curve-Station 11 at Goba Village

Looking at velocity duration curves (Figure 8) it can be drawn that (with reference to period 1981-1985), the stream velocity of 0.20 m/s is 92% of time available, and 0.64 m/s is 15% of time available throughout the year. However the firm velocity for energy generation should be available 100% of time all days of the months.

From 1982 to 1983, the river depth is in average of 0. 7 m. In 1984, the river reached 2.4 m of minimum water depth. At Station 638, the fluctuation of flows velocity through the years is very high. Such behaviour is shown in the hydrograph of figure 9.

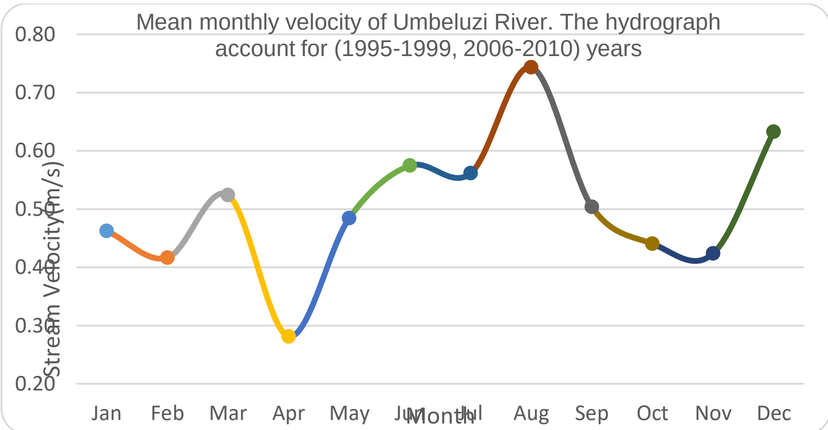

Figure 9: Umbeluzi Mean Monthly Velocity-Station 638

The Flow velocity data, taken as averages for the time in analysis (1995-1999, 2006-2010) show that the stream flow velocity ranges from 0.28 to 0.74 m/s where the maximum was registered in August.

The availability of firm velocity for hydrokinetic turbine installation in the last ten years (1995-1999, 2006-2010) of observation shows that 0.28 m/s is 92% of the time available, while above stream velocity of 0.6 m/s is only 8% time available (Figure 10). This means that, the river flows at 0.28 m/s from January to December and 0.6 m/s during less than one month.

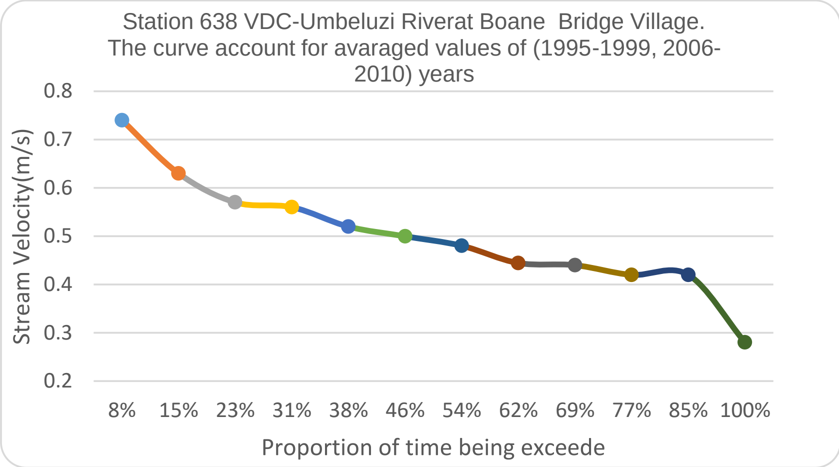

Figure 10: Umbeluzi Velocity Duration Curve-Station 638

According to figure 10, at this stream section 638, Umbeluzi registers 5.91 m and 2.64 m maximum and minimum water depth respectively.

Toward downstream, at Station 395, the maximum and minimum river depth of Umbeluzi are 1.0 and 0.55 m respectively. The stream velocity throughout the month can be seen from hydrograph curves of figure 11.

