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Assessment of Reservoir Based Hydropower System, a Case Study: Dwangwa River, Malawi

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Authors' contributions

This work was carried out in collaboration among all authors. Author SWC designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors SWC, SRC and LC managed the analyses of the study. Author SWC managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Unreliable power in Malawi mainly results from fluctuating water levels in most run-of-river hydropower plants. These power outages worsen during the dry season making it difficult to accommodate the existing demand of electricity. The best solution to ensure reliability of the hydropower system is to incorporate reservoir storage. This study aimed at designing a reservoir based hydropower system to ensure reliability and maximum generation of power at a low cost. The system was designed to export all the energy to national grid for distribution. The monthly average design flow was 29.129 m^3/s. Reservoir storage capacity of 536.998 Mm^3 was estimated using mass flow curve in MS-Excel while potential head of 100 m was deduced using Google Earth. RETScreen software was used to calculate hydropower potential and determine financial viability of the project. The results showed that the hydropower potential was 22.70 MW and the initial capital

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cost was $79,434,044 with payback period of 4.8 years. This paper's levelised cost of energy (LCoE) was 0.099 $/kWh which relatively smaller than grid cost of 0.155 $/kWh. Therefore, this paper presents part of the solution for the persistent power outages and also overcomes the serious power problems during dry season in Malawi.

Keywords: Design flow; Google earth; mass flow curve; RETScreen; storage.

1. INTRODUCTION

Large population of Africa including Malawi have no access to electricity and the population is constantly increasing making it difficult to satisfy the future energy demand [1,2]. The current world reserves of fossil fuels are rapidly depleting [3]. On the other hand, non-oil producing countries like Malawi have expensive petroleum products hence expensive to run a fossil fuel based power plant. Therefore, it is essential to promote renewable energy based power systems to augment current energy supplies.

Electricity generation in Malawi is largely dominated by hydroelectric power, with Nkula Station as the main station located in the Shire River. The overdependence of using this river amidst climate change is critical in power generation due to high fluctuations in the dry season. Malawi is also facing a lot of power outages due to fluctuating water levels especially during the dry season [4]. Currently, Malawi has electrification rate of about 12.7% with population of about 18.1 million [5]. Malawi's hydropower plants have been operating for decades with poor maintenance and have obsolete technology. Thus, additional power plants can help to solve the electricity challenges. However, power sector development is greatly affect by structural issues within the power sector and shortfalls in funding. One of the funding challenges is failure to recover bills [6,7]. This has led plants to fall out of production or underperform, reducing the already short supply of electricity. Urban areas in the country have not been spared with electricity challenges specifically unreliable availability of power which in turn affect business activities. Increase in electricity demand in cities like Blantyre, Lilongwe and Mzuzu forced government to install peaking diesel generators [8].

Malawi has significant rivers such as Shire, Bua, Dwangwa, North Rukuru, South Rukuru, Rumphi, Songwe, Wovwe, Lufira, Dwambazi, Luweya and Ruo [9] feasible for electricity generation. However, fluctuation of water levels and heavy siltation affects the capacity of energy generation. Reservoir storage is one of the ways to solve these problems.

Dwangwa river was assessed for water supply activities which include fish pond, domestic consumption, irrigation and hydroelectric power. Two sites on the river were identified for water storage at Kwengwele village and Lingadzi river confluence with storage capacity of 210 Mm^3 and 201 Mm^3 respectively [10]. Thus, the main objective of this research is to investigate the possibility of constructing a dam for hydropower plant in order to export all the produced electricity to the grid. The proposed project contributes to solving the problem of frequent power outages especially during dry season.

1.1 Theory of Hydropower Capacity

Energy storage through storing water in hydropower reservoirs adds resiliency against droughts and system flexibility. However, reservoirs affect flora, fauna, and ecosystem services. The dam also blocks the natural river flow, affecting the migration of aquatic species and resulting in changes in the oxygen, thermal, and sedimentary conditions in the reservoir area. In some cases, flooding and decaying of large stocks of biomass in the reservoir area lead to greenhouse gas emissions. Furthermore, large hydropower projects also affect the local population through the resettlement of people [11]. Hydro energy, generated by the reservoir, can be calculated according to [12]:

$$\mathrm{E_{H(gross)}} = \rho.\mathrm{g.H.V} \quad \text{(J)} \tag{1}$$

And hydro accumulation power:

$$\mathrm{P_{H(gross)}} = \rho.\mathrm{g.H.Q} \quad \text{(W)} \tag{2}$$

Where V (m^3) is water volume in reservoir, H (m) is elevation difference between the lower and upper water level, g (m/s^2) is gravity acceleration, ρ (kg/m^3) is the water density and Q (m^3/s) is river discharge. Therefore, the accumulated water, i.e. reservoir V (m^3) and the available height difference H (m) determine the energy production and installed turbine capacity Q (m^3/s)

determines the power. Local conditions regarding reservoir construction (volume and elevation) will determine which combination of height difference H and water volume V is the better solution for the planned fulfilling of the consumers' demands – energy production. In addition, the selected drop H and flow Q will define the most efficient type of turbine. Net electric energy produced by the hydroelectric power plant is given by:

$$E_{el(HE)} = \rho . g . H_n . V . \eta_{TG} \text{ (J)} \tag{3}$$

Where H_n is the net available drop and η_{TG} is total turbine and generator efficiency which ranges from 75% to 92% [12].

