National University of Lesotho

Energy Research Centre

Feasibility study of micro-hydropower resources at three selected mini-grids sites for potential integration of micro-hydro with solar mini-grids.

Mamokhomo Mateboho Sekaleli

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Abstract

The study investigated the availability of water resources in three (3) sites earmarked for solar mini grids development for potential integration with micro-hydro power to form a hybrid system. Geographic Information System (GIS) together with other tools were used to select the study sites based on the availability of water resources, population size, accessibility, catchment area and availability of hydrometric stations. The three selected sites were Matsoaing, Sehonghong and Mashai. Flow rates data for the rivers near the study sites was acquired from the Department of Water Affairs (DWA) and Lesotho Highlands Development Authority (LHDA) and processed in Microsoft Excel to find the average flow rates for development of Flow Duration Curves and determination of design flows. Topographic maps, GIS and other GIS tools were used to evaluate the available heads at the three study sites. Based on the average flow rates, available heads, gravitational force and density of water, the maximum hydropower that can be produced in Matsoaing, Mashai and Sehonghong was found to be 171.71 kW, 44.15 kW and 3,112.63 kW, respectively. The study further assessed the possibility of hybridization of micro-hydropower with solar mini grids using Hybrid Optimization of Multiple Electric Renewables (HOMER). HOMER software assesses the feasibility and profitability of renewable energy systems. Net Present Cost (NPC) has been used as the main selection criteria for the optimum system. Based on the available solar radiation and water resources, system components costs and specifications, together with different sensitivity variable values, the NPC-optimized systems for all the three sites were found to be PV-hydro-diesel hybrid systems. The Levelized Cost of Electricity (LCOE) and NPC of the systems were found to be $0.184 and $79.184 for Matsoaing, $0.666 and $375,411 for Mashai and lastly $0.483 and $369,725 for Sehonghong.

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List of acronyms

ADCP	Acoustic Doppler Current Profiler
Aster-GDEM	Aster Global Digital Elevation Model
DSM	Digital Surface Models
DTM	Digital Terrain Model
DWA	Department of Water Affairs
EDM	Electricidade de Moçambique
ESKOM	Electricity Supply Commission
FDC	Flow Duration Curve
GEF	Global Environment Facility
GIS	Global Information System
HEC-HMS	Hydrologic Engineering Centre- Hydrologic Modeling System
HOMER	Hybrid Optimization of Multiple Electric Renewables
IPP	Independent Power Producer
LCOE	Levelized Cost of Electricity
LEWA	Lesotho Electricity and Water Authority
LHDA	Lesotho Highlands Development Authority
Li-DAR	Light Detection and Ranging
LPG	Liquidated Petroleum Gas
MEM	Ministry of Energy and Meteorology
NASA	National Aeronautics and Space Administration
NPC	Net Present Cost
PV	Photovoltaic
RS	Remote Sensing
SADC	South African Development Community
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SAPP	South African Power Pool
SE4ALL	Sustainable Energy For All
SMA	Soil Moisture Accounting
SSA	Sub-Saharan Africa

TPM Model	Two Parameter Monthly Model
UAV	Unmanned Aerial Vehicle
UNCDF	United Nations Capital Development Fund
UNDP	United Nations Development Programme

Chapter 1: Introduction

1.1 Background

Rural electrification is a recent topical issue owing to the need to attain Sustainable Energy for All (SE4All) by 2030. However, there are challenges especially in developing countries, in achieving 100 percent electricity access. These challenges include difficult terrain, coupled with scattered human settlements for expansion of national grids [1]. In Lesotho, the terrain makes places difficult to access by land and it becomes very costly to extend the national grid to most remote places. The result is low or no return on capital investment by the government due to factors such as higher rates of unemployment in rural areas among others.

Energy, an essential input for achieving sustainable development in any country, leads to exploring other alternatives to satisfy remote rural areas' energy needs. Stand-alone or off-grid renewable energy systems have proven to be the most feasible way to satisfy the electrification requirements of the hard to reach areas [2], [3]. This is highly possible because such areas are in most cases endowed with necessary renewable resources such as solar, wind, and water for the development of hybrid systems.

Even though Lesotho has a vast renewable energy potential [4], [5], lack of energy supply in its rural areas is still a problem, the reason being difficult-to-reach topography and sparsely populated rural settlements. To meet their energy needs, people in these areas use kerosene, which is even difficult for them to afford; and firewood, cow dung, and other traditional biomass resources, which lead to deforestation and soil degradation. Access to other cleaner energy sources such as Liquefied Petroleum Gas (LPG) is also a problem because of inaccessibility of most places by road.

The Ministry of Energy and Meteorology (MEM), in partnership with the United Nations Development Programme (UNDP) and the United Nations Capital Development Fund (UNCDF), is working to change this situation with financial support from the Global Environment Facility (GEF). In this endeavour, ten (10) areas have been identified for developing and implementing solar mini grids. The identified areas are Matsoaing, Tlhanyaku, Sehlabathebe, Lebakeng, Tosing, Sebapala, Sehonghong, Mashai, Ribaneng, and Ketane[6]. This work serves as the feasibility study of micro-hydropower resources for potential integration with solar mini grids at three (3) of the ten (10) sites above.

1.2 Lesotho's electricity situation

Lesotho's electricity sector has been sluggish for a long time due to policy inertia, which has been reflected by the lowest access to electricity in the Southern African Development Community (SADC) [7]. The electrification rate in the country was at47% as of 2020 with the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) of 79.2 and 26.4, respectively [8]. The majority of the people without electricity reside in the foothills, Senqu Valley and rural areas of the country. Presently, access to the national electricity grid is much greater in the urban areas (80%) compared to the rural areas at only 10% [9].

Lesotho's imports of electricity from Electricidade de Moçambique (EDM) and Electricity Supply Commission (ESKOM) have increased from 59% in 2018/2019 to 65% in 2019/2020 [10]. This is an alarming situation because the local generation has been stagnant at 76 MW since 1998 albeit the baseload and peak load deficit which were at 24% and 44% in 2018, respectively [11], with peak load rising from 153 MW in 2016 to 166.91 MW in 2018 [12]. The projected peak load demand under business as usual and high demand scenarios by 2025 is 254 MW and 232 MW, respectively [11].

1.3 Lesotho's hydro and solar energy potential

Lesotho is located within the Orange River basin with 3 major sub-basins which are Senqu, Makhaleng, and Mohokare with catchment areas of 24,485 km^2, 2,911 km^2, and 6,890 km^2, respectively (within Lesotho's boarders). This is supplemented by a large network of rivers from altitudes over 2000 m which make most of the areas possess good heads due to steep topography [13]. These make hydropower development more feasible from an economic viewpoint as such areas may not require expensive infrastructure for hydropower development [7].

