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Improving Discharge Prediction for Poorly Gauged Hydropower Potential Sites – A Case Study of Mabula Kapi Site

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Abstract:- According to estimates from previous energy studies, Zambia has a hydropower generation potential of more than 6,000 MW. Development of small hydropower plants which are widely considered to be renewable energy technology will help to foster sustainable development as well as increase access to electricity in the country. However, most of the small hydropower potential sites which are located in rural or remote areas are poorly gauged, lacking adequate streamflow and/or rainfall data required for hydropower planning and design. As a result, a number of sites are crudely planned, merely using hydrological data transposed from donor catchments, leaving uncertainties about project bankability. Mabula Kapi site located on Kaombe River, in Serenje District for example was initially investigated using hydrological data from an adjacent catchment on Lusiwasi River, which was considered to be hydrologicaly similar. However, the presence of a natural lake on Lusiwasi catchment raised uncertainties about the accuracy of the transposed hydrological data.In this study, satellite rainfall point data known as the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), which has adequate time series was adopted as one of the modeling inputs. Statistical analysis was done to compare the two data sets and the results indicated a good correlation. Hydrologic modeling, including calibration was done using South African open-source software known as the WRSM2000/PITMAN model and a 30-year discharge time series was simulated for Mabula Kapi site. The derived time series were used to estimate the installed capacity (8 MW) and annual energy yield (38 GWh) for the hydropower site. It is recommended that satellite rainfall point data such as CHIRPS be considered as alternative input data in hydrologic modelling of poorly gauged hydropower sites in Zambia. Such data can be useful in extending or deriving adequate discharge time series, required for design of water resources infrastructure projects.

Keywords:- *CHIRPS, Hydropower, Modelling, Rainfall, Streamflow.*

I. INTRODUCTION

- *Background*

According to estimates from previous energy studies, Zambia has a hydropower generation potential of more than 6,000 MW (Tokyo Electric Power Company, 2008). Most of the hydropower potential sites are in rural areas and their capacities range from small to large. Development of small hydropower plants which are widely considered to be renewable energy technology will help to foster sustainable development as well as increase access to electricity in the country. In 2015, only 31% of households had access to electricity in Zambia. The electrification rates for rural and urban households were estimated to be 4.4% and 67.3% respectively (Republic of Zambia, 2015)

The liberalization of the power sector in Zambia has opened opportunities for private entities to invest and participate in energy development in the country. As such, Kafue Gorge Regional Training Centre (KGRTC) intends to develop Mabula Kapi hydropower site. The site is located on Kaombe River, in the Central Province of Zambia on latitude 13º 19’ 28.02” and Longitude 30º 47’ 14.02” (WGS84 coordinate system). Mabula Kapi site was handed over to KGRTC by ZESCO Limited, a state-owned power utility in Zambia. ZESCO had completed prefeasibility studies for Mabula Kapi site in 2018, recommending an installed capacity of 7.4 MW and an annual energy output of 34 GWh.

KGRTC installed a hydrological gauging station at the site, known as Manangwa, in September 2019, for collection of onsite streamflow data at Mabula Kapi site. As part of full feasibility studies for the site, KGRTC engaged the principal investigator to undertake a study to improve discharge prediction for Mabula Kapi site. This paper highlights the methods used to accurately predict discharge at Mabula Kapi hydropower site.

- *Hydrological Uncertainties From Previous Studies*

The main input parameters considered in estimating capacity of hydropower plants and energy output are flow rate (discharge) and hydraulic head. Sufficient hydrological streamflow data are needed to select a hydropower site and to develop the optimum plant design. Due to lack of onsite data or sufficient streamflow record at Mabula Kapi site, the energy modelling during prefeasibility studies was based on transposition of hydrological data from an adjacent catchment on Lusiwasi River, which was considered to be hydrologically similar. However, the catchment area-ratio method which was applied is a simple approximation because catchment characteristics between donor and target catchments rarely match perfectly. The method works best when the donor gauging station is close to the respective intake (Nruthya & Srinivas, 2015). This method does not consider the influences of vegetation, soil type, and geology on the flow in the investigated area. Use of this method may leave hydrological uncertainties which present a risk to hydropower development (FICHTNER, 2015).

For Mabula Kapi site, the presence of a natural lake on the Lusiwasi donor catchment raised uncertainties about similarities in the drainage network and therefore the accuracy of transposing hydrological data (See Figure 1).