1.2 Hydropower Project Costs

The weighted average investment cost for large-scale and small-scale hydro in Africa is 1400 $/kW and 3800 $/kW respectively [13]. Globally, typical costs for largescale hydropower projects range from 1000 to around 3500 $/kW. For hydropower plant greater than 10 MW, investment costs range from 1750 $/kW to 6250 $/kW [14]. However, some projects may fall outside the range such as installation on existing dam with about 500 $/kW. On the other hand, projects at remote area with poor infrastructure and far from transmission networks can cost significantly higher [15].

Worldwide, the cost of installing hydropower plants varies with Europe as the most expensive region to install hydropower plant as shown in Fig. 1. In Europe, for large hydro, it ranges from about 1000 $/kW to 5000 $/kW while for small hydro, it ranges from about 1000 $/kW to 8000 $/kW. Fig. 1 further highlights that Africa has a relatively lower installation cost which ranges from 1000 to 2000 and 2000 to 4000 $/kW for large and small hydropower project respectively [14,15]. Regardless of these ranges, specific African countries have different costs of installation as shown in Fig. 2. For instance, Rwanda indicated an installation cost of about 2800 $/kW for less than 2.5 MW whereas on the similar amount Uganda installed about 8 MW. However, Fig. 2 shows that hydropower projects of less than 5 MW are more expensive as compared to projects greater than 15 MW [15].

A reservoir based hydropower plant comprises of a reservoir, a tunnel, powerhouse equipment, shafts and a powerhouse. All these components have a contribution towards the total capital cost. Additionally, costs are also incurred in engineering, procurement and construction management. Large contributions come from the reservoir which is 26% whereas powerhouse equipment contribute 16%. The smallest contribution comes from project management with 7% contribution. Fig. 3 shows contribution of main components costs of a hydropower project [16].

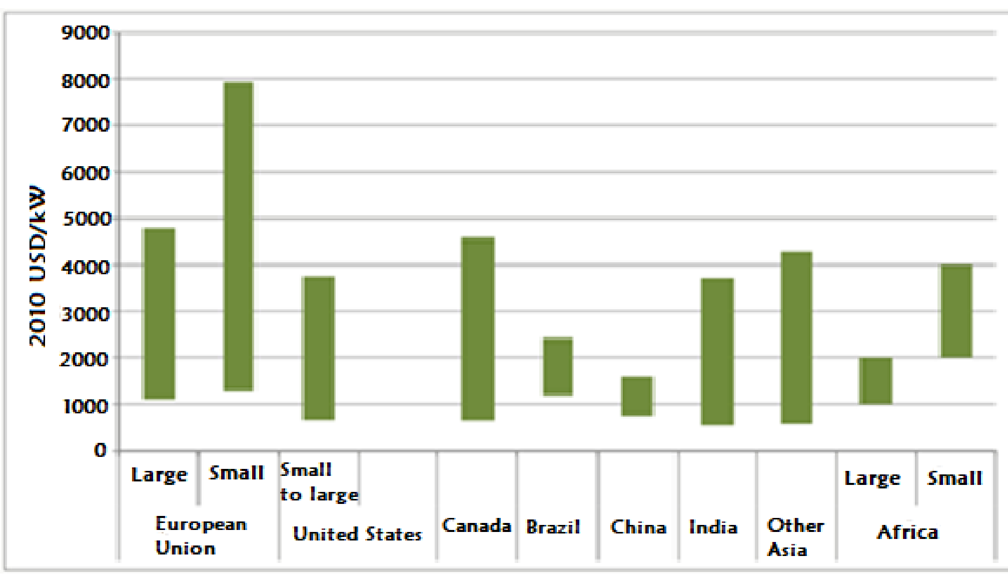

Fig. 1. Total installed hydropower cost ranges by country [15]