The country also has profuse solar energy resources with about 3200 to 4000 sunshine hours per year and a high level of solar radiation regime estimated at an average of 20–24 $MJ/m^2/day$ on a horizontal surface. The annual daily mean global radiation ranges from 19.03 to 28.44 $MJ/m^2/day$ in December, and from about 10.30 to 13.48 $MJ/m^2/day$ in June and it never drops below 10 $MJ/m^2/day$ even in winter months [7], [13], [14].

The above enabling parameters put Lesotho at a hydropower generation potential of 450 MW with twenty-two (22) sites identified for small hydropower development with a combined potential of 20 MW while the solar generation potential is at 188 MW [4], [5], [7]. However, due to huge capital requirements for renewable energy projects, e.g. the Muela Hydropower station was constructed with £75.6 million [15], it has been impossible for a developing country like Lesotho to afford the development of projects to harness this available potential [7].

1.4 Other initiatives to exploit the available renewable energy potential

The government of Lesotho is planning to develop and implement some off-grid and grid-connected renewable energy projects for wind and solar to harness the available renewable energy potential with a capacity of 375 MW and estimated demand to be met of 300 MW by the year 2030, the excess of which will be traded at Southern African Power Pool (SAPP) [12], [16],[17]. As a step in creating an enabling environment for implementing these plans, the government has issued a request for expression of interest in the year 2019 to assess the impacts of variable renewable energy generation on the existing transmission and distribution network [18].

It has been Lesotho's vision as stipulated in the National Energy Policy, to meet at least the base load energy requirements through local generation [19]. The set access target was 75% of households by 2020, made possible by 7,756 connections annually [20]. Even though this has not been met, there has been interest from the private sector for the development of mini-grids by a local private company, 1Power, which identified potential sites for commissioning of solar Photovoltaic (PV) mini-grids at Ha Makebe [20] and the government issued the Independent Power Producers (IPP) procurement for it [11].

Of great importance to mention as part of the initiatives is the first biggest in the country photovoltaic power plant which has been under construction since 2020 at Ha Ramarothole in the district of Mafeteng, with a planned generation capacity of 70 MW [21]. Although the planned overall capacity is 70 MW, the project will be implemented in two phases, the first phase producing 30 MW and the remaining 40 MW will be produced after the monitoring and evaluating of the first phase [21].

1.5 Statement of the problem

Of all renewable energy resources, solar energy has a more serious intermittency problem: the sun not shining at night and during the daytime when it is cloudy or rainy. Consequently, this intermittency and unpredictability make solar energy less reliable. This challenge has often been addressed using the not-so-environmentally friendly and less cost-effective ways such as battery storage or having backup diesel generators which ultimately also increase the cost of the system. The most suitable way of solving the intermittency problem with solar energy is the integration with other renewable resources like hydropower and/or wind to form a hybrid system. Hybridization can reduce the system's cost in the long run and Levelized Cost of Energy (LCOE), while at the same time ensuring environmental protection [22]. It is therefore important to study the possibility of hybridization of the solar mini-grids with the micro-hydropower at least at three of the ten mini-grids sites earmarked for development in Lesotho by 1Power (Pty) Ltd.

1.6 Objectives of the study

The overarching objective of the study is to assess the potential of micro-hydro power generation at sites identified by 1Power (Pty) Ltd. Two main objectives, and the specific objectives, emanating from the overarching one are stated as follows:

1. To assess the potential of micro-hydropower resources at three (3) selected sites by 1Power (Pty) Ltd which was achieved through the following specific objectives:
    a. To use GIS data and tools for rapid selection of the sites for hydropower capacity assessment.
    b. To estimate the hydropower potential at the study sites.

2. To assess the potential for integration of solar power with hydropower at three (3) selected sites which was achieved through the following specific objective:
    a. To use the available solar potential assessment results and hydropower potential results from this study to simulate the integration of solar with micro-hydropower at three (3) selected sites using Hybrid Optimization of Multiple Electric Renewables (HOMER).

1.7 Research questions

This study attempts to answer the following research questions:

- What is the potential of micro-hydropower resources on the three selected mini-grids sites understudy to produce hydroelectric power?
- Is there a possibility of hybridization of solar PV with micro-hydropower that is generated at the study sites?

1.8 Justification

The community-based micro-hydropower plant is an alternative cost-effective energy generation technology with particular advantages for Lesotho's mountainous regions characterized by difficult access. This work demonstrated the extent of hydropower resources at the three (3) selected areas; and the project output will inform decisions in regard to integration of solar mini grids with micro-hydropower generators to present a unique opportunity for ensuring universal, affordable and reliable energy and promoting economic development in Lesotho using renewable energy resources.

1.9 Organization of the study

The rest of the dissertation is organized as follows: Chapter 2 gives the literature review, which is both empirical and theoretical. Chapter 3 outlines the methodology adopted including data and assumptions while chapter 4 presents the results and their interpretation. The last chapter (chapter 5) presents a summary of conclusion of the study and gives recommendations for future planning and use.

Chapter 2: Literature review

2.1 Hydropower theoretical framework

The final output production in a hydropower system depends on many factors, starting from the geography of the area to the mechanical equipment used. Once hydropower plant is operational, the final output production can be constrained by the energy that drives the turbine and the installed capacity that controls the rate at which hydraulic energy can be turned into hydroelectricity. The following sections outlines how hydropower works, classification of hydropower plants, key components of a typical hydropower plant, and essential parameters and how they are measured.

2.1.1 The Mechanics of hydropower

The schematic of a conventional hydropower plant is depicted in Figure 1. Water from the reservoir enters the Penstock through the intake which has the trash rack for the removal of impurities if there are any. The water then travels through the penstock to the turbine. The turbine then converts the potential energy of water into mechanical energy. The mechanical energy is then converted into electrical energy through the generator. The electrical power produced at the end of the turbine shaft is determined using Equation 1 [23].

$$P = \rho \eta g Q H \qquad \text{Equation 1}$$

Where

P - Power (W)

ρ - Density of water (kg/m^3) at ambient temperature

η - Overall efficiency of the turbine (usually 80 to 90%)

g- Acceleration due to gravity (m/s^2)

Q - Discharge/ flow rate (m^3/s)

H - Net Head (m)

