Evaluation of potential sites for the construction of hydropower plants in the Revuboe River

Extended Abstract

Thesis to otain the Master of Science Degree in

Civil Engineering

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1. STATE OF THE ART

In the past few years, Africa is having much higher economic growth rates than those experienced by European countries. However, the economic growth, which had a 7% peak, is now slowing down due to global crisis. Extreme poverty had also lowered from 57% in 1990 to 43% in 2012 but remains high (World Bank, 2016). Drinking water and electrical energy are two important factors as far as reducing poverty is concerned. Industrial and agricultural production are highly reliant on those two factors and poverty can only be reduced if food security is guaranteed. The Mozambican overview is close to African reality. Electrification rate in Mozambique is just 14% (Klunne, 2014). Only the big urban areas in Mozambique have electrical energy provided by the national electrical network. This means that a major part of the country has an electrical deficit.

Mozambique is located downstream of important African rivers such as Zambezi, Save and Limpopo. With the big quantities of water available in these rivers there is also a great potential for hydroelectric power schemes to produce clean energy. There are predictions that show an incredible 18 GW of hydropower potential available in Mozambique. Half of that can be found in the Zambezi River basin in the province of Tete (Gesto et al., 2014).

There are several existing or designed hydropower plants that cover most of the head of the Zambezi River. However, there is room to exploit more energy potential if we look to its tributaries like the Revuboe River. The Revuboe River is located on the left bank of the Zambezi River, in the north side of the Tete province. It starts at the Antagonia district to finally meet Zambezi at the city of Tete. In the Revuboe River basin, agricultural and industrial activities require energy and water. With good topographic and climatic conditions, the Revuboe River is an example of a river that justifies the development of hydropower facilities. For that reason, the subject of this report is the study of site locations for the construction of hydropower schemes.

This study has four different parts. In the first part the goal is to find the best locations for a Hydropower facility. The second part of the study is a hydrological analysis for the Revuboe River basin. The third part shows the economic analysis made to the chosen locations. The fourth part of the study brings the best solution of the energetic analysis into close detail.

2. TOPOGRAPHIC ANALYSIS

Hydropower generation depends on the head of the facility and on the flow at a given location. However, it has to be taken into account that the costs of the facility increase with bigger dams. Therefore, it is understandable that narrower cross sections of the river return lower dam volumes and bigger dam heights return more dam volume. It is also possible to extend the length of the conveyance system to increase head with local topography instead of with dam height. However, if the conveyance system is too extensive it may turn the facility unprofitable.

In order to find good locations to implement a hydropower facility the topography for the Revuboe River basin was analysed with two different softwares: Google Earth and ArcGIS. A Digital Elevation Model (DEM) was downloaded from the NASA's Shuttle Radar Topography Mission which mapped the World using satellites. The downloaded file represents a raster elevation map that covers the location of the Revuboe River basin. The elevation map was processed using the ArcGIS software to obtain the geomorphologic definition of the basin, the river network and the river profile. The main characteristics of the basin are described in Table 2.1.

Table 2.1 Basic characteristics of the Revuboe River basin.

Drainage area (Km^2)	17669,34	**Revuboe River length (Km)**	302,58
Basin perimeter (Km)	780,46	**Mean river slope (%)**	0,43
Mean basin slope (%)	8,88	**Maximum Altitude (m)**	1419,50
		Minimum Altitude (m)	121,00

Watching the river profile (Figure 2.1), it is easy to know where the biggest slopes occur. With the 2D and 3D capabilities of Google Earth software, an extensive search was made to find the locations with narrower cross sections nearby those slopes. Only 12 cross sections were considered in this study with 8 sections in the main water stream, 3 in the Condedzi River, and 1 in the Pônfi River. With Google Earth topography, the gross head, the conveyance system length and the river cross section width were defined for each location in order to satisfy feasibility conditions.