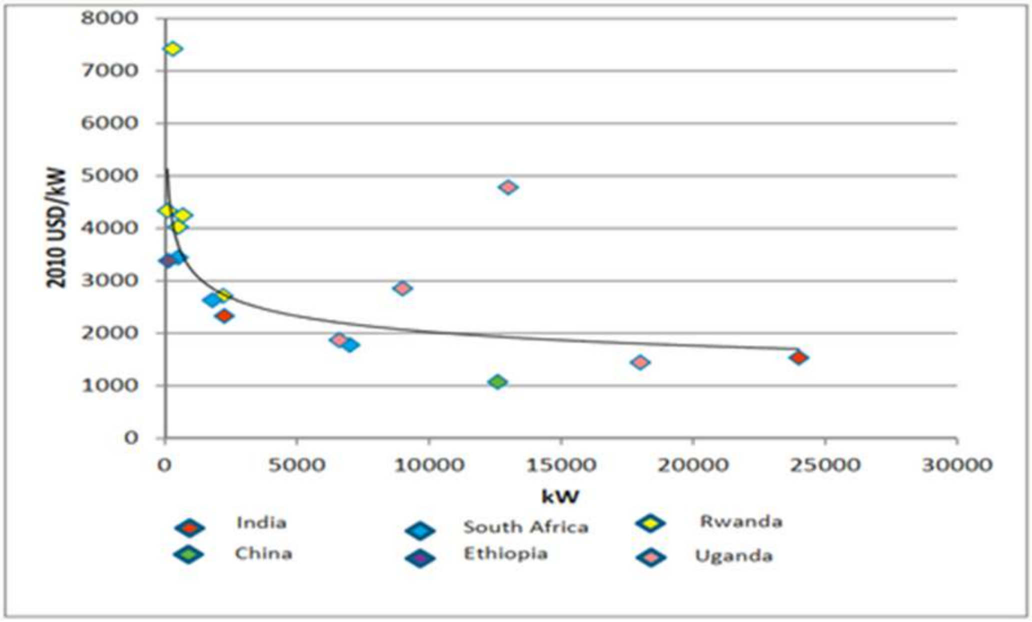

Fig. 2. Hydropower capital cost in developing countries [15]

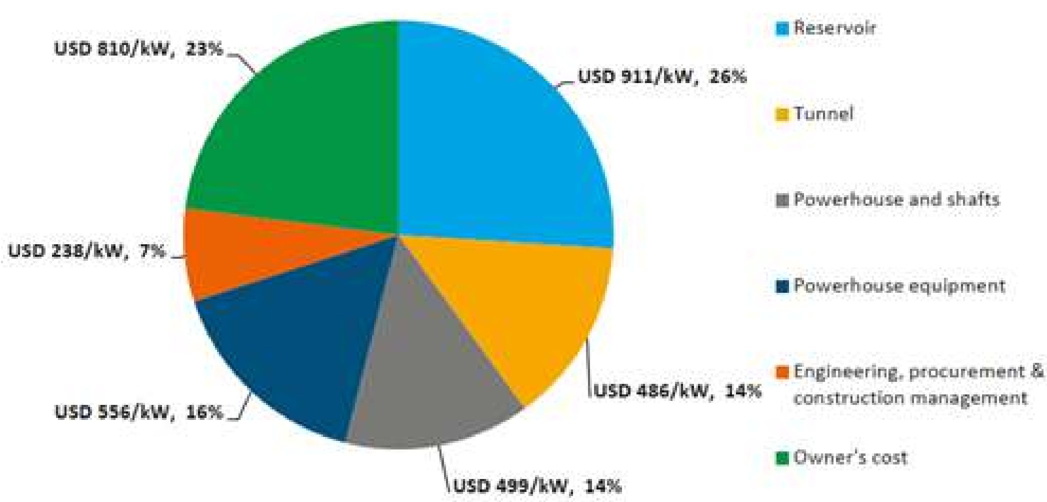

Fig. 3. Hydropower capital cost breakdown [16]

2. MATERIALS AND METHODS

2.1 Study Area

The proposed Dwangwa reservoir is located in the Central region of Malawi within the Dwangwa river basin. The location of Dwangwa catchment area is close to the coordinates 33°0'0"E and 34°0'0"E and 13°0'0"S as shown in the Fig. 4. According to NASA climatic data, the annual precipitation varies from 3.8 mm to 289.93 mm while the temperature varies from 18.8°C in winter to 24.8°C in summer. The spatial-temporal variations in temperature are not uniform in the whole basin. The relative humidity for the region varies from 44.1% to 80.3%. The region has moderate wind speed with an average of 3.9 m/s and daily horizontal solar radiation average of 5.21 kWh/m^2.