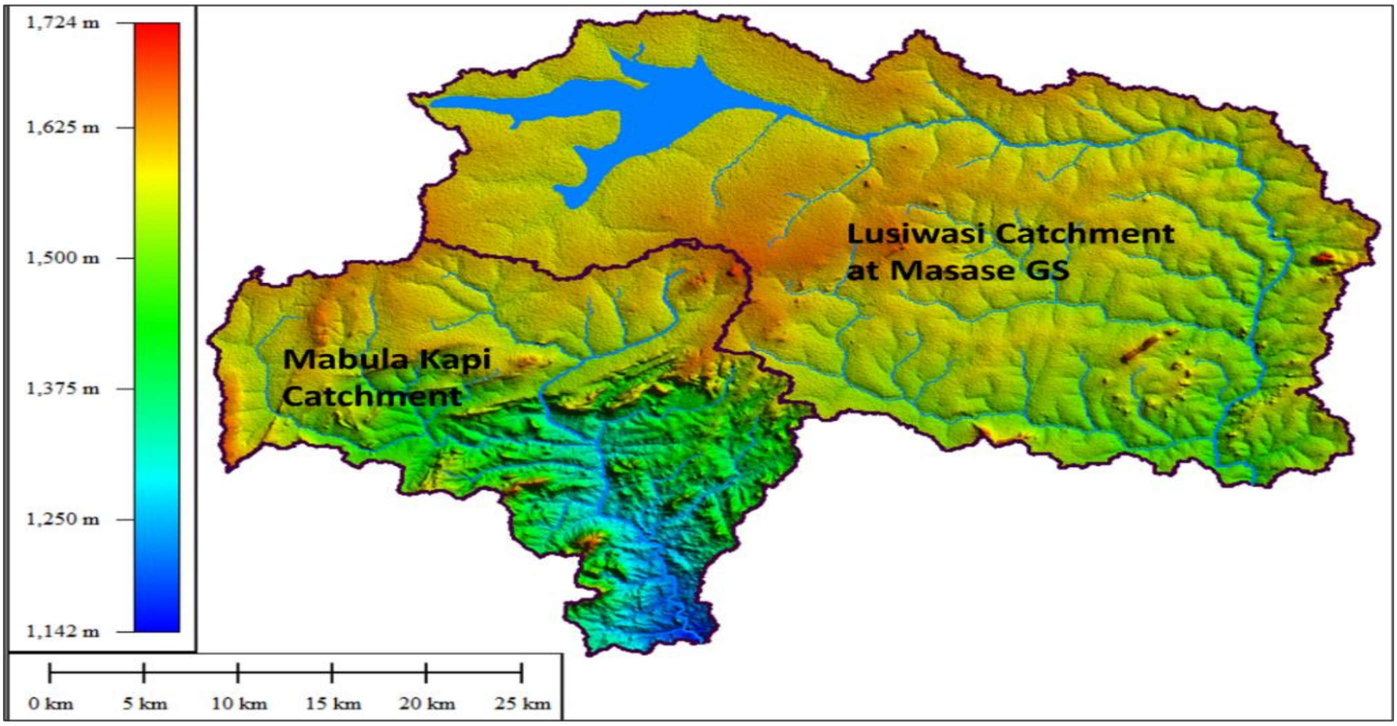

Fig 1 Proximity of Mabula Kapi and Lusiwasi Catchments

The catchment area-ratio method may be sufficient for a prefeasibility study. However, when development of a hydropower station reaches the feasibility and design phase, hydrology should be verified, by other methods and where possible, by installing a permanent gauge at the future water-intake location (FICHTNER, 2015).

The gauging station installed on site by KGRTC in 2019 provided an opportunity to verify and firmly establish discharge time series required for the design of Mabula Kapi HPP with a view to minimize hydrological uncertainties. However, a short-term time series collected on site would be inadequate. Typically, hydrological data for at least 15 years are required and should include not only the flow rate but also the annual distribution (FICHTNER, 2015). A one-time measurement of instantaneous discharge in a stream has little value (ESHA, 2004).

II. DICHARGE PREDICTION METHODS

Various methods and techniques can be applied to predict streamflow at poorly gauged sites. These vary from simple methods that can only be used for preliminary estimates of power potential to complex methods that may be used to establish technical and financial viability. Commonly used methods include Mean Annual Flow method, Catchment Area Ratio method, Relationship between Specific runoff and Altitude method, Simultaneous flow measurement method and Rainfall-Runoff Modelling.

Broadly speaking, both statistical and hydrologic modelling can be used for prediction of discharge at Mabula Kapi Site. However, the selection of the specific methods to use depends on several factors. For Mabula Kapi site, the rainfall-runoff modelling method was selected as the best method for prediction of discharge.

➢ *The Other Commonly Used Methods Discussed Above were not Selected for Accurate Prediction of Discharge at Mabula Kapi Site Due to the Following Reasons:*

- The Mean Annual Flow method – While this method gives an idea of a river's power potential, it does not provide a firmer knowledge of the river's flow regime as obtained from a flow duration curve.
- Catchment Area Ratio method – This method does not consider several factors including site geology, soil type, land use and vegetation which have a significant influence on the unique flow characteristics.
- Relationship between Specific runoff and Altitude method – This method requires use of data from several gauging stations and profiles in the area to generate a regional function. The scarcity of data in the Mabula Kapi region presents a challenge for application of this method.

- Simultaneous flow measurement method – In this method, a new gauging station at a point of interest (intake location or its vicinity) along a river may be compared with an existing gauging station in a nearby catchment with similar hydrological and meteorological conditions. The simultaneous flow measurement method in this case was not selected due to a major difference in the drainage network between the Lusiwasi and Mabula catchment as shown in Figure 1.

III. RAINFALL-RUNOFF MODEL - PITMAN

A. Input Data

Following careful and extensive review of available open-source hydrologic modelling software, the principal investigator selected a model known as the WRSM/PITMAN model for rainfall-runoff modelling of the Mabula Kapi catchment. The model was found suitable due to input data limitations and project budget. It can create a conceptual representation of relevant processes and storages in a hydrologic catchment such as interception, soil moisture capacity, groundwater flow, wetlands, lakes, and attenuation in channel systems.

➢ *The Main Inputs and Drivers of Streamflow in the Runoff Module of the Software are:*

- Catchment area
- Rainfall
- Pan evaporation
- Calibration parameters

Rainfall and evaporation data are required as input in hydrological modelling of Mabula Kapi catchment. For calibration of the rainfall-runoff model, the rainfall time series to be used in modelling should correspond to the measured discharge time series at Mangawa streamflow gauging station. The updated streamflow record runs from September 6, 2019 to April 30, 2022. Unfortunately, there is no rainfall station within Mabula Kapi catchment to provide on-site rain fall input data for modelling. The nearest weather stations operated by the Zambia Meteorological Department (ZMD) are in Kabwe, Serenje, Mkushi and Mpika Districts as shown in Figure 2 below.