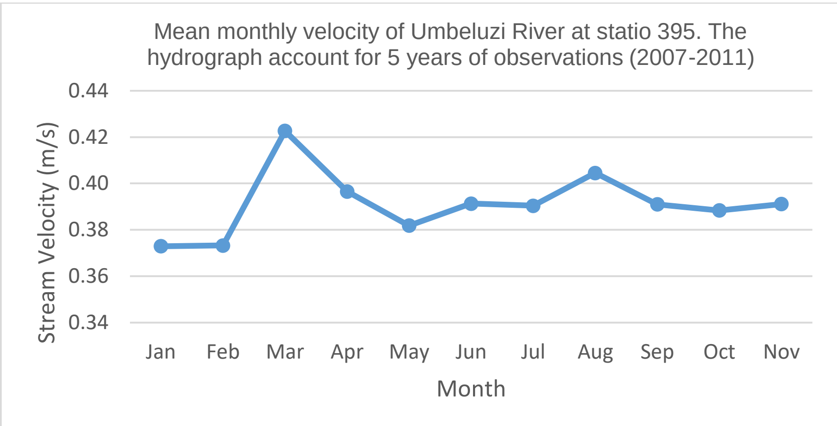

Figure 11: Mean Monthly Velocity Over Umbeluzi River-Station 395

During four years of observations (2007, 2008, 2009, 2010 and 2011 curves) Umbeluzi reached the maximum flow velocity during March and August being 0.42 m/s and 0.40 m/s respectively. The minimum stream flow velocities occurred in January and February. From May up to August, the stream flow increases from 0.38 m/s to from 0.40 m/s. From August to December, it drops from 0.40 m/s to 0.38 m/s. Figure 12 shows the time such range of stream flow can be harnessed for hydrokinetic application.

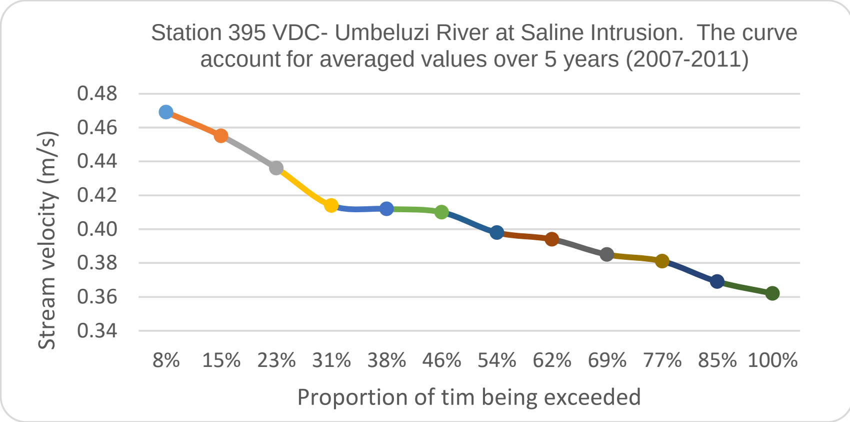

Figure 12: Umbeluzi Velocity Duration Curve-Station 395

As it can be seem from figure 12, Velocity Duration Curves above 0.36 m/s is 100% of time of the year available (From January to December) while 0.47 m/s is 8% of time available throughout the year. It means that the firm stream flow available for energy generation and provide power all months is 0.37 m/s.

The last stream flow observation was done at Station 8, whereby Umbeluzi River observes maximum and minimum water depth of 5.3 and 0.55 m respectively. Its mean monthly stream flow velocity it is shown in figure 13.

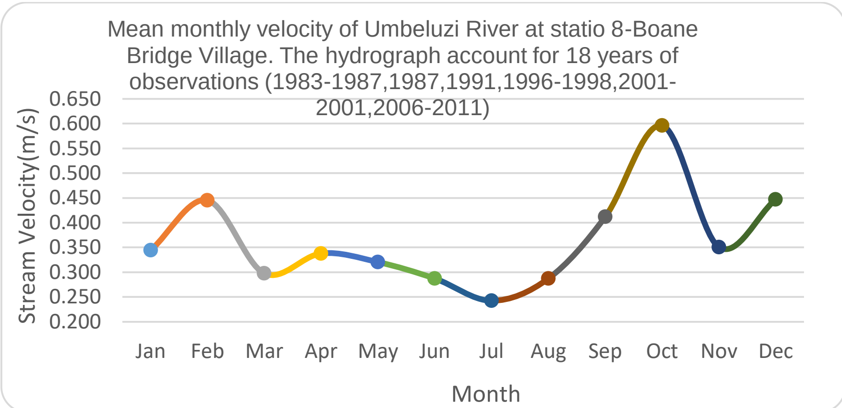

Figure 13: Mean Monthly Velocity over Umbeluzi Main Course-Station 8, Boane Village

The hydrograph curve of figure 13 shows that the stream velocity ranges from 0.3 m/s to 0.60 m/s from March to July. In February, has reached 0.44 m/s while October, Umbeluzi reaches 0.6 m/s. Figure 14 shows the analysis of stream flow velocity availability at station 8.

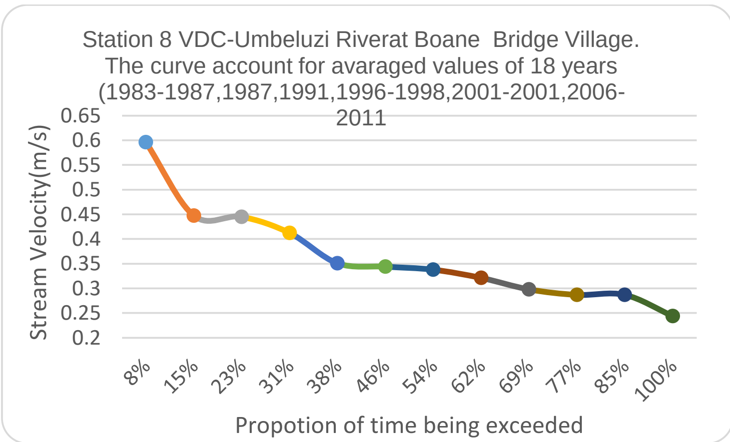

Figure 14: Umbeluzi Velocity Duration Curve-Station 8 at Boane Village

From Velocity Duration Curves shown in Figure 14, it is figured out that 0.244 m/s of flow velocity is 100% of time available throughout the year while 0.60 m/s is 8% of time available. Thus, similar to the station 395, 0.24m/s is the firm flow available for energy generation during all months at this section.