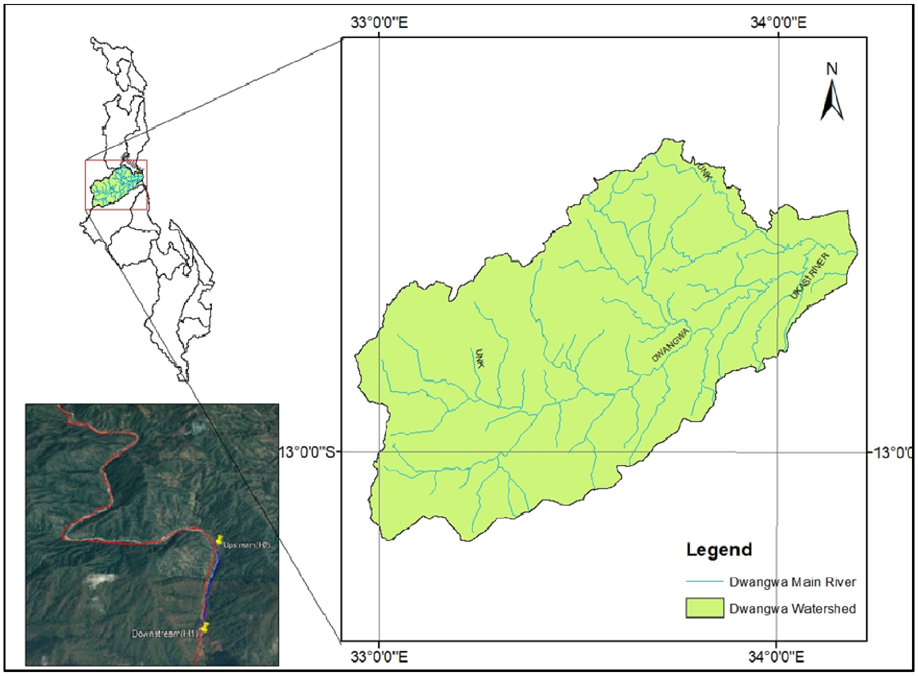

Fig. 4. Dwangwa watershed location

The basin covers a catchment area of 7768 km^2 and drains into Lake Malawi. A major part of Dwangwa river basin lies between 477 and 1788 metres above mean sea level as shown in Fig. 5. The east and central part of the basin comprises the Kasungu plain which is gently undulating with altitudes between 975 and 1300 m above sea level. The Dwangwa river passes through the Nkhotakota lakeshore lowland before flowing into Lake Malawi. Natural vegetation in most of the basin is the Braschystegia – Jilbernadia woodland while grassland is available in depression (dambo) areas [17].

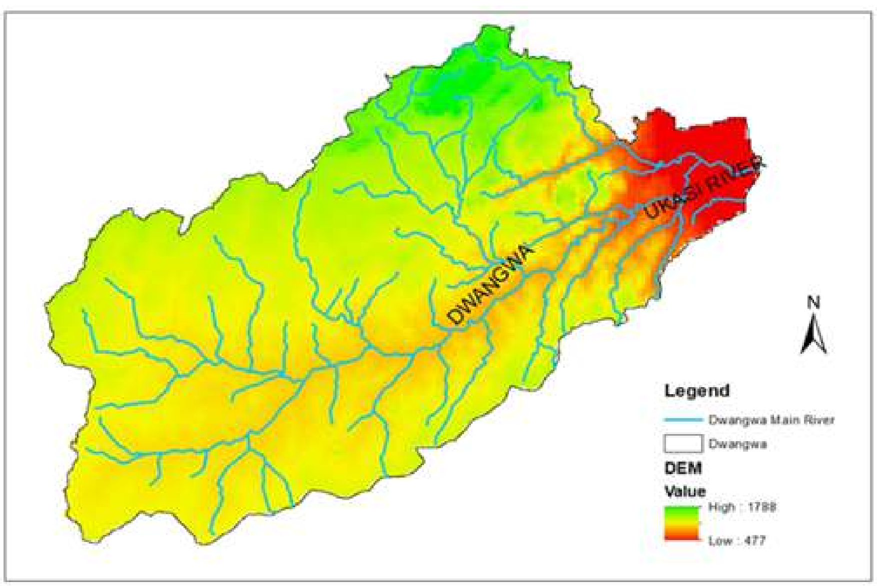

Fig. 5. Dwangwa digital elevation model and dwangwa river drainage pattern

2.1.1 Dwangwa river

Dwangwa river receives more waters during rainy season and nearly dry during dry season. Thus, in January the average flow rate was 112,025.33 L/s while in September the value was 168.351 L/s. The river discharge was measured at a period of 24 years from January, 1986 to January, 2010. However, due to some missing data the most recent dataset with complete data for the year 2005 was chosen. Fig. 6 shows the monthly average river discharges for the year 2005.

The annual average flow for Dwangwa river was 29,129.47 L/s which was a huge amount of discharge potential for energy generation. However, this discharge cannot be realized in run-off-river since the water levels decrease significantly during dry season. Therefore, this proposed system was aimed at designing reservoir based hydropower system to ensure reliability and maximum generation of power at low cost. The study was twofold in that it addressed sequentially technical and economic aspects. This means that the results in the technical feasibility phase were used in the economic feasibility phase.

2.2 Technical Analysis

The average river discharge for Dwangwa and DEM (Digital Elevation Model) were obtained from the Ministry of Irrigation and Water Development, Malawi Government. Wind speed, solar, temperature and other relevant data were obtained from NASA Surface meteorology and solar energy database.

2.2.1 Mass curve

Mass curve is defined as the accumulative plotting of net reservoir inflow against time duration. Mathematically, it is expressed as:

$$V(t) = \int_0^t Q(t)dt \quad (4)$$

Where $V(t)$ is the volume of run off and $Q(t)$ is the reservoir inflow, both as function of time.