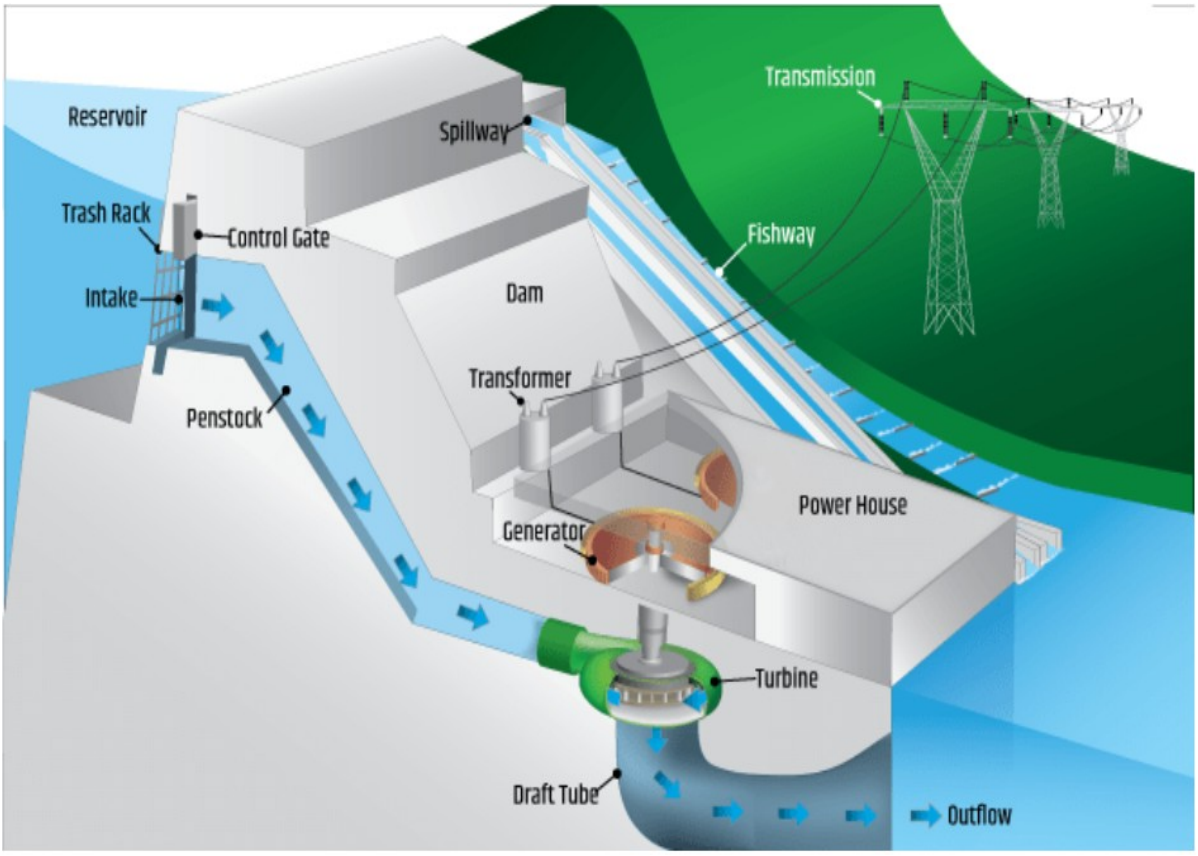

Figure 1: Schematic of a conventional hydropower plant [24]

2.1.2 Classification of hydropower plants

Although different countries, organizations and research groups use various references to classify hydropower plants, they may generally be classified according to electricity output, head range and operating system usage [25]–[27]. Table 1 shows the classification of the hydropower plants based on the three parameters.

Table 1: Classification of hydropower plants

Classification reference	Description
1. Power output	
Large	>100 MW
Medium	10-100 MW
Small	1-10 MW
Mini	100 kW-1 MW
Micro	5-100 kW
Pico	<5 kW
2. Head range	
High head	100 m and above
Medium head	30- 100 m
Low head	2- 30 m
3. The operating system	
Run of river type	This type of hydropower scheme does not regulate the flow of a river, as it produces electricity by applying the natural flow rate of the river. Subsequently, it suffers shortage of water in the dry seasons and is loaded with water sources during the rainy seasons.
Reservoir type	This type of scheme stores an excessive amount of water sources from the river and controls the power production based on the seasonal load demand.
Pumped storage type	This type of scheme uses off-peak electricity/power to pump up water from a water reservoir which is located at a lower level to the top of the water reservoir.

2.1.3 Key components of a typical hydropower plant

There are several types of hydropower plants classified by different characteristics as mentioned in section 2.1.2. For each type, there are essential components needed as explained below.

2.1.3.1 Reservoir

The hydroelectric reservoir is a large collection of water simply referred to as water storage. The water in the reservoir has a certain amount of potential energy that is converted into rotational motion by turbines. This is because the reservoir is usually placed at the highest level of the hydropower plant [25].

2.1.3.2 Penstock

The penstock is a pipe that carries water from the dam to the turbine. The material, length, inner diameter and layout of the penstock are very important in influencing the overall performance and capital cost of the plant. The penstock helps to channel the water to make the flow faster and powerful to turn the turbine. Reducing the length and diameter of the penstock will certainly reduce the costs as it is one of the expensive components of the plant. Different authors such as Fraenkel et al [28], Alexander and Giddens [29], Edeoja et al [30], Harpendi et al [31], Tapia et al [32] and Kravanja[33] have tried to invent penstock configurations that ensure its optimum performance.

2.1.3.3 Turbine

Turbine is the principal part of the hydropower generator. It is the part in the power house that converts the gravitational potential energy of water into rotational mechanical power. This happens when the running water hits the blades of a turbine which is attached to the generator by a shaft. After converting the kinetic energy of water into mechanical energy by the turbine, the generator then converts the mechanical energy into electrical energy.

Turbines can be classified into four broad categories: Impulse, Reaction, Archimedes screw and water wheels, all of which have different types under each. Figure 2 shows the classification of turbines and examples that fall under each class. Francis turbine is however the most commonly used and trusted turbine for hydropower plants.