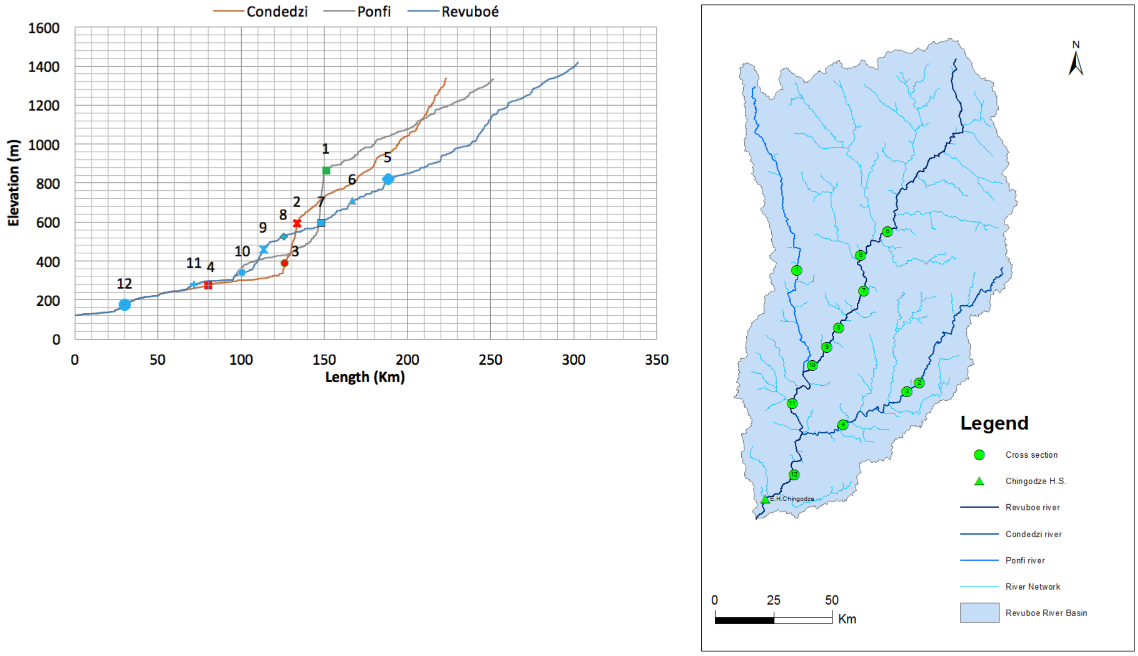

Figure 2.1 Revuboe River profile and river basin with the location of the 12 cross sections.

3. HYDROLOGIC ANALYSIS

Power generation depends on flow. Larger quantities of water generate more energy. So it is important to know how much water is available in the Revuboe River basin. To determine the volume of water available it is necessary to have an annual flow duration curve. Unfortunately, it is extremely difficult in these zones of the planet to find proper hydrologic data since most of the few existing hydrographic stations were destroyed or deactivated. The only information available is 22-year-old records with daily data of the Revuboe water level at the Chingodze hydrometric station, located nearby the city of Moatize. In order to predict the mean annual flow, two different methods were used. The first approach was to use a map of mean annual precipitation along with a mean annual runoff map of Mozambique obtained from Gesto et al. (2014). With ArcGIS software it was possible to georeference both maps upon the Mozambique coordinates and cross the information from the maps with the Revuboe River basin map previously defined and obtain the precipitation and runoff maps for the Revuboe River basin (Figure 3.1). This software also enables the prediction of both precipitation and runoff values for the 12 sections by calculating the area of influence of the map isolines on the drainage areas of each location. The mean annual precipitation for the Revuboe River basin in the Chingodze hydrometric station is 928 mm. The mean annual runoff for the same location is 149 mm. These numbers return a runoff coefficient of about 16%, which according to Korzum (UNESCO 1978), is an acceptable value in this part of Africa.