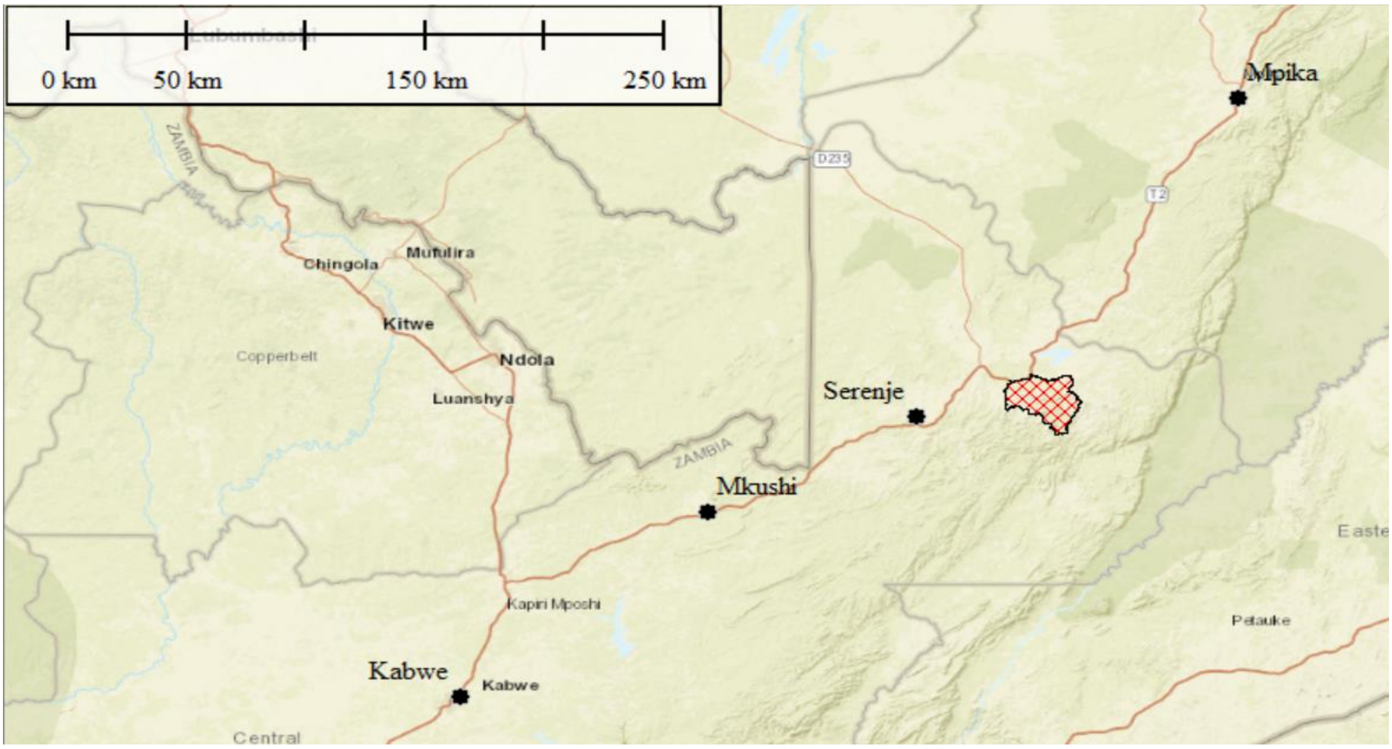

Fig 2 Proximity of ZMD Rainfall stations to Mabula Kapi catchment

Data from these nearby stations can be used to calculate the areal precipitation over the Mabula Kapi catchment. However, the data collected contain gaps and do not have time series for the period spanning from September 6, 2019 to April 30, 2022 which is required for calibration of the model. Table 1 shows the rainfall time series collected for the four rainfall stations.

Table 1 Rainfall Times Series For Local Stations

Station Location	Data period	% Missing data (gaps)
Serenje	1981 - 2017	12 %
Mkushi	1993 - 2015	2.9 %
Mpika	1981 - 2012	0%
Kabwe	1981 - 2015	38%

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A decline in the number of rainfall stations has motivated scientific studies to understand the extent to which satellite data can fill the gap left by the availability of rainfall stations. In recent years, studies have been conducted to compare satellite data with measured data from rainfall stations. A 2021 study in South Africa compared rainfall data sourced by the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) satellite database with data from several rainfall stations. The analyses yielded good results overall, except in the winter rainfall region, where CHIRPS performed poorly. The study concluded that CHIRPS would have a role to play in future water resources studies (Pitman & Bailey, 2021).

CHIRPS data has been considered and analysed for possible use on the Mabula Kapi catchment. CHIRPS is downloadable from a google climate engine website (Desert Research Institute, 2021). Rainfall data was downloaded as point data for Serenje, Mkushi, Kabwe Mpika using coordinates for the local meteorological stations from the google climate engine facility. Average point rainfall over Mabula Kapi catchment was also downloaded to ascertain its suitability for modelling. Both data sets span from span from January 1, 1981 to September 30, 2021.

To determine the suitability of CHIRPS data, a comparison has been made between the four rainfall stations near Mabula Kapi site and CHIRPS point data downloaded at these station locations. A comparison of daily time-steps showed a very poor correlation. Nevertheless, a monthly time-step comparison yielded a good association. Figures 3, 4, 5 and 6 below are presentations of scatter plots showing the association between the two sets of data for Serenje, Kabwe, Mkushi and Mpika respectively.

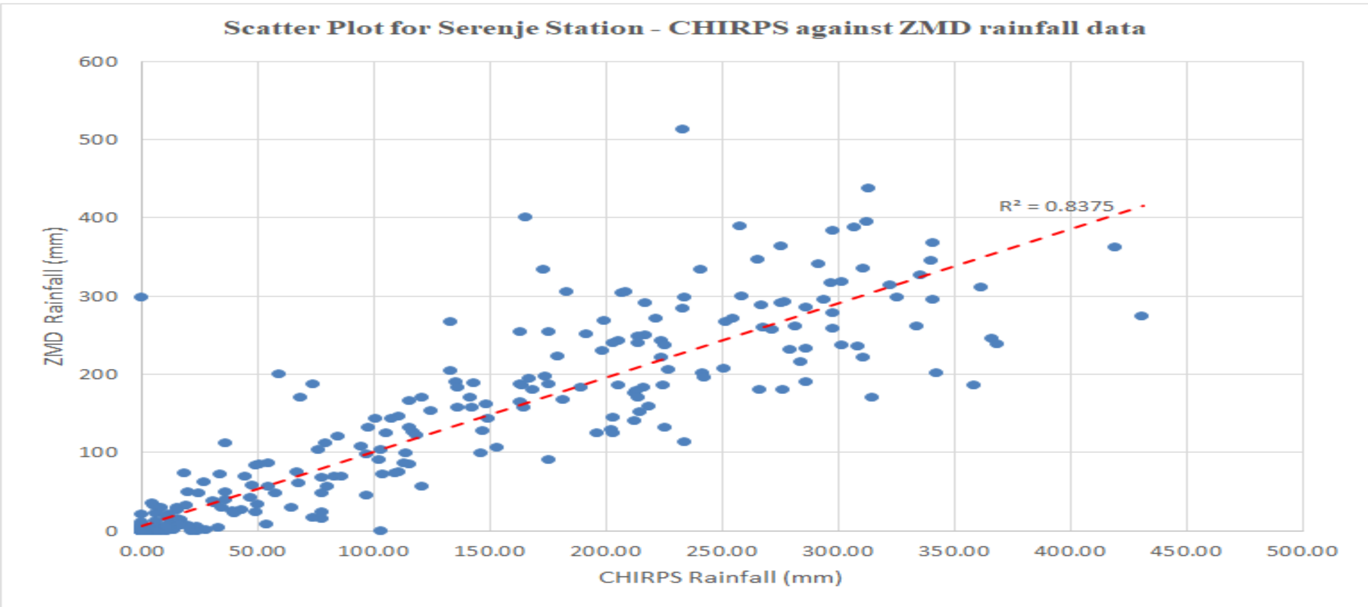

Fig 3 Scatter Plot For Serenje Rainfall Against CHIRPS Data (1981 -2017)