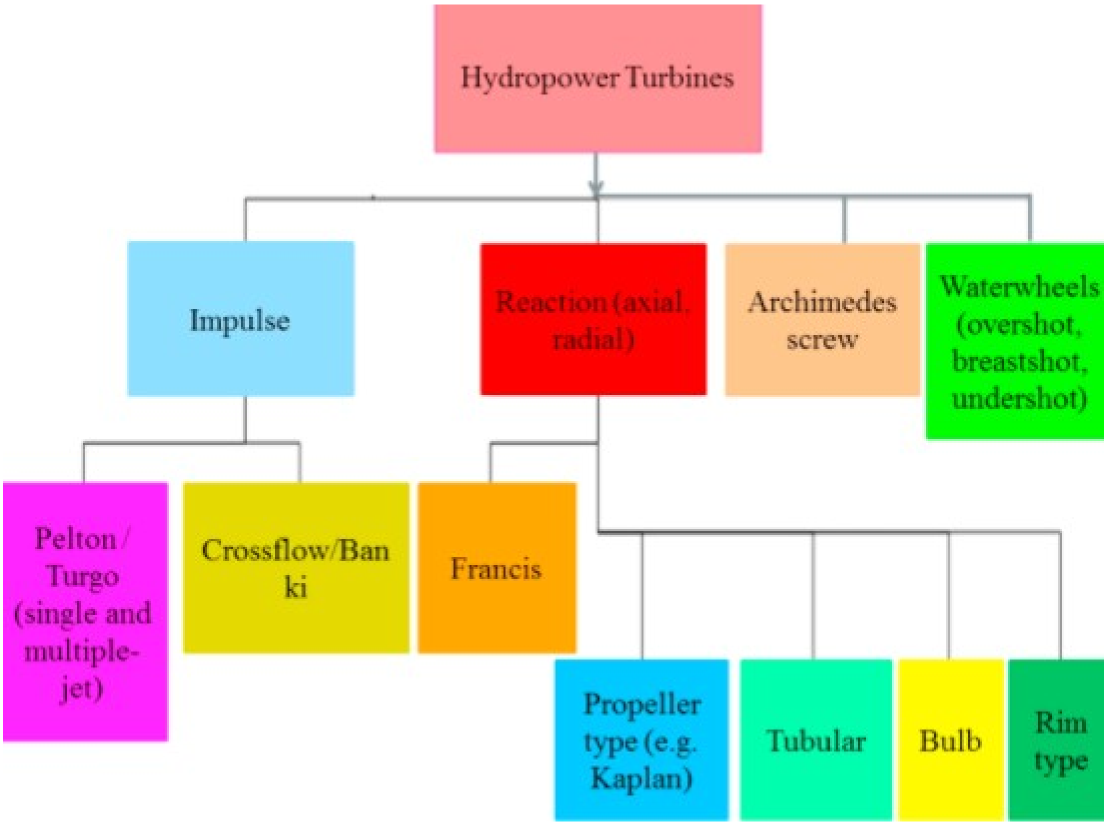

Figure 2: Turbine classification [25].

It is important to choose the right turbine for the hydropower plant as choosing the wrong one may lead to many losses [25]. According to Williamson et al [34], turbine selection depends on many factors including net head, variation of water flow through the turbine, speed of the generator; for which the ratio of the rotational speed and turbine must be less than 3:1, cavitations problem and cost of the turbine. They went further to develop the criteria and divided it into quantitative and qualitative criteria as shown in Table 2.

Table 2: Range of turbine selection criteria [34]

Quantitative criteria	Qualitative criteria
Rated flow/ head efficiency	Environmental- regulatory, weather, location
Part flow/ head efficiency	Required civil works
Cost	Portability
Turbine rotational speed	Maintainability and serviceability
Power for given site or required site conditions	Reliability
Size of system	Ease of manufacture
	Design modularity

2.1.3.4 Generator and power house

Generator is an essential component of the hydropower plant which converts the rotational energy produced via the turbine into electrical energy. Theoretically, the shaft rotates at the same speed as the generator and generates a magnetic field, which is converted into current in the coils of the generator by electromagnetic field induction. The selection of a suitable generator depends on many factors such as the approximate power of the generator, types of delivery system and electrical loads and cost [35].

The power house is a structural enclosure which houses the turbine, generator and other electrical components. In order to increase the system head and output, the location of the power house has to be as low as possible. Nonetheless, the power house has to be built above the river or dam level to ensure safety of the electrical devices during floods or river/dam overflow.

2.1.4 Key parameters and their measurement

The two most important parameters that determine the feasibility of any hydropower project are head and flow rate/ discharge. The head is the vertical distance that the water falls while the flow is the amount/quantity (volume) of water falling per unit time (normally seconds). The volume of the flowing water and the change in elevation or fall, determine the amount of available energy in moving water. The greater the water flow and the higher the head, the more electricity a hydropower plant can produce. This relationship is determined using Equation 1.

2.1.4.1 Flow rate measurement

There are several methods used to measure water flow rate, and these are either conventional or advanced. These methods measure water velocity, cross sectional area and flow rate (discharge). The conventional methods are simple and easy to use, but have low accuracy and are used to measure low flow rates while advanced methods are used to measure high flows and with high level of accuracy. Continuous records of discharge are used to determine and construct the Flow Duration Curve (FDC).The FDC is a suitable way of studying the flow characteristics of a river or stream with flows in the range of 70-99% of time exceedance normally used as design flows [36]. The FDC is not only informative for hydropower development, but also for irrigation projects, and there is requirement for a lengthy record in order to develop a reliable FDC which ranges from six (6) to thirty (30) years [37]. The following methods are used to measure the flow rate.

i. Bucket method:

In this method, all the water flowing down the river/ stream is diverted and captured into the bucket over the time interval. The method is used to measure the flow of up to 15 litres/s [38]. The procedure involves placing a bucket at collection point and starting time recording. The bucket is then removed quickly when it is full and the stop watch stopped. The water collected is then measured using a measuring cylinder. The ratio of volume of water collected over time taken to fill the bucket is then equal to the flow rate. The procedure should be repeated two to three times and results recorded. A record of these measurements covering low flows to high flows, and their relations are used to construct the FDC.

ii. Float method:

This method measures the velocity and flow rate in a river using a floating object placed just beneath the water and release to reach a measured distance. The time taken for the floating object to travel from point A to B is then recorded. Also, depth and width of the water are measured using a ruler for calculation of the area. When this area is multiplied by a constant (which varies according to the degree of roughness of the river) and divided by the time taken by the floating object to reach point B, the result is the flow rate. The limitation of this method is that it is affected by wind and flow direction [39].

iii. Dilution method:

The method is used with rivers that have turbulent flow and non-uniform channel shape that limit the accuracy of other discharge calculation methods [40]. The dilution method uses a chemical tracer which is injected into the river or stream to travel a given distance in order to be completely mixed with water. Although the tracer substance has to be a fluorescent or radioactive material, the most commonly used is sodium chloride or common table salt because it is less expensive, easily accessible and quick to dissolve in water. The amount of chemical tracer to use depends on the distance and the amount of water. The flow rate is calculated using Equation 2.

$$Q = \left(\frac{c1 - c2}{c2 - c0}\right) * q \qquad \textbf{Equation 2}$$

Where c_0 is the background concentration existent in water, c_1 is the known concentration of the tracer injected at a constant rate q and c_2 is the final concentration of the tracer.

iv. Indirect flow rate measurement:

In ungauged catchments, indirect flow rate measurements are usually applied. These include hydrological modelling such as rainfall-runoff models, catchment area ratio method, regression and spatial interpolation techniques. The rainfall-runoff model was assessed and described in this study. The catchment area ratio method is applied when the ungauged catchment is near the gauged catchment and the assumption is that both catchments have the same hydrological regimes such as same topography, geomorphology, lithology and land use. In that case, the mean annual flow of the ungauged catchment is equal to the ratio of ungauged and gauged catchment area, multiplied by the mean flow of the gauged catchment [41].

v. **Other advanced methods** of measuring the stream flow are summarized in Table 3 by Mdee et al [39].