The slope of the tangent at any point on the mass curve shows the rate of flow at that point on the mass curve. Mathematically, it is given as:

$$Q(t) = \frac{dV(t)}{dt} \quad (5)$$

In order to determine the reservoir storage capacity, the following mass curve preparation procedure was done using MS-Excel:

Firstly, plot mass inflow curve from the river discharge of the site for a number of consecutive years. Secondly, Plot the mass demand curve with respect to the given rate of demand. Thirdly, draw the tangential line parallel to the mass demand curve at peak point of mass inflow curve. Then, determine the vertical intercepts between the tangential lines and the mass inflow curve. Finally, determine the largest of the vertical intercept between the tangential lines and the mass inflow curve. This largest vertical intercept represents the storage capacity required [18].

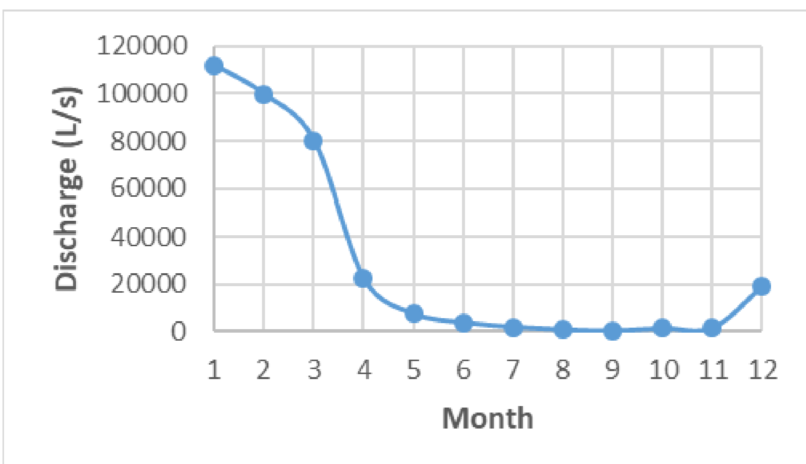

Fig. 6. Monthly average river discharge for Dwangwa river

2.2.2 Hydropower potential head

Google earth was used to estimate the hydraulic head on potential sites along the river. The computational tool in Google Earth provided the elevation profile along a section of a river drawn on the satellite view of the terrain of Dwangwa watershed. The resulting elevation profile shows the downstream elevation (H1) and upstream elevation (H2) as shown in Fig. 7. The upstream point indicates the probable flow intake point and downstream point indicates the probable turbine location. The downstream elevation was 672 m and the upstream elevation was 772.7 m. Thus, the estimated head was found to be 100.7 m. However, for design purposes, a head of 100 m was considered for hydropower generation. The horizontal distance between H1 and H2 was found to be 1410 m.

2.3 Economic Analysis

The RETScreen software was used to carry out economic prefeasibility analysis. RETScreen is a Clean Energy Management Software system for energy efficiency, renewable energy and cogeneration project feasibility analysis as well as ongoing energy performance analysis [19]. Several different types of projects have been studied with this tool in different parts of the world. For example, it was used in comparing landfill gas and waste incineration for power generation in Ghana, feasibility study of solar power plants in Iran and in the assessment of the prediction capacity of wind-electric generation models [20].

2.3.1 RETScreen input data

Dam construction increases daily energy output since the reservoir covers up for the dry season. Thus, the design flow for the hydropower was the annual average river discharge of 29.13 m^3/s with residual flow of 0.8739 m^3/s which is 3% of the design flow for environmental reasons which include aquatic plants and animals. Similarly, the gross head calculated using Google Earth will be used as RETScreen input data. The maximum head loss was set at 2%. Table 1 shows a summary of losses assumed for the design purpose. Dwangwa river has gross head of 100 m and design flow of 29.13 m^3/s hence Francis turbine was selected for the site using the chart in Fig. 8. Fig. 8 summaries turbine option for a particular site in relation to their head and flow rate.

Fig. 7. Dwangwa river elevation profile

Table 1. Summary of estimated losses for design purpose

Type of loss	Amount
Maximum hydraulic losses	3%
Miscellaneous losses	2%
Generator efficiency	95
System availability	96%