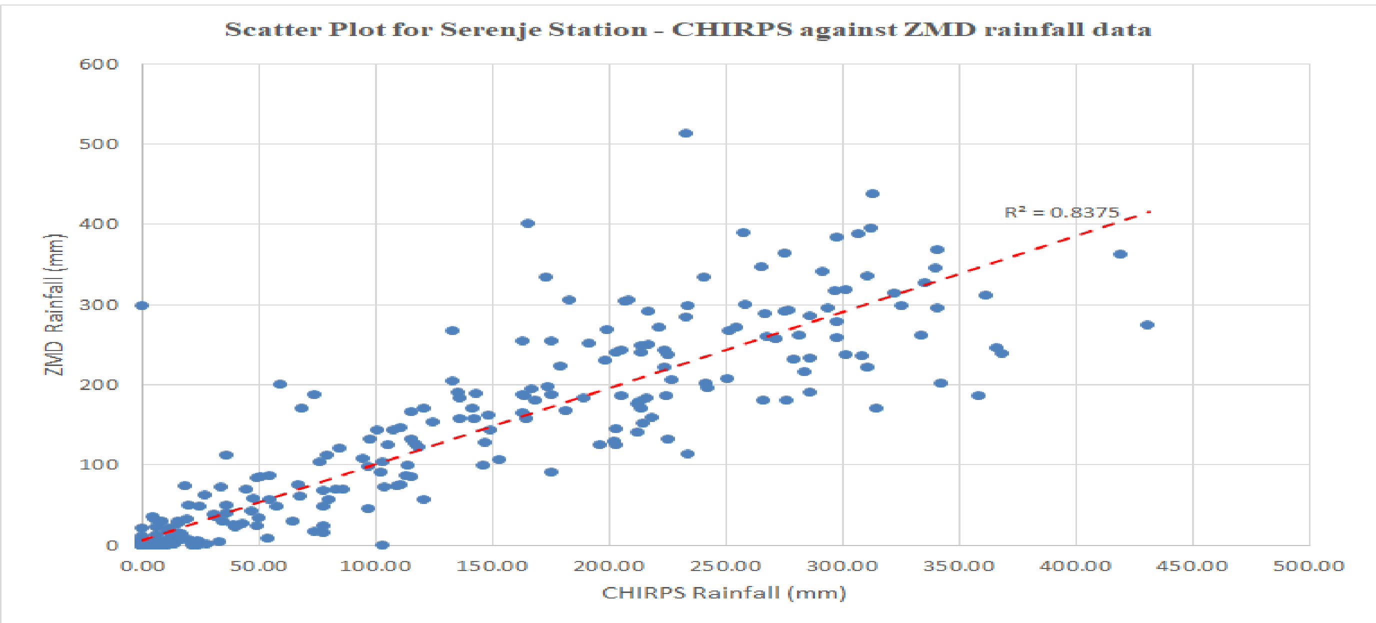

Fig 4 Scatter Plot for Kabwe Rainfall Against CHIRPS Data (1981 -2015)

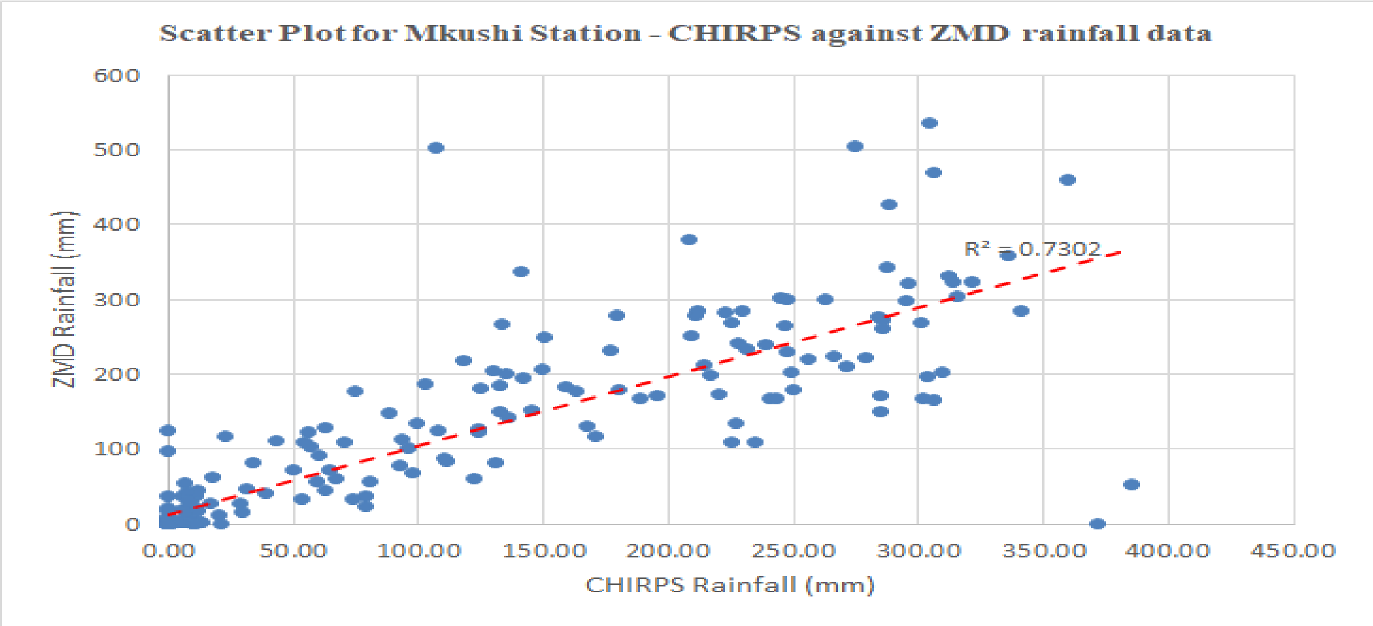

Fig 5 Scatter Plot for Mkushi Rainfall Against CHIRPS Data (1993 -2015)