Table 3: Advanced methods for flow rate measurement [39]

Instrument	**Description**
Price AA and Pygmy Current Meters	i. The number of revolutions of bucket wheel over a given period of time used to determine the velocity [42] . The standard rating table for each Pygmy meter is provided by manufacturer to read the number of revolutions per seconds with respect to flow velocity. ii. Recommended flow velocity to use the current meter range from 0.1 to 12m/s [43].
Hydraulic Structure	i. Two hydraulic structure methods which include weir and flume are discussed. A weir is an obstruction in an open channel which tightens the flow and causes it to fall over a crest [44] ii. Various types of weir are available including triangular or V-Notch, rectangular, and trapezoidal together with their empirical equations in [45]. iii. Most common flume is the Parshall flume with parameter dimensions as illustrated in [46] and [47]. A single measurement of water surface level in or near the restriction of hydraulic structure and empirical equations used to estimate the flow rate up to 150l/s are described in [48].
Slope-area Manning	i. The flow rate calculated depends on the surface slope, cross-sectional area and wetted perimeter over a length of uniform section channel. The method depends on the Manning factor n values. ii. The manning n values depend on straight uniform channels, cross-sectional area irregularity, variety of channels, relative effect of obstructions, type and density of vegetation and the degree of meandering. More detail discussed in [49] and [50]. iii. It is mostly used after floods to estimate the flow rate.
Electromagnetic flow Meter	i. Faraday attempted to determine the flow velocity of the river

	Thames in 1832 by measuring the voltage induced in flowing water with the earth's magnetic field [51] ii. The induced voltage in the electromagnetic flow meter depends on the magnetic field strength, mean flow velocity and tube diameter. The induced voltage is picked up to signal sensor converter for digital recording data or measured flow velocity is multiplied with diameter to obtain the flow rate.
Ultrasonic device	i. Acoustic Doppler Current Profiler (ADCP) technologies are attached to moving boats [52]. ii. During the traverse of a boat across the stream, a sonic sounder records the profile of the cross-section and a continuously operating current meter senses the combined stream and boat velocities [53]. iii. The ADCP uses the Doppler effect principle of sending a sound pulse into the water and reflected back by sediment or other particulates to determine the change of frequency, which is then translated into water velocity [54].

2.1.4.2 *Gross head measurement*

Of the two important parameters that help in determination of available hydraulic power, it is generally better to have more head than more flow because with high head, less water can be used to produce a given amount of power with smaller and less expensive equipment [55]. Several methods are used to determine the gross head and those include:

i. Topographic map

A topographic map gives an idea of vertical drop along the river or stream. In this case the head is calculated by taking the difference of the contour lines between the two points which should be the intake and the power house. The commonly used topographic map is of the scale 1:50,000 [42].

ii. Digital Elevation Model (DEM)

The DEM raster map is developed using GIS software with spatial analysis tool. The procedure is the same as in topographic map. To develop DEMs, Light Detection and Ranging (LiDAR) surveys are done. LiDAR is an active telemetry instrument. It uses a vector, aircraft, helicopter, or Unmanned Aerial Vehicle (UAV) whose position and altitude are precisely determined using a differential Global Navigation Satellite System (GNSS), carries a side-scanning laser that emits pulses under the vector [56], [57]. Maps produced from LiDAR data are Digital Surface Models (DSM) that show the top of all objects. To obtain a Digital Terrain Model (DTM), buildings can be removed by using a vector map of the building to delineate the areas of the points to be deleted. Aster Global Digital Elevation Model (Aster GDEM) is another data set that can be used to determine the gross head as used by Hidayah et al [58] where they used Aster GDEM to not only determine the slope of the area, but also delineate watersheds boundary and determine the river network. .The advantage of this approach is that it also allows mapping of vegetation and soil moisture and can be applied for large study zones [57].

iii. Other methods that involve physical site visit surveys include hose level, hose with pressure gauge, sight level and spirit level. On top of these methods, there are advanced methods as summarized by Mdee et al [39] as shown in the following Table 4.

Table 4: Advanced methods for gross head measurement [39]

Instrument	Description
Altimeter	i. It works by using the change of atmospheric pressure with the head of 9mm of mercury for every 100m [59]. ii. The principle of the altimeter and sources of error are described in [60]. iii. Surveying altimeter gives errors of less than 3% in 100m [61] or accuracy in gross head measurement of ±5m [62].
Hypsometer	i. Hypsometer is a device used to measure the height above sea level or elevation difference. ii. It requires the shooter with hypsometer directed to the reflection device to measure the elevation iii. It provides fairly accurate when used correctly and used the principle of trigonometric [63].
Clinometer/ Inclinometer	i. It measures the gross head with respect to gravity. By holding the instrument to the eyes and targeted to the uphill within the zone of visibility. ii. It measures the horizontal distance, percentage values to reach the uphill and downhill. Elevation difference is obtained by multiplying the horizontal distance and subtraction of percentages [64].
Theodolites and Total Stations	i. It is the most accurate survey instruments and consists of a pole with a prism, tripod, computer interface, batteries and radio. ii. The control points are required before taking measurements. iii. It needs the skills and knowledge of surveying to operate the instrument [65].

2.2 Hydropower as a renewable and sustainable energy resource

Hydropower is a clean renewable energy source that is fuelled by water and is sustainable even in future climate change scenarios [66]. Some individuals argue that hydropower is not a renewable energy source because of its potential to harm natural biodiversity, particularly fish, while some government energy policy makers in countries such as United States, Canada, European nations and even United Nations still hold hot debate on the renewability and sustainability of hydropower [66]–[70].

Frey and Linke [66], tried to defend the renewability nature of hydropower by stressing the point that if the technology does not consume the natural resources in its energy generating process, then the technology is renewable. This notion has also been supported by Ibrahim et al [71], [72] stressing the point that since water used in the generation of power is not consumed, but rather passed down to benefit communities down the slope, while at the same time allowing natural water cycle processes to happen, also qualifies the hydropower technology as sustainable. They went further to show that, hydropower projects have considerable benefits to other sectors and are often multi-purpose in nature. Examples they gave on top of energy production include control of floods, water supply to nearby communities and recreational benefits.

It is true that hydropower projects do have some negative impacts on the environment in which case trade-off of the benefits and negative impacts is a societies' value system [67], [68] An example of such scenario was clearly seen in the development of Hoover Dam on the Colorado river, which before its construction, floods destroyed an area which was a promising agricultural land. The construction of the dam served as a water repository for electricity generation, irrigation, municipal and industrial water supply for economic development in three states and a recreational resource facility for tourist attraction [73].

2.3 Hydropower situation in Lesotho and Sub-Saharan Africa, challenges and prospects

Lesotho possesses all the necessary characteristics needed for hydropower development; the country has a wide hydrographic network, steep topography and relatively large amounts of precipitation per year [74]. However, the country still underutilizes the available hydropower potential. Apart from the large hydropower station at 'Muela, Lesotho used to own 4 mini hydropower plants established between 1983 and 1993, but they have all faced siltation problems which is mainly caused by severe soil erosion due to the low vegetation cover on the steep topography of the country and are no longer operational. These 4 mini plants failed because of, among other reasons; the operational costs that were more than the revenue they generated, equipment for their repair was not available in the country, they operated on run-of-river water with diurnal storage silting more often and leading to frequent power failures. Finally, they did not have any private sector participation which could give financial and technical support for the sustainability of the plants [7].