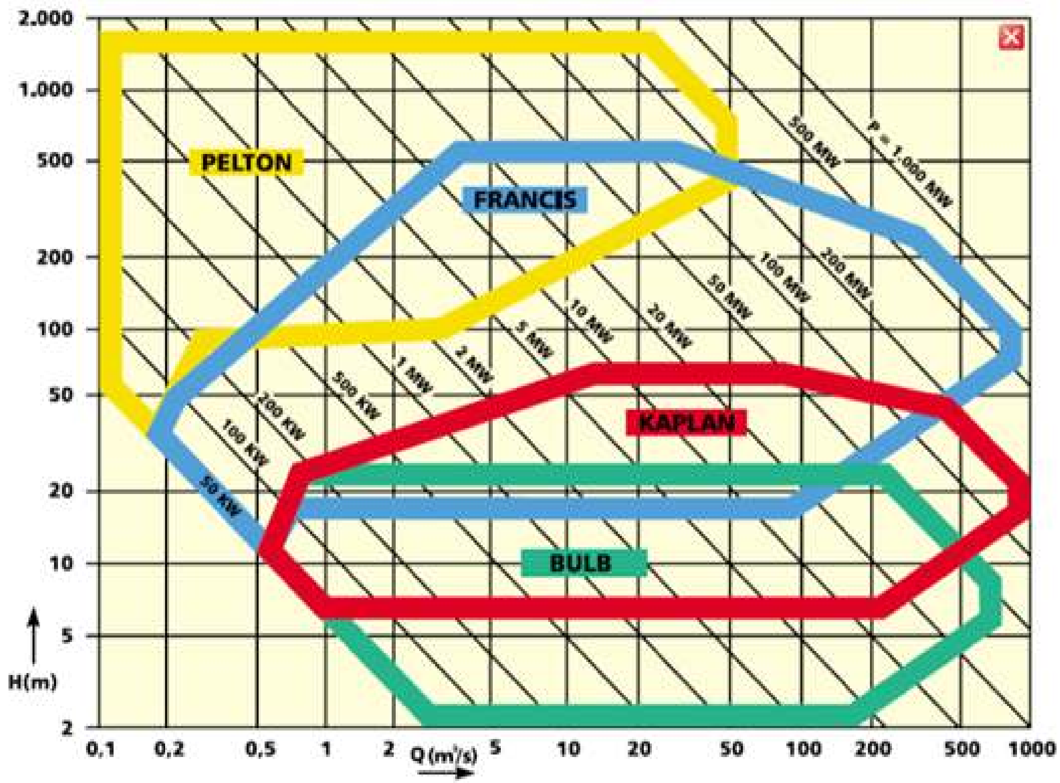

Fig. 8. Working areas of different turbine types [21]

2.3.2 Financial input data

Global analysis on cost of installation has been made on different hydropower projects. Africa has also been compared to the Global trends of installation costs. Thus, for this paper, cost of installation was considered to be 3500 $/kW. Annual operation and maintenance costs are often quoted as a percentage of the investment cost per kW per year. Typically values range from 1% to 4%. Thus, O&M cost is set at 3% of the initial cost which is 105 $/kW per year. The project life time is set at 20 years and inflation rate in Malawi was at 12.3% in 2018 while in 2020 was 11.4% hence 12.3% was considered [22]. According to the reserve bank of Malawi discount rate in Malawi in 2020, discount rate was set at 13.4% [23]. Table 2 gives the summary of cost related input data in RETScreen software. The flow chart in Fig. 9 shows the Methodological framework of reservoir capacity and hydropower potential employed in this study.

Fig. 9 presents the methodology framework of the reservoir capacity and hydropower potential. Monthly river discharge for Dwangwa river was processed in Excel to obtain the mass flow curve and to determine reservoir capacity. Google Earth was used to estimate the potential head. The outputs of Google Earth and Excel were simulated in RETScreen to perform economic analysis of the system.

Table 2. Cost related input summary

Input type	Units	Amount
Initial cost	$/kW	3500
O&M cost	$/kW/yr	105
Inflation rate	%	12.3
Discount rate	%	13.4
Life time	yr	20
Reinvestment rate	%	15