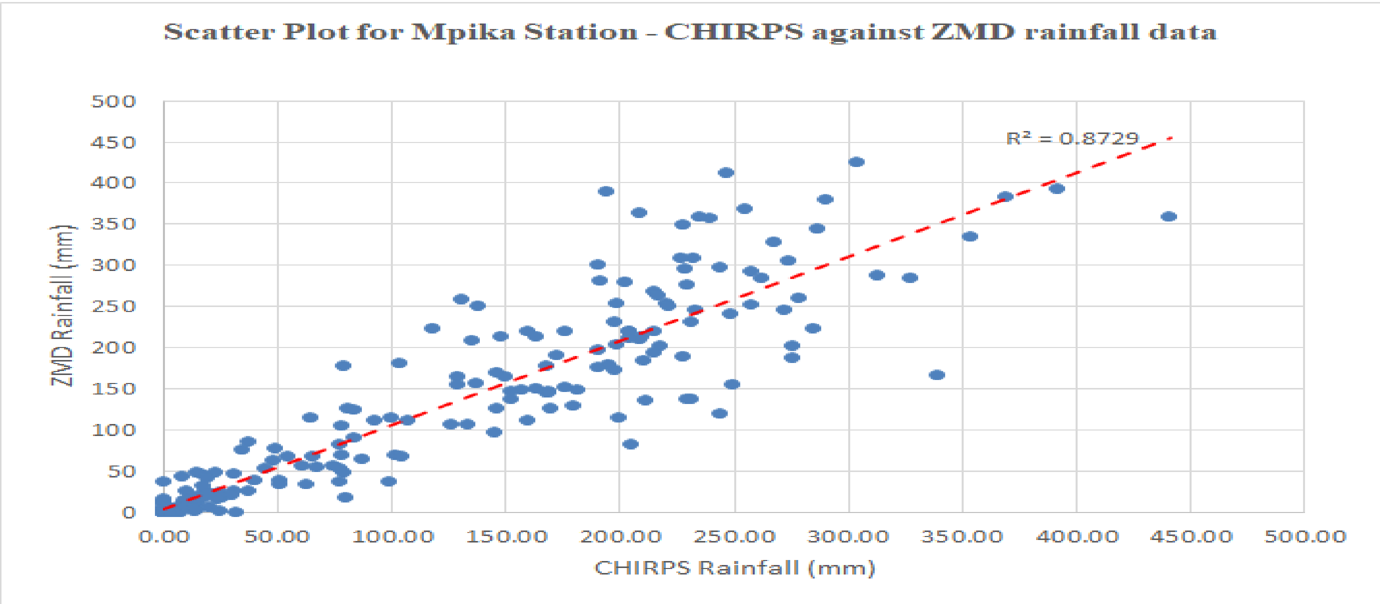

Fig 6 Scatter Plot for Mpika Rainfall Against CHIRPS Data (1981 -2012)

Statistical validating parameters used to compare the gauge data and CHIRPS data indicate a close relationship. Correlation coefficients for all sites indicate a very close association. The bias, the mean error and the mean absolute error are very low for all the sites as shown in Table 2

Table 2 Validation Statistics Results between Local Stations and CHIRPS Rainfall

Station Name	Correlation Coefficient	Mean Error	Bias	Mean Absolute Error
Serenje	0.91	-2.13	0.96	28.23
Kabwe	0.95	-0.45	1.11	17.91
Mkushi	0.85	-5.66	0.93	30.31
Mpika	0.93	-2.67	0.96	21.76

The close association between the point rainfall data at Serenje, Mkushi, Kabwe and Mpika justify the use of CHIRPS data as an input to rainfall-runoff modelling on Mabula Kapi site. The monthly time-step CHIRPS rainfall data is therefore recommended to be used in the PITMAN model for prediction of discharge.

B. Modelling

As previously stated, the Pitman Model was selected for hydrologic modelling on Mabula Kapi project. The model requires substantial manipulation of the input data, to arrange it in the format required in the model. The input data that was added to the model is listed the Table 3 below.

Table 3 Input Data for PITMAN Model

S/N	Input Data Type	Description
1	Catchment area	Delineated using GIS software – 511 km2
2	Rainfall	CHIRPS time series from October 1981 to September 2021 (Mpika station, Serenje station and Catchment average)
3	Pan evaporation	Monthly averages from 1930 to 1995 (JICA, 1995)
4	Observed discharge	Time series from October 2019 to September 2021

CHIRPS point data downloaded as average rainfall over the catchment seemed to overestimate the rainfall over the catchment when compared with an isohyet map produced by the Tropical Applications of Meteorology using satellite and ground-based observations (TAMSAT) from 1983 to 2012. Thus, caution was applied when using it in modelling of the catchment. A decision was made to carry out independent simulations using CHIRPS point rainfall (for Serenje and Mpika stations) and the average catchment rainfall point data over Mabula Kapi catchment. The data set that would yield good calibration results in the model would be adopted for simulations and extension of time series at Manangwa gauging station.

A model network was created for Mabula Kapi with appropriate modules for the catchment. The schematic network diagram in Figure 7 below shows a simple representation of the model for Mabula Kapi catchment on Kaombe River. It shows the catchment area (runoff module), river reaches (route) and a stream flow gauge.

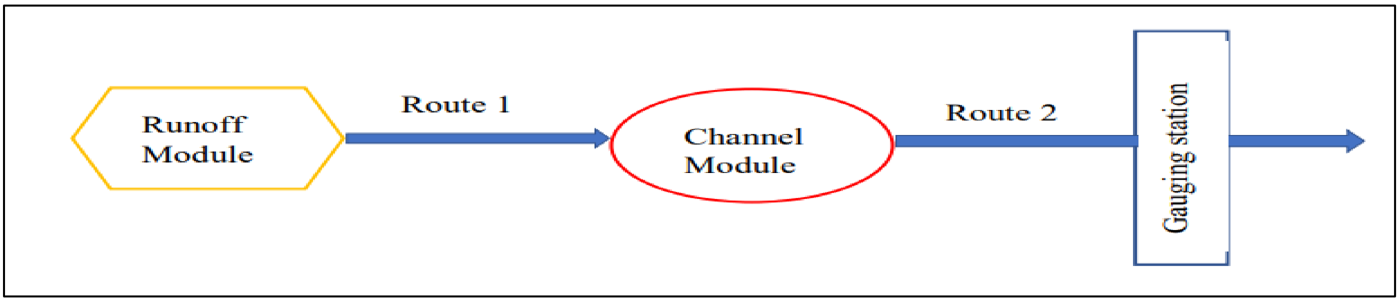

Fig 7 Network Diagram for Mabula Kapi Model

Upon completion of the model setup, a first simulation was initiated in the PITMAN model with the default parameters which govern the amount, rate and timing of the runoff generated. Thereafter, the default parameters were changed with good judgement, based on knowledge of catchment characteristics, to match or calibrate the simulated and observed flows as closely as possible. Observed flows used were based on data collected from the newly installed gauging station known as Manangwa gauging station. Observed flows running from October 2019 to September 2021 made possible the calibration of the Mabula Kapi PITMAN model.

Selecting the correct parameters when calibrating the model was an iterative process. Most of the parameters are not quantifiable, and the exact values are unknown to the user at the start of the calibration process. The calibration parameters are chosen based on the fit between observed and simulated flows, rather than a predetermined parameter value which determines the flows. Therefore, the (fit of) flows determine the parameters, and it is not a case of the 'known' parameters determining the flows. It is consequently not a case of choosing a 'correct' parameter for the catchment at the outset, generating the 'correct' simulated flows using the 'correct' calibration parameter. It is rather a case of iteratively changing the parameters which drive the flows to be as close as possible to the observed data. The simulated flows are a function of these parameters; therefore, the result of this process is the calibration parameters, as they are the factors which dictate the simulated flows (EDF-GIBB, 2019).