One of the major hindrances for the exploitation of the existing hydropower potential in the country is lack of financial and technical capacity. The capital investment used for commissioning of the 'Muela hydropower amounted to £75.6 million (M1,454,846,400 in 2022 monetary value) [15] and that amount of money was from different external financiers and is not affordable for a developing country like Lesotho. Moreover, lack of required expertise (mechanical, electrical and civil engineering) in the country hinders the country's ability to perform the maintenance and servicing of the plants to ensure their sustainability[7].

Furthermore, Lesotho Electricity and Water Authority (LEWA) [75] on its Electricity supply cost of service study has stated that on top of lack of finance, lack of economically viable technologies is one of the hindrances to the deployment of renewable energy in Lesotho. The study also highlighted the need for promotion of research on renewable energy which will enhance knowledge and understanding of appropriate renewable energy technologies and existing opportunities for exploitation of renewable energy in Lesotho. It is agreeable that LEWA's notion is serious factor considering limited studies of which some are outdated and focused on regional instead of national levels to assess the potential of different renewable energy resources in Lesotho like [76], [7].

In Sub-Saharan Africa (SSA), there are about 10,216 potential sites for mini hydropower with estimated generation capacity of 3,421 MW and 5,383 potential sites for small hydropower with an estimated generation capacity of 21,800 MW, which (these potentials) are not sufficiently exploited as shown in Figure 3 [77]. Some of the reasons for the low exploitation of the potential are shown in Table 5 [77].

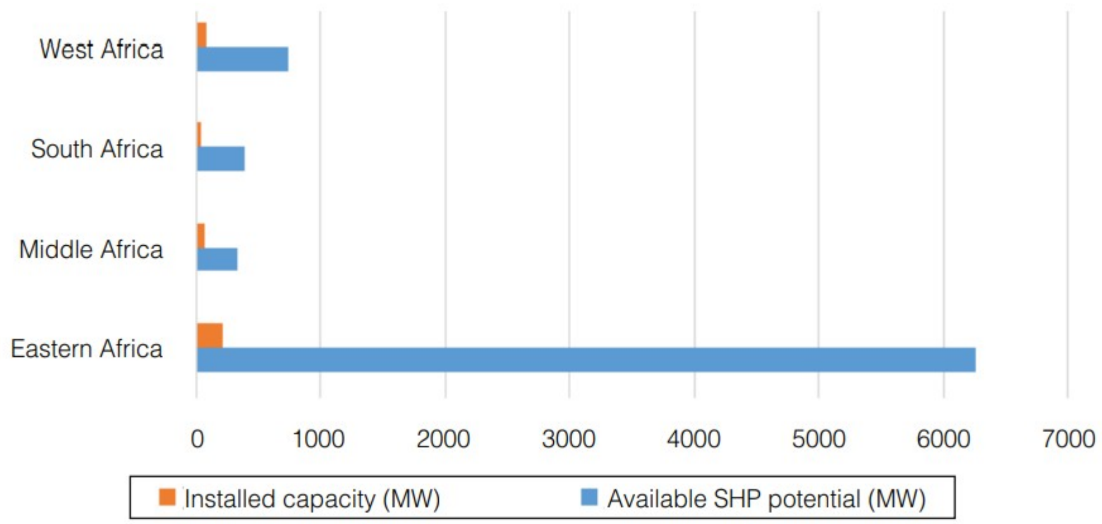

Figure 3: Small hydropower potential and installed capacity in SSA [77].

Table 5: Small hydropower development barriers in SSA [77]

Regions of Africa	SHP Barriers in SSA
Eastern	Lack of hydrological and up to date data Insufficient awareness of SHP Lack of road infrastructure to access sites in the in remote areas Lack of public–private partnership with both domestic and foreign investors Inadequate human capacity Power distribution cost
Middle North	Lack of a clear cut renewable energy policy Lack of motivation and suitable SHP site Lack of SHP merits awareness by the public Lack of support policies and technical capacity
South	Lack of SHP components and system, insufficient human capacity on SHP Unfavourable climatic condition
West	Lack of reliable and up to date hydrological data Inadequate SHP project financing and no incentive to attract domestic and foreign SHP investors Various degrees of insufficient technical expertise for equipment design, manufacturing, civil construction, operation and maintenance Effect of climate change on water bodies like a river
Other common barriers	The long distance between potential sites and consumption points Low electricity demands due to low population density The long distance between consumers (scattered settlement) Low utilisation factor Prohibitive high capital costs

2.4 Calculation of discharge for estimation of hydropower potential in ungauged catchments

There are different techniques to evaluate hydropower potential in different catchments which possess different characteristics. The potential of hydropower resources at any area starts from the theoretical potential as presented in section 2.1.1 and forms a stepwise pyramid structure. To calculate the potential of hydropower resources, it is important to know different aspects of the area, such as the natural environmental conditions, geographic conditions, technical elements (energy efficiency, operation rate, collection rate, etc), environmental performance, and technological progress through by accumulating data over a long period [78].

Since hydropower potential depends on the availability and quantity of water, discharge or flow rates data is the most important parameter in the estimation of the potential [79]. While some researchers use water level and discharge relationship to calculate the discharge data which is mainly aimed at calibrating the hydrologic model, the method does not easily apply to large catchments due to expensive requisite hydrometric instrumentation. These physical instruments set on the ground could be vandalized or be destroyed by other factors such as floods. In cases of very low water levels, the set level instruments may not be of use, which may give a false picture of the discharge. In Nigeria, stream flow measurement was done using the hydrological gauge reader to measure the water level which is then converted to the discharge [80]. The more advanced methods are hydrological models coupled with GIS and sometimes Remote Sensing (RS).

There is no standard methodology for generating discharge record for estimation of hydropower potential and different stream flow generation methods produce different results even if they relied on the same input precipitation data and even the same stream flow observations during their calibration. In the case of ungauged basins or poorly gauged basins, precipitation data is used and modelled into runoff. Other studies use climate change scenarios to calculate future discharge [78]. Such studies include Jung et al [78] who estimated the future hydropower potential generation in ungauged basins using Kajiyama formula, modified Two Parameter Monthly (TPM) Model which uses hydro-meteorological data to calculate runoff and also used Tank Model which calculates runoff based on the rainfall-runoff processes. The study tried to accommodate all types of precipitation and did not concentrate only on rainfall, making the study to be authentic as other types of precipitation also contribute to generation of runoff. This makes the study's approach appropriate to any other area.

In another study, Jung et al [81] assumed the three gauged basins of Deoksong, Hnseok and Socheon in Korea were ungauged and simulated their discharges using the Kajiyama formula, modified TPM model and Tank model to compare the results obtained using flow duration characteristic model. The results from the study showed that the Kajiyama formula and modified TPM model had the best results than the flow duration characteristic model while the Tank model results were not fitted with the observations. The researchers used four blending techniques (simple average method, Multi-Model Super Assemble, Simple Model Average and Mean Square Error) to minimize the uncertainty of the results which made the results to be more reliable. These researchers could not develop a reliable FDC with the available flow data, hence, the need for performing a rainfall run-off model to extend the length of records.