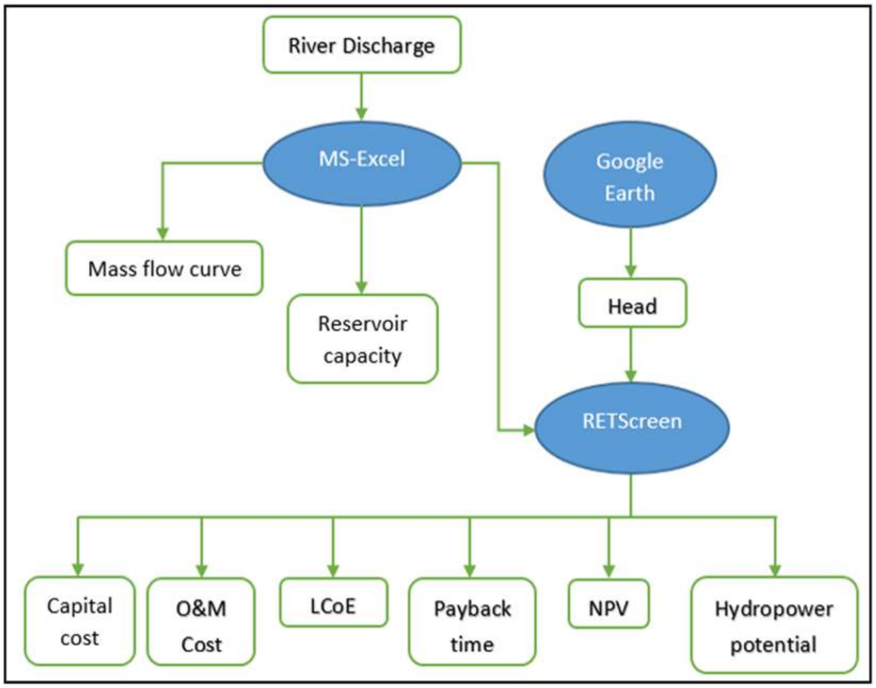

Fig. 9. Methodology framework of reservoir capacity and hydropower potential

3. RESULTS AND DISCUSSION

The gross potential head from the proposed reservoir to powerhouse was considered as 100 m. However, this head cannot be realized due to loses hence 2% head loss in the conveying has been considered. Similarly, 10% of total reservoir storage capacity is used for dead storage capacity of sediment trapping for the design period. Thus, the volume of dead storage capacity was 53.7 Mm^3. The mean monthly discharges for the entire year are summaries in Table 3. The average river discharge for 12 months was 29.129 m^3/s. Using mass curve shown in Fig. 10. the estimated reservoir storage capacity was 536.998 Mm^3. Analytically, the reservoir storage capacity can also be estimated from the monthly mean inflow as shown in Table 3. The estimated reservoir storage with design flow of 29.129 m^3/s resulted in increased capacity as compared to design flow for run-of-river of system with design flow of 0.159 m^3/s based on operating at 100% time of the year.

Table 3. Mean monthly inflow and proposed reservoir capacity

Month	Discharge (m^3/s)	Inflow (Mm^3)	Demand (m^3/s)	Demand (Mm^3)	Deficit (Mm^3)	Surplus (Mm^3)
January	112.03	300.049	29.129	76.552		223.496
February	99.79	250.038	29.129	76.552		173.485
March	80.11	214.574	29.129	76.552		138.022
April	22.18	57.485	29.129	76.552	19.067	
May	7.44	19.920	29.129	76.552	56.632	
June	3.71	9.606	29.129	76.552	66.947	
July	1.79	4.787	29.129	76.552	71.765	
August	0.67	1.797	29.129	76.552	74.755	
September	0.17	0.436	29.129	76.552	76.116	
October	1.27	3.397	29.129	76.552	73.156	
November	1.35	3.501	29.129	76.552	73.052	
December	19.06	51.044	29.129	76.552	25.509	
Total					**536.998**	**535.004**

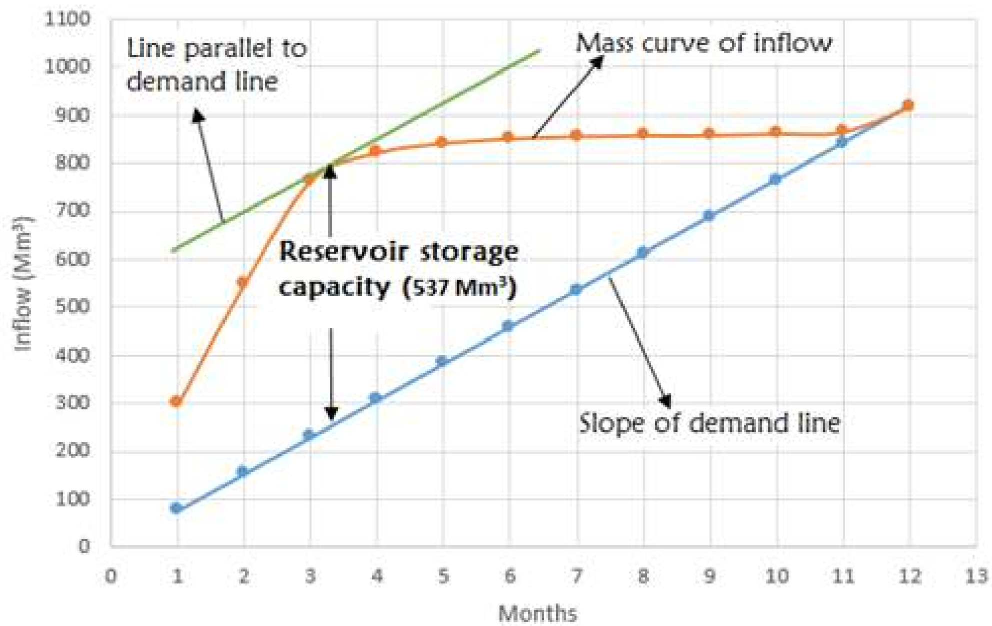

Fig. 10. Mass inflow curve diagram of the reservoir

Based on the estimated reservoir capacity and the design flow, RETScreen software was used to determine the hydropower potential which was calculated as 22.70 MW. This took into account all the possible losses. The initial capital cost of the project was calculated as $ 79,434,044 while annual operation and maintenance cost for the project was calculated as $ 2,383,021. The levelized cost of energy was calculated as 0.099 $/kWh with simple payback time of 4.8 years. Table 4 gives the summary of financial viability of the project. The cumulative cash flow for the project in life time of 20 years showed that the project has relatively small payback period. Fig. 11 shows the cumulative cash flow for the project.