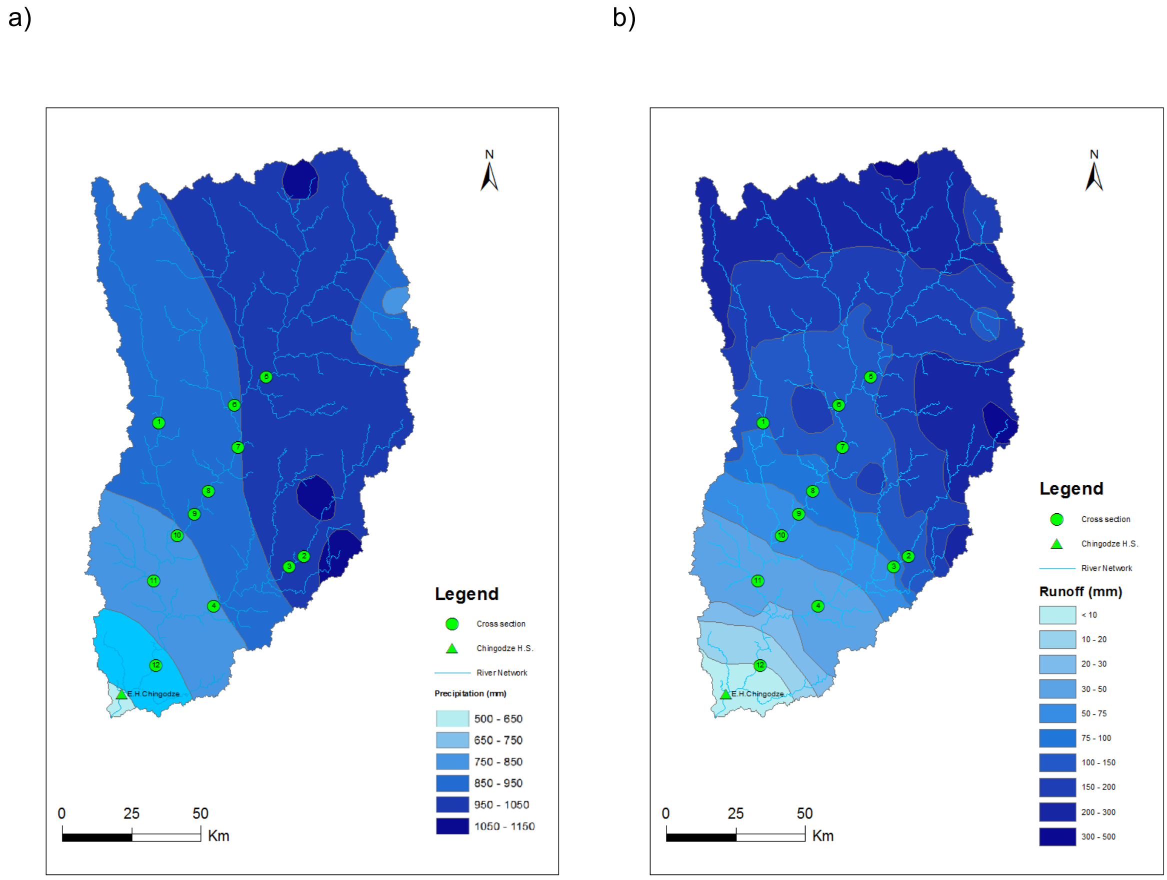

Figure 3.1 a) Mean annual precipitation map of the Revuboe river basin. b) Mean annual runoff map of the Revuboe river basin.

The second approach was to find specific mean discharges for the Revuboe River basin or similar basins nearby the area. A World Bank (2010) report, presents several river discharge values and respective areas. All the values used come from rivers that are next to the case study. The discharge values were divided by their areas in order to have specific discharges of each basin. After calculating the average it was admitted as specific discharge for the Revuboe River Q_{sp} = 0,006 $m^3/s/Km^2$ (Table 3.1). The discharge values predicted with the two methods are described in Table 3.2. It is clear that both methods give similar predictions, especially for the upstream sections, where the drainage area is smaller, but the first method returns lower discharge values for the most downstream sections. This is why the first method was the one used to calculate water volumes. By doing this, energy generation can be more accurately predicted without falling into water shortages.