Each time a parameter was changed the model was re-run and the results re-valuated. The results were assessed by means of the numerical statistics and the graphical results generated. This process was carried out for the Mabula Kapi catchment and repeated after each parameter change, until the simulated flows were as similar as possible to the observed flows for the gauging station. Simulations were done independently using CHIRPS rainfall time series point data for Serenje, Mpika and Mabula Kapi catchment average rainfall point data. The average catchment rainfall point data for Mabula Kapi catchment and the point data at Serenje station could not yield satisfactory calibration results, despite multiple simulation runs.

On the other hand, simulations using CHIRPS point data at Mpika station were satisfactory and yielded reasonable results. The final runoff module calibration parameters used to arrive at a reasonable fit are shown in Figure 8 below.

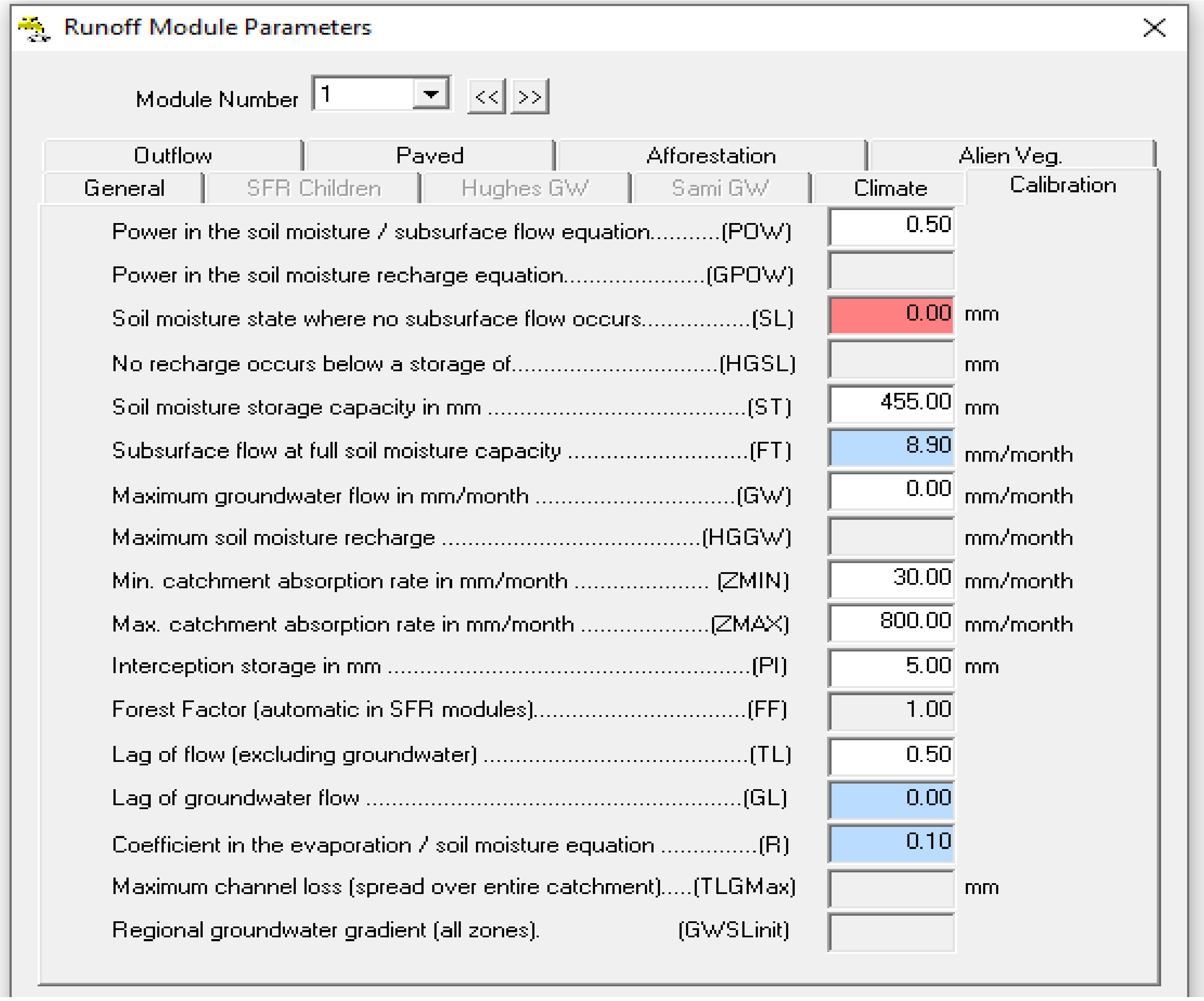

Fig 8 Runoff Module Parameters Used to Achieve Reasonable Fit between Observed and Simulated Flows

Once all the data has been entered into the various modules and routes, the graphs and statistics are used to check on the calibration between simulated and observed (known) streamflow and storage. Streamflow can be checked at any route where there are observed stream flows. There are no firm criteria as to what constitutes a "good fit" but one can use the following guidelines (Pitman, et al., 2015):

- Error in MAR and mean (log): < 4%
- Error in std. dev (natural & log): < 6%
- Error in seasonal index:< 8%

IV. RESULTS

The final calibration results statistics for Mabula Kapi catchment indicating the closeness of fit between simulated flows and observed flows are presented in Table 4.

Table 4 Statistics (Simulated Vs Observed)

S/N	Statistic	Observed	Simulated	Percentage difference	Remarks
1	Mean Annual Runoff (MAR)	70.63	71.02	0.55%	Good fit
2	Mean (Log)	1.83	1.83	0%	Good fit
3	Standard Deviation	30.90	31.05	0.48%	Good fit
4	Log Standard Deviation	0.20	0.20	0%	Good fit
5	Seasonal Index	40.11	39.46	1.62%	Good fit

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The annual hydrograph for the final calibration is shown in Figure 9 below. The fit for observed versus simulated flows for Manangwa gauging station is considered reasonable. However, it is evident that for very high flows, the model is unable to accurately simulate these closely. However, the troughs are very well simulated, as are the mean monthly flows which indicate the distribution of rainfall over the year.