3.2 Feasibility for Installation of Hydrokinetic Turbines in the Umbeluzi River

The following analysis was done with reference to turbines operation requirements in natural current river flows provided in table 1. The parameters analyzed are: river flow velocity and river depth compared to operational flow velocity of the turbines and their rotor diameter (for axial type) or the height of the turbine (in case of cross-flow turbines type).

In Goba Village (station 11), the velocity duration curves plotted from 1981 to 1985 show that the river flow velocity of 0.20 m/s is 100% of time available (Figure 8). The minimum water depth observed from 1981 to 1985 is 0.69 m. In such flow velocity, Under Water Electric Kit (Figure 4), could be used to extract kinetic energy. However, the turbine requires 2 m of minimum river depth, which is not available at the site.

At Station 638, the last five years of observation (2007,2008, 2009, 2010 and 2011) show the stream velocity of 0.28 m/s is 100% of the time available and the stream velocity of 0.40 m/s is available 85% of the time throughout the year (see Figure 10). At this stream section, Umbeluzi River registered 5.9 m maximum and 2.64 m minimum of water depth.

The maximum and minimum river depth at Station 395 is 1.0 and 0.455 m. Stream flow velocity 100% of time available throughout the year is 0.36 m/s (see Figure 12).

At Station 8 located in Boane Village, Umbeluzi River observes a maximum and minimum water depth of 5.3 and 0.55 m respectively. Figure 14 shows that less than 0.244 m/s of flow velocity is 100% of time available throughout the year.

Looking at the turbines specification in table 1 and compared to the river flow velocity, it is found that the river meets operating flow velocity of Under Water Electric Kit at stations 11, 638 and 395. However, when the river depth is brought into comparison with the turbines specification, only Under Water Electric Kit could be used to extract kinetic energy at station 638, as the minimum river depth is 2.64 m, matched with 2 m rotor diameter.

3.3 Evaluating Extractable Power by Under Water Electric Kit Turbine

Under Water Electric Kit (UEK) is claimed to operate under extremely low velocities (Verdant Power, 2006). Therefore, it will be used to evaluate the hydrokinetic potential in station 638. At this section, the natural stream flow conditions are: 0.42 m/s is 85% of time available (see Figure 10); the stream cross-section area is 4.24 m^2 and minimum river depth of 2.64 m.

The hydrokinetic power available in the river computed using Equation 1 is 157.07 W and the extractable power by the turbine with 2 m rotor diameter computed by equation 5 results in 69.01 W (see Table 2). If the cross-section area of the river is strangulated from 4.24 m^2 to 2.12 m^2, the stream flow increased up to 0.84 m/s. The hydrokinetic power available in the river, calculated using equation 1 is 628.27 W and the extractable power by the turbine, using Equation 5 result in 552.09 W, which is enough to meet the basic needs of 10 households at World Bank standards for rural electrification using solar energy.

Table 3: Increased Flow Velocity and Output Power by the use of Under Water Electric Kit

Cross-section Area (m^2)		Flow Velocity (m/s)		Hydrokinetic Power (W)		Extractable Power (W)	
A_{c0}	4.24	V_0	0.42	P_{K0}	157.07	$P_{g\text{-}max0}$	69.01
A_{c1}	2.12	V_1	0.84	P_{K1}	628.27	$P_{g\text{-}max1}$	552.09

4. Conclusion

Hydrokinetic technology are designed to supply power for low demand communities living close to the rivers, hence increase the provision of energy services in rural areas. However, its exploration is dependent on availability of the water resources at the site, which are the river flow velocity and river depth. In that context:

Umbeluzi flows at 0.60 m/s maximum velocity, which is 8% of time available. Flow velocity ranging from 0.23 to 0.36 m/s is 100% of time available throughout the year. In addition, almost all stations have registered the minimum river depth in a range from 0.55 to 0.7 m.

Comparing the range of flow velocities to the turbines requirements, it is found that low flow velocities for hydrokinetic technology characterize Umbeluzi River. However, kinetic energy can be extracted at station 638 if augmentation device is used to strangulate the river channel. The river flow at 0.42 m/s is 100% of time available throughout the year in an average cross-section area of 4.24 m^2.

The extractable power using Under Water Electric Kit is 69.01 W. However, if the cross-section area is reduced from 4.24 to 2.12 m^2, the flow velocity increases from 0.42 to 0.84 m/s. The corresponding extractable power is 552.09 W, useful to charge some batteries.

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