Table 3.1 Specific discharges calculated for the river basins nearby the Revuboe river basin (World Bank, 2010).

RIVER	**Q** (m^3/s)	**AREA** (Km^2)	**Q_{SP}** ($m^3/s/Km^2$)
LUANGWA	518	159615	0,0032
LUENHA	180	57004	0,0032
ZAMBEZI TRIBUTARIES ON TETE	987	103393	0,0095
SONGWE	35,2	4060	0,0087
S.RUKURO + N. RUMPHI	47	12483	0,0038
NIASSA’S LAKE TRIBUTARIES	528	80259	0,0066
SHIRE	162	23183	0,0070
		Average	0,006

As was already said, to calculate water volumes it is necessary to have a flow duration curve. The flow duration curve represents the number of days a certain discharge is equalled or exceeded. Since the only information available is daily water level records on the Revuboe River, it was necessary to convert these water levels into discharge values. To do this, the Manning-Strickler equation was used. To use this equation, the cross section profile of the Chingodze hydrometric station was extracted from Google Earth as well as the river slope. The daily discharge values obtained with this process could induce errors since this process does not take into account movable riverbeds. One way to overcome the problem was to calculate the discharge modulus of the flow duration curve and divide every mean daily discharge by this modulus. This way, the flow duration curve has non-dimensional values that can be extrapolated to the other locations by multiplying those values by the mean annual discharge value presented in Table 3.2 of the respective location. The flow duration curve and the non-dimensional flow duration curve are presented in Figure 3.2 for the Revuboe River in the Chingodze hydrometric station cross section.

Table 3.2 Hydrologic characteristics for the 12 sections studied.

Section	1	2	3	4	5	6
Area (Km^2)	1230	848	973	3486	4506	6994
Precipitation (mm)	900	1007	1006	980	986	980
Runoff (mm)	192	233	218	141	210	206
Runoff Coefficient	0,21	0,23	0,22	0,14	0,21	0,21
Discharge 1st method (m^3/s)	**7,52**	**6,28**	**6,74**	**15,64**	**30,00**	**45,84**
Discharge 2nd method (m^3/s)	**7,39**	**5,09**	**5,84**	**20,92**	**27,04**	**41,97**

Section	7	8	9	10	11	12
Area (Km^2)	8210	8791	8931	9088	12121	16690
Precipitation (mm)	983	979	977	976	949	944
Runoff (mm)	198	193	191	189	171	155
Runoff Coefficient	0,20	0,20	0,20	0,19	0,18	0,17
Discharge 1st method (m^3/s)	**51,55**	**53,78**	**54,16**	**54,50**	**65,79**	**82,50**
Discharge 2nd method (m^3/s)	**49,26**	**52,75**	**53,59**	**54,53**	**72,73**	**100,14**