According to [24], the end user tariff in Malawi is around MK115 per kWh ($0.155 per kWh). This implies that the cost of energy for the proposed system was relatively lower, making electricity affordable to the people. Thus, this paper can be part of the solution for the persistent power outages and also overcomes the serious power problems during dry season in Malawi.

Considering run-of-river with 100% availability of power, Dwangwa has a potential of 140 kW which was very small as compared to the inclusion of a dam. Bitar et al. [25] carried out technical and economic analysis of a mini hydropower plant in Syria and they found out that the cost of energy was 0.051 $/kWh with recovery time of investment of 14 years. Gagliano et al. [26] made similar analysis using simulation tool, called “MadoWatt” and found the electricity energy tariff of 0.154 €/kWh with simple payback period of 3 years. RETScreen software was employed in a grid-connected small hydropower plant and the estimated energy production cost was 0.05€/kWh with a repayment period of 12 years [27].

Table 4. Summary of financial viability of the project

	Units	Amount
Initial capital cost	$	79,434,044
O&M cost	$/yr	2,383,021
Cost of Energy	$/kWh	0.099
Net Present Value (NPV)	$	17,382,770
Annual life cycle savings	$/yr	2,777,097
Simple Payback time	yr	4.8
Benefit-cost ratio	-	1.2

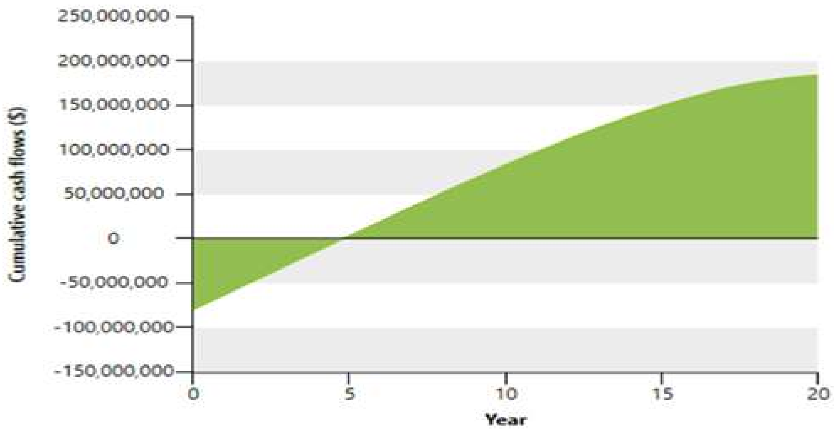

Fig. 11. Cumulative cash flow for the project

In [28], Girma used HOMER and RETScreen software for a hydropower in the Kulfo River and it was found to be technically and economically feasible with total net present cost of $ 13,345,150, cost of energy 0.028 $/kWh, simple payback period of 12.4 years, and internal rate of return 12.9%. Elbatran et al. [29] stated that the fluctuation of the water flow can be reduced by the reservoir. However, Landscape and the nature of sites are the main factors which decide the type and design of reservoirs and in many countries around world are surrounded river valleys where the reservoir is an artificial lake. These papers have demonstrated that the results found from this study match with other systems and support data.

4. CONCLUSION

In this study, a reservoir based hydropower system was designed which should be connected to the grid for distribution. The main objective was to ensure reliability of electricity due to reservoir storage and also system's development affordability. However, the sizing and the optimal operation of this hydropower plant must be correctly done in order to ensure maximum benefits. Hence, mass curve method and RETScreen software was used for simulation and optimisation of the proposed system. The mass curve analysis found the optimum size of the reservoir for reliable supply of electricity while RETScreen demonstrated the economic justification of the system. In summary, the estimated reservoir storage capacity was found to be 536.998 Mm^3 with maximum possible design flow of 29.129 m^3/s as compared to design flow for run-of-river of system with design flow of 0.159 m^3/s based on operating at 100% time of the year. With the aid of RETScreen software, the project's initial capital cost was found to be $ 79,434,044 and cost of energy of 0.099 $/kWh. The project's lifetime of 20 years has payback period of 4.8 years. On the other hand, the cost of energy for the proposed system was relatively lower as compared to cost of energy on the grid.

This research has demonstrated that reservoir based hydropower system can be part of the solution for the persistent power outages and also overcomes the serious power problems during dry season in Malawi. Therefore, government through incentives and policies should ensure maximum utilisation of small hydropower plants in order to increase electrification rate and reliability. Additionally, construction of this power plant would give job opportunity to the people in community and also ensure constant business activities.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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