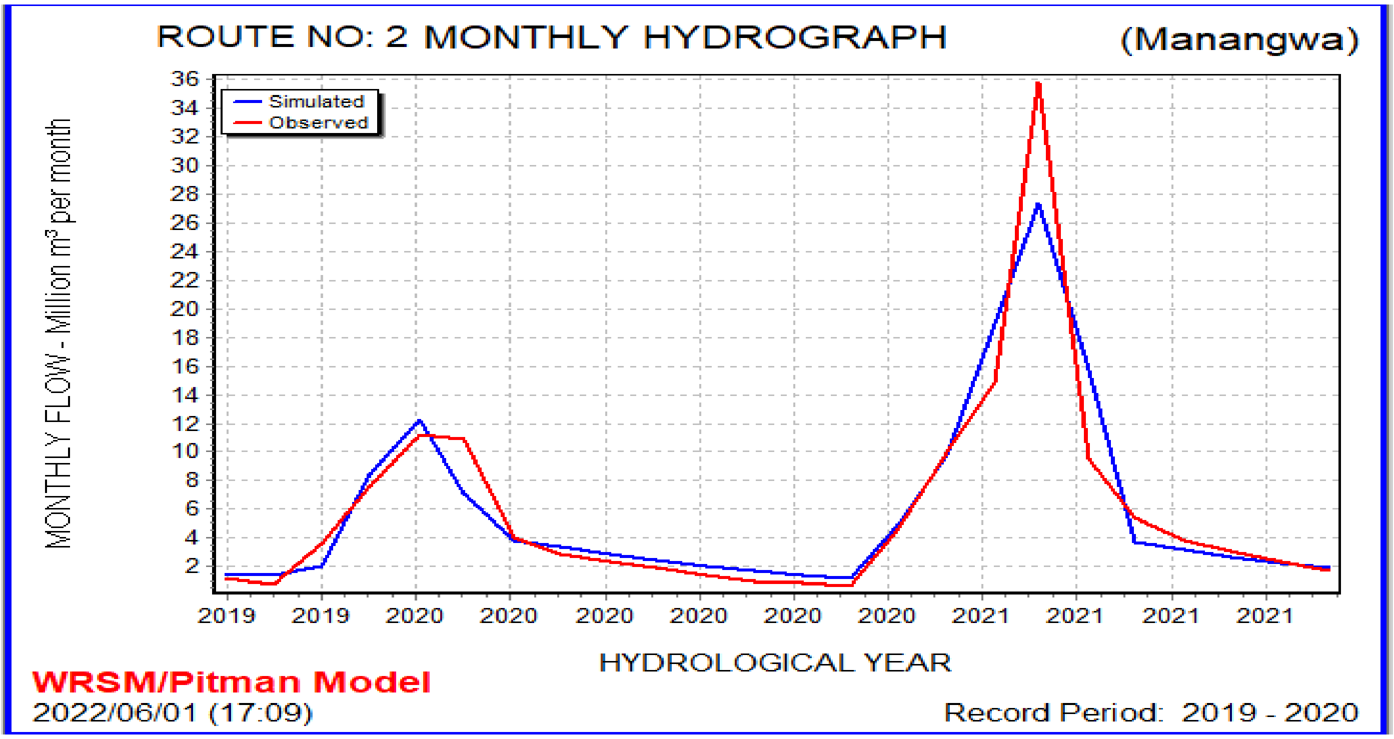

Fig 9 Annual Hydrograph For Manangwa Gauging Station (Simulated Vs Observed)

The coefficient of determination r^2, was calculated using Microsoft excel as 0.885 while the Nash-Sutcliffe coefficient of efficiency was computed as 0.882. This shows a good fit as both figures are close to 1. Figure 10 below shows the scatter plot between observed and simulated flows in MS excel.

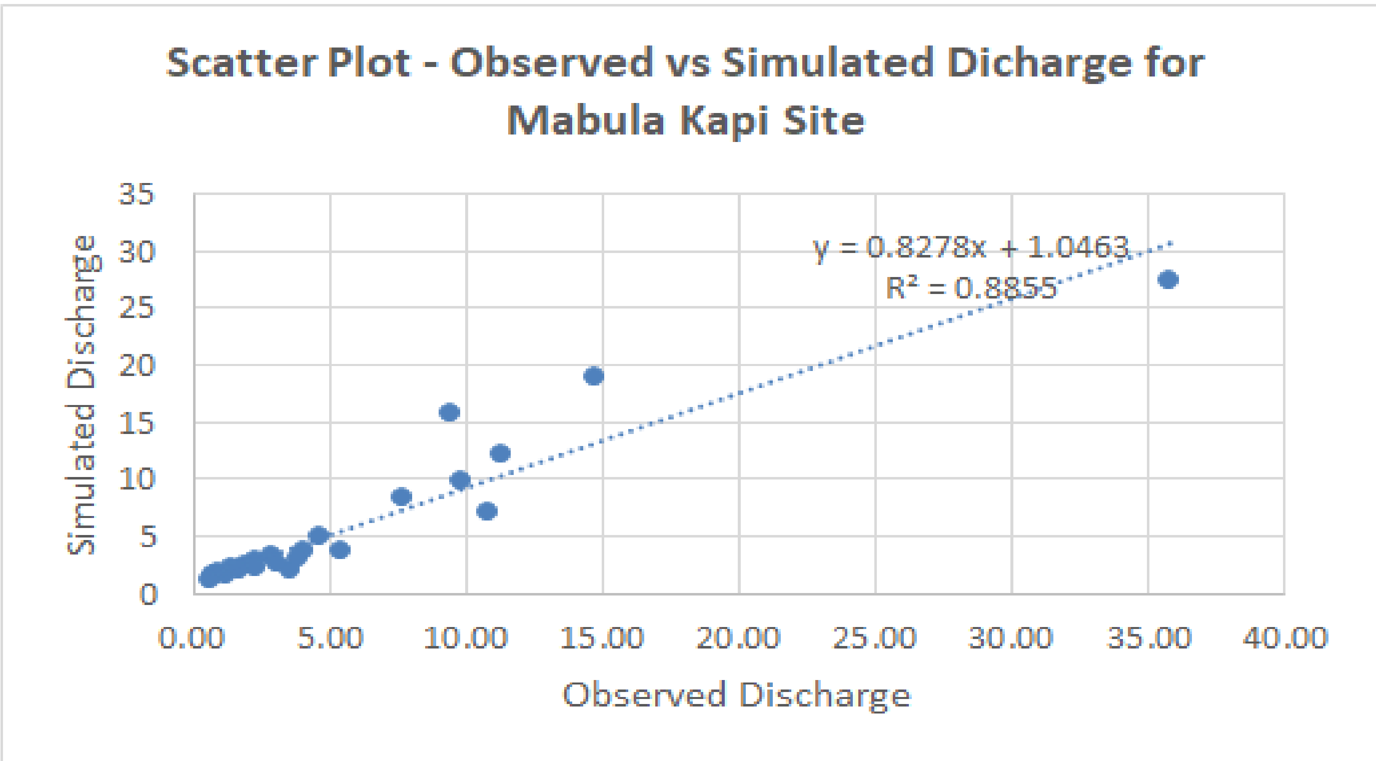

Fig 10 Scatter Plot - Observed Vs Simulated Flows

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The PITMAN model has therefore been used to simulate runoff and to extend the discharge time series at Manangwa gaging station. A 30-year long discharge time series has accurately been obtained for Manangwa gauging station, running from October 1991 to September 2021. The time series are plotted on the annual hydrograph shown in Figure 11.