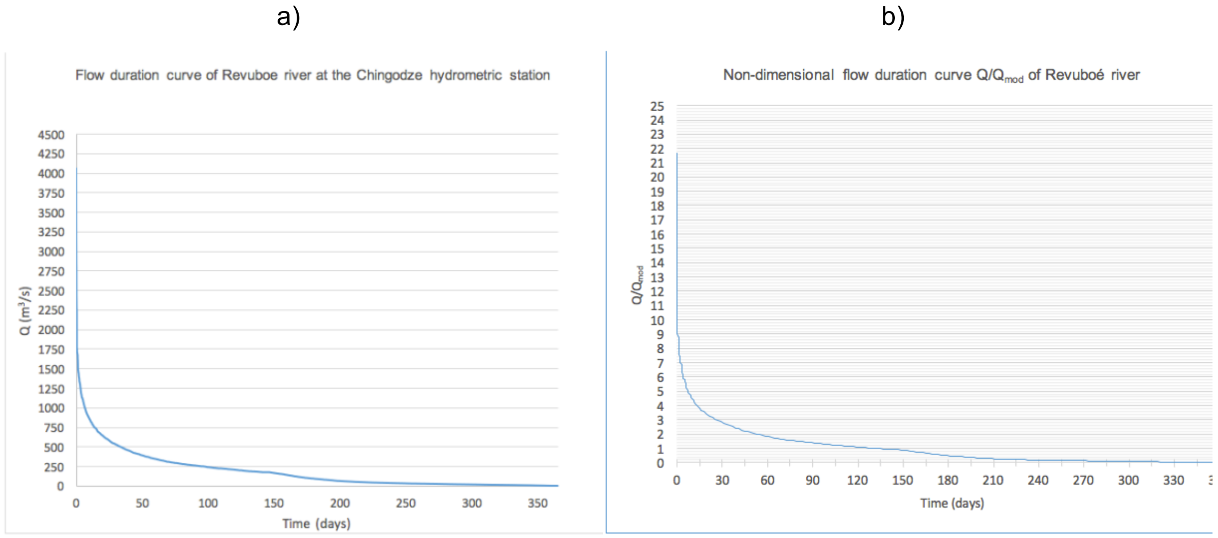

Figure 3.2 a) Flow duration curve of the Revuboe River at the Chingodze hydrometric station. b) Non-dimensional flow duration curve of the Revuboe river.

4. ENERGETIC AND ECONOMIC ANALYSIS

The energetic analysis of a hydropower facility implies the optimization of a design discharge Q_{dim}. This discharge will define all the parameters for the construction of the facility and is the value for which the turbines will operate in normal conditions. The optimization of the discharge will take into account the cost/benefit relation where the costs refer to the construction costs and the benefit is the power generated. The chosen design discharge value for each location is the one with greater net present value.

The procedure starts by defining a value for the design discharge. Different turbine sets can operate in different range of discharge values. One Francis turbine can operate between a maximum of 110% Q_{dim} and a minimum of 40% Q_{dim}. If two Francis turbines are used the minimum value drops to 20% Q_{dim}. For a Pelton turbine with 2 nozzles the discharge can vary between 110% Q_{dim} and 10% Q_{dim}. In the first approach the net head of each facility is considered to be 90% of the gross head of the respective facility. The turbine efficiency is considered to be $\eta = 0{,}85$. With those two variables defined it is possible to know the installed capacity of a facility for a given discharge Q_{dim}.

The cost estimation of each facility was predicted with a curve that was obtained by comparison with the costs of existing facilities in Africa. This curve relates installed capacity with cost per unit of installed capacity. With the installed capacity previously defined, it is possible to know the cost per unit, and the total cost by multiplying the unitary cost by the installed capacity.

The generated power is calculated by knowing the volume of water that passes through the turbine. This volume is calculated through the calculus of the area between the maximum and the minimum discharge on the flow duration curve and by deducing the ecological discharge from the flow duration curve. This ecological discharge was considered to be 5% of the discharge modulus for each section. The annual energy benefits are calculated by multiplying the mean annual generated power by the energy price. Taking maintenance and operation costs into account, the annual benefits were considered to be 90% of the gross annual benefits.

In the first analysis the energy price was considered to be 0,10€/kWh and the discount rate 10%. For each location, the design value, the net head, the installed capacity, the construction costs and the net present value are presented in Table 4.1. As shown in the table, the best alternative is section 9 which has the higher net present value.

To confirm that alternative 9 is the best section of the 12 sections studied, a sensitive analysis was made by changing some parameters. The energy price changed from 0,10€/kWh to 0,075 and 0,125 €/kWh. The discount rate changed from 10% to 5, 7,5 and 12,5%. The last parameter was the exploitation time that now was considered to be 30 or 40 years, instead of the initial 20 years. This analysis has confirmed section 9 as the best alternative. In the report it is also visible that sections 2, 3 and 4 have failed in this analysis as they presented negative net values for some parameters.