Amongst several hydrologic models that researchers use to estimate the discharge is the Hydrologic Engineering Centre- Hydrologic Modelling System (HEC-HMS) which is a rainfall runoff model that transforms the precipitation into runoff and produces hydrographs. This model transforms the watershed drainage paths and boundaries into hydrologic data that shows how the watershed responds to precipitation. The model has been used in Iraq by Hamdan et al [82], in Ethiopia by Tassew et al [83], in East Java by Hadiyah et al [44] , and good results were obtained. The advantage of this model is that it can be used for event and continuous modelling, implying that it caters for both wet and dry season modelling. The model can be suitable for Lesotho as it experiences both dry and wet seasons.

2.4.1 HEC-HMS as the most common and trusted rainfall run-off/ hydrological model

This study reviewed applicability of a rainfall run-off model using Hydrological Engineering Centre –Hydrologic Modelling System (HEC-HMS) software which generates long term discharge for the planned hydropower locations. HEC-HMS transforms the drainage paths and watershed boundaries into hydrologic data structure that shows how the watershed responds to precipitation and then produces the hydrographs. Soil Moisture Accounting (SMA) method within the model which is suitable for both dry and wet conditions can be appropriate for Lesotho. SMA method simulates several components of hydrologic cycle such as canopy interception (precipitation that is intercepted on trees, shrubs, grasses and does not reach the soil profile), surface depression (water held in shallow surface), infiltration into the soil profile storage (water stored into the top few inches of the soil), percolation to the ground water aquifer and base flow caused by available soil storage vs. maximum saturated capacity of soil layer [84].

The order of simulations happens after one of the two processes based on which one is occurring between evapotranspiration and evaporation. During precipitation, canopy storage is filled first. Excess precipitation in the canopy combined with water in surface storage at the beginning of the time step infiltrates into the soil. If canopy storage and surface storage exceed infiltration, the excess water returns back to the surface as runoff. Figure 4depicts the conceptual schematic of a continuous Soil Moisture Accounting Algorithm.

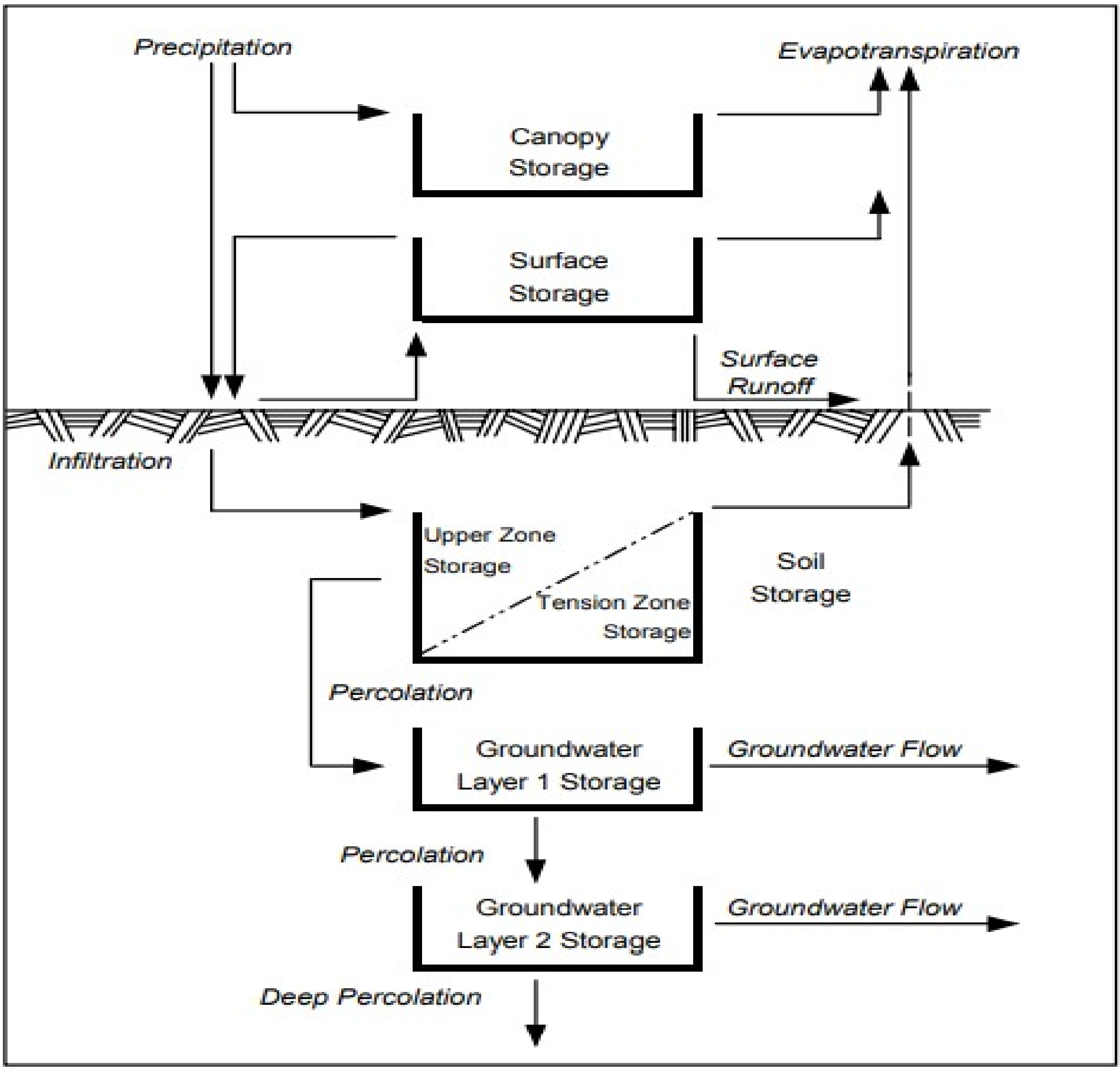

Figure 4:Conceptual schematic of the continuous SMA Loss Method [84]

2.5 Improving the reliability of hydropower plants

Hydropower can be combined with other renewable sources like wind or solar to increase the stability and reliability of the power generation. That is called hybridization. Hybridization allows PV panels or wind turbines to produce electricity when they are available, thereby saving water for hydropower during times the sun or wind go down. Another advantage of hybridization is that the same electrical infrastructure can be used for both generators, thus cutting capital expenditure costs and ultimately the cost of electricity to the end users.