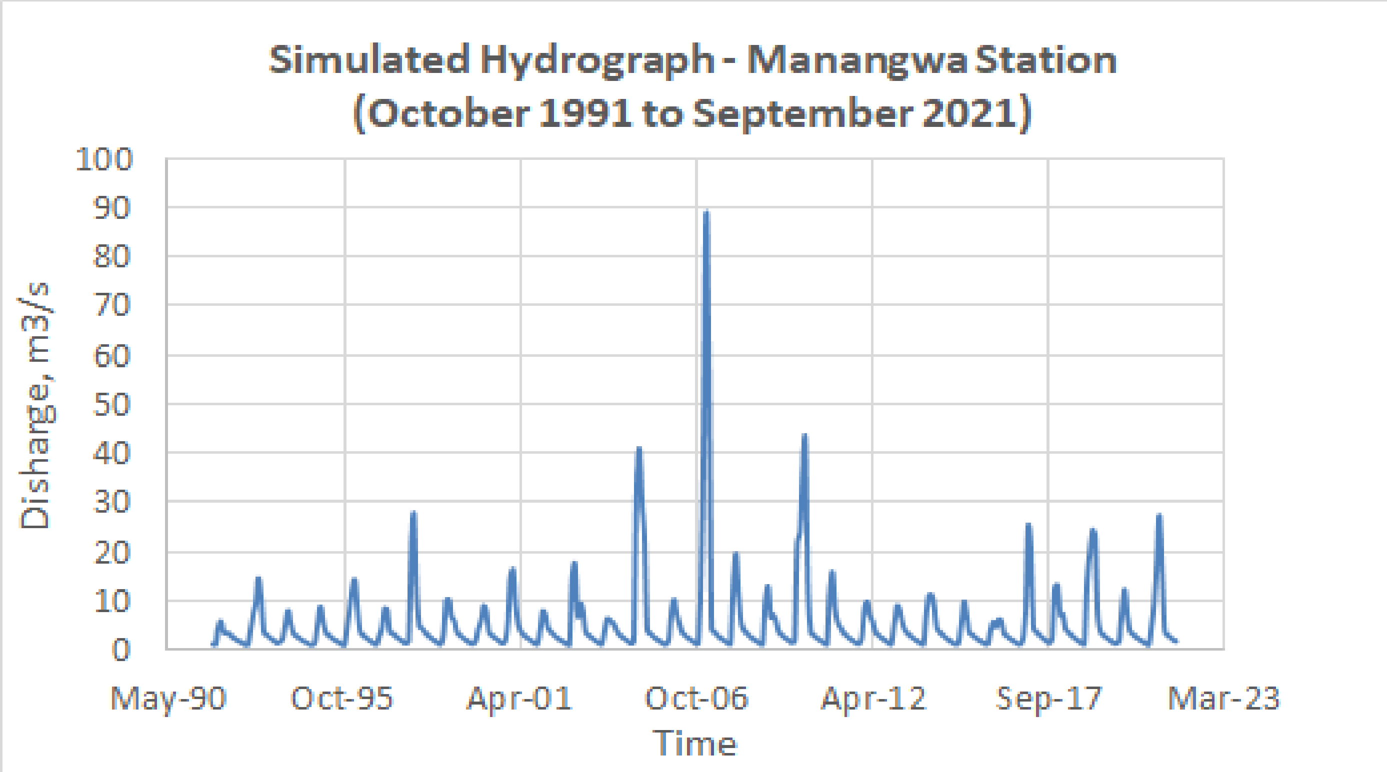

Fig 11 Simulated Hydrograph – 30-Year Time Series

Table 5 below shows a comparison of the parameters and results between the previous prefeasibility study and the current study. The comparison indicates an improvement in the prediction of design flood, residual flow and the design discharge. The increase in the design discharge leads to a corresponding improvement in installed capacity and annual energy.

Table 5 Comparison of Results between Previous and Current Study

S/N	Description	Previous study (Prefeasibility)	Current study	Remarks
1	Gross head	203.38m	203.38m	
2	Turbine type/Number of turbines	Pelton/3	Pelton/3	
3	Residual (e) flow	0.20 m^3/s (5% of mean flow)	0.58 m^3/s (10% of mean flow)	Improvement
4	Firm flow	90% Probability exceedance	90% Probability exceedance	
5	Maximum hydraulic losses	4%	4%	
6	Turbine efficiency	88%	88%	
7	Generator efficiency	97%	97%	
8	Plant availability	90%	90%	
9	Time series duration	9 years	30 years	
10	Design flood	59 m^3/s	120 m^3/s	Improvement
10	Design Discharge (30% Probability of exceedance)	4.5 m^3/s	5.0 m^3/s	Improvement
11	Capacity factor	52%	52.7%	
12	Installed capacity	7.4 MW	8.2 MW	Improvement
13	Annual Energy	34 GWh	38 GWh	Improvement

V. CONCLUSION

A more accurate design discharge time series for Mabula Kapi catchment site has been predicted by using the rainfall-runoff modelling method, selected from a review of several statistical and empirical discharge prediction methods. The principal investigator selected a computer-based rainfall-runoff model known as the PITMAN model to perform modelling and prediction of discharge for the Mabula Kapi catchment. The PITMAN model can create a conceptual representation of relevant processes and storages in a hydrologic catchment such as interception, soil moisture capacity, groundwater flow, wetlands, lakes, and attenuation in channel systems.

Data collected from a newly installed gauging station known as Manangwa gauging station made possible the calibration of the Mabula Kapi PITMAN model. Observed discharge ran from October 2019 to September 2021. Since this short-range time series would not be adequate for hydropower energy modelling, which typically requires a minimum period of 15 years, the PITMAN model was used to simulate longer time series. This was done by calibrating the model through the matching of the observed discharge with the simulated discharge time series. The simulated time series which ran from September 1981 to October 2021 were derived using satellite-based CHIRPS rainfall data. This is because CHIRPS data was found to have a good correlation with ground measured data from meteorological stations located in the vicinity of Mabula Kapi catchment.

Based on the simulated longer discharge time series from the model, the design discharge and the design flood for the proposed Mabula Kapi HPP were estimated as 5 m^3/s and 108 m^3/s respectively. Using the design discharge, the Installed Capacity was computed to be 8.2 MW and the average annual energy output was found to be 38 GWh. These results are an improvement from the prefeasibility study done in 2018 where the installed capacity was estimated to be 7.4 MW and the annual energy as 34 GWh.

RECOMMENDATION

It is recommended that satellite rainfall point data such as CHIRPS be considered as alternative input data in hydrologic modelling of poorly gauged hydropower sites in Zambia. Such data can be useful in extending or deriving adequate discharge time series, required for design of water resources infrastructure projects.

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