Table 4.1 Economic and energetic analysis for the 12 locations.

Section	**1**	**2**	**3**	**4**	**5**	**6**
Q_{dim} (m^3/s)	10	7	6	14	40	61
Net Head (m)	297,90	165,60	65,70	30,60	70,20	54,90
Installed Capacity (MW)	25	10	3	4	23	28
Estimated Cost (Million €)	55,08	26,85	11,82	12,59	52,66	60,21
VAL (Million €)	29,03	7,42	0,76	1,06	24,01	31,24

Section	**7**	**8**	**9**	**10**	**11**	**12**
Q_{dim} (m^3/s)	68	72	**86**	70	92	110
Net Head (m)	36,90	37,80	**108,00**	49,50	49,50	31,50
Installed Capacity (MW)	21	23	**77**	29	38	29
Estimated Cost (Million €)	48,34	51,42	**130,87**	61,80	76,08	61,80
VAL (Million €)	20,49	22,75	**99,82**	34,51	45,09	32,82

5. PRELIMINARY STUDY OF THE BEST ALTERNATIVE

In order to prove the economic feasibility of alternative 9, the facility costs which had been previously predicted with hydropower construction costs data were recalculated. A provisional budget for the facility is proposed which was estimated with a preliminary bill of quantities. To achieve this bill of quantities, the construction works based on the design made for the main hydraulic structures were calculated. The hydraulic structures analysed were the dam spillway, water intake, the tunnel, the penstock, the surge tank and the powerhouse. The solution presented in Figure 5.1 is just a preliminary study since important data was missing.

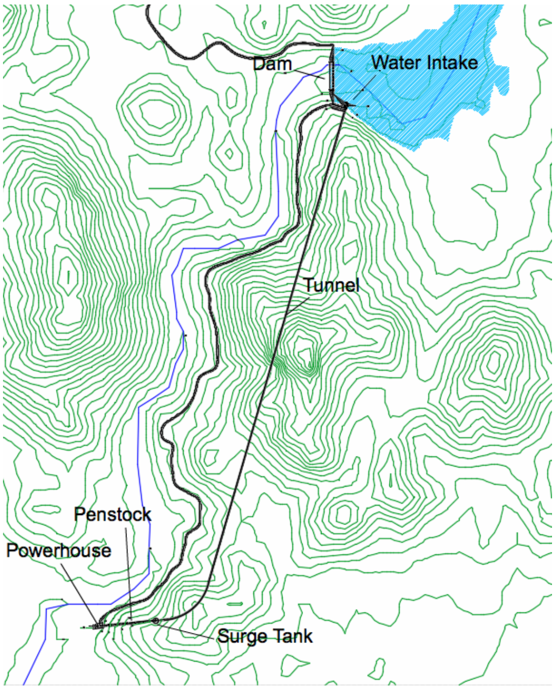

Figure 5.1 Solution for the Hydropower plant at the alternative 9.

The main characteristics of the solution studied for the construction of a hydropower plant located at the Moatize district of the Tete province, Mozambique, are described below:

DAM:

- Gravity dam without flow regulation
- Net head .... 104,60 m
- Dam's Height .... 35,00 m
- Maximum Storage Level 484,00
- Minimum Exploitation Level 475,00
- Maximum flood level (T = 1000 years).. 488,20
- Spillway discharge (T = 1000 years).. 3720 m^3/s
- Spillway length .... 222,80 m
- Mean annual power generation .... 263,57 GWh
- Water intake discharge .... 86,00 m^3/s
- Water intake hole .... 5,00 × 10,00 m^2

CONVEYANCE SYSTEM:

- Circular tunnel made of reinforced concrete.
- Tunnel length .... 4566 m

- Tunnel diameter .... 6,00 m
- Steel Penstock
- Penstock length .... 437 m
- Penstock diameter .... 3600 mm

POWERHOUSE:

- Powerhouse located outside on the left bank of the Revuboe River equipped with two Francis turbines.
- Installed capacity .... 74 235 kW
- Downstream level 361,00

The costs of the construction, C_c were estimated with a preliminary bill of quantities. It was considered that constructions works were to last 5 years, so construction costs would follow the same 5 years according to the yearly work distribution. It was also considered that the facility would operate for 40 years and start running after the construction is finished. The estimated annual operation and maintenance costs, C_{op}, are 10% of the revenues, R. The annual Net Present Value (NPV) was calculated along the 40 years of the facility operation and Figure 5.2 was obtained. The NPV at year 40 is:

$$NPV = R - (C_c + C_{op}) = 157{,}83 - (86{,}13 + 15{,}78) = 55{,}92\ Million\ €$$

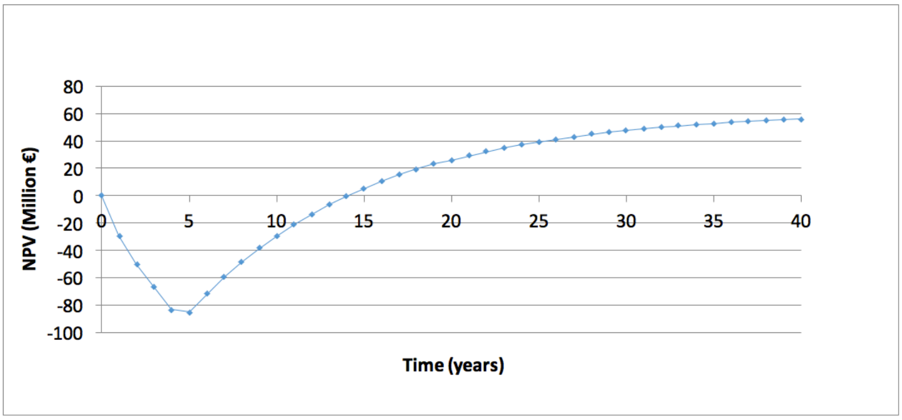

Figure 5.2 Net present value evolution curve

6. FINAL CONCLUSIONS

Mozambique is a country with great hydropower potential which can be used to reduce poverty and increase internal value. This type of renewable energy can be isolated or combined with other renewable energies to develop the most remote areas of the country by feeding local electrical networks.

The studies found about the Revuboe River and nearby areas show that there are political and social interests for hydropower development. However, the lack of topographic and hydrologic data brings difficulties to the inventory studies. To overcome the lack of topographic maps, the Digital Elevation Models processed with ArcGIS software allowed to gather elevation data for the basin. With these data, 12 locations were identified and studied. Despite the lack of hydrometric data, the flow duration curves for the 12 alternatives were obtained. These curves allow the prediction of the mean annual energy production for each alternative and the optimization of the design discharge. The economic analysis showed alternative 9 as the best solution which was then the target of a preliminary study.

To verify alternative 9 as the best solution, a sensitive analysis was made where some basic parameters were changed. This analysis kept showing that alternative 9 is the best location for the hydropower plant.

The preliminary study made for alternative 9 allowed to better predict the construction costs of the facility and to verify that the economic feasibility study previously made for this location is positive.

The Revuboe River has strong hydropower potential that should be used with small hydropower plants. This potential is especially driven by the topographic characteristics of the region, where the African plateau creates big falls and more precipitation.

For the following studies it is recommended the creation of hydrometric stations and geologic and topographic studies for the location of alternative 9. It is also necessary to perform studies about water and energy demand for population, agriculture and industries in Tete province.

Finally, the following studies can include different scenarios with multiple water uses or other renewable energies that can cover with water and energy the rural areas of the region.

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