There are several studies conducted to evaluate the feasibility of hybrid off-grid power generation globally. Different researchers used different approaches to evaluate configurations of various renewable energy resources, such as solar energy, wind energy, small hydropower together with their hybrid configurations. Kusakana et al [2], investigated the possibility of using a stand-alone solar/micro hydro hybrid power system for low-cost electricity production in Kwazulu Natal. In their study, the feasibility and dimensions of the hybrid system were determined according to the availability of the renewable energy resources and the load energy requirements. Thereafter, the economic performance of the system was compared with that of other options such as grid extension or diesel generation, and the hybrid system was found to be the best option to provide cost-effective, sustainable and clean electricity [2].

Syahputra and Soesanti, planned and investigated the potential of a micro-hydro solar hybrid system in one of the rural areas of Indonesia. They conducted field research to obtain data for micro-hydro by direct measurement from targeted irrigation channel while data for solar radiation was obtained from the National Aeronautics and Space Administration (NASA) database. The results showed that hybrid power plants would be able to meet the energy needs of the surrounding villages and also produce an excess that could be sold to national electricity providers [85].

In Ethiopia, Somano and Shunki assessed the potential of a hybrid PV-micro hydropower system at Jimma zone where they got positive results that the hybrid system could be more cost effective than the grid system. The results also showed that integrating available renewable energy resources and designing as a hybrid power system minimized the system costs and energy per kWh in the long term. The results of the study were used to encourage private investors to invest in renewable energies in Ethiopia [86].

In Lesotho, a study for hybridization of Semonkong mini hydropower plant with other available renewable energy resources in the area was carried out by Thamae [87]. The results of the study showed that the hydro component of the system is only effective during rainy summer season and needs a backup during dry winter season. The hydro/diesel hybrid system that has existed was ranked the least cost-effective feasible option by the simulation results while other simulated hybrid options that included more renewable energy technologies seemed to be more cost effective with decreased Net Present Cost (NPC) and Cost of Energy (COE), as well as increased renewable energy fraction. This proves the economical (decreased cost of energy) and environmental (increased renewable energy) benefits of hybridization.

A conclusion drawn from the mentioned studies is that hybridization has proven to improve output, cost effectiveness and reliability of the renewable energy systems in most areas where it is done. Considering the intermittency of solar resource and the availability of water for runoff the river micro-hydropower systems in Lesotho, which is seasonal, it is important to combine mini-grids with micro hydro systems to increase the reliability and reduce the cost of energy.

2.6 Hydropower in the midst of climate change

Hydropower is one of the vulnerable technologies to climate change compared to others. This is because the amount of water runoff which is used as fuel for hydropower depends entirely on the amount of precipitation. The main factors that determine the impact of climate change on hydropower are run-off, the temporal distribution of run-off and sedimentation [88]. The attractiveness and bankability of hydropower projects depends on long-term assessment of their generation capacity that may hugely be affected climate change [89]. This is why most countries are starting to allocate considerable amount of resources to new research and development that is meant to understand the impact of climate change on hydropower.

Research on the impacts of climate change on water resources and hydropower specifically, were started a while ago using different approaches such as run-off and climate change scenarios as well as qualitative approaches [90]–[93]. All of these studies concluded that reduction in the amount of precipitation could potentially reduce hydropower production significantly, leading to challenges in the management of water resources. The impact of climate change on hydropower can hit hard the run-off the river type of hydropower plant more than the ones with reservoirs, as with reservoirs, water can always be made available. Such negative conclusions can lead to hydropower projects being abandoned.

Chapter 3: Methodology

3.1 Methodology adopted

GIS tools were used to select specific locations for infrastructure installations within the three (3) areas from the ten (10) areas earmarked for micro-hydropower development based on elevation, water resources availability and accessibility. Should stream flow record have been unavailable or insufficient, it would be generated prior to micro-hydropower assessment using hydrological modelling and potential for integration with solar was assessed using the results from the previous solar feasibility study and satellite solar resources data. Figure 5 summarizes the methodology followed.

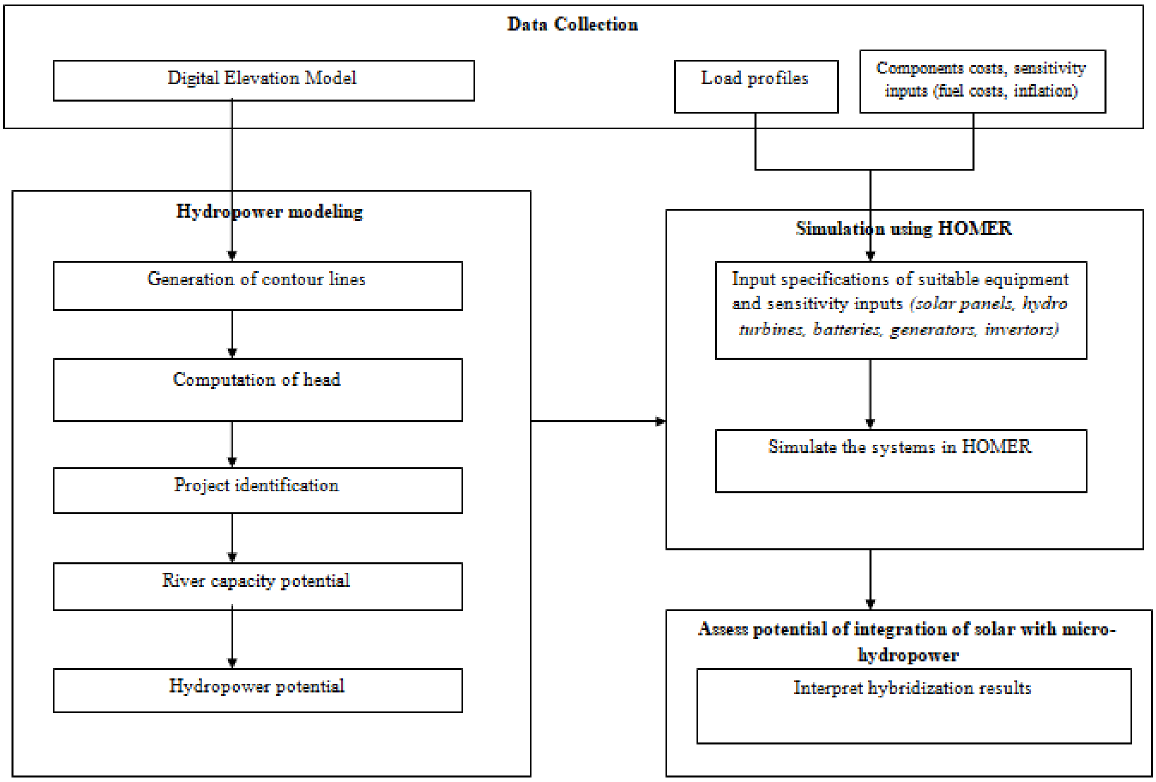

Figure 5: Methodology flow diagram [Source: This study]

3.1.1 The study areas

The potential of hydropower depends on the availability of water flow and vertical fall (head); the steepness of rivers and generous flow rates in rural areas are potential sites for hydropower development. This study therefore focuses on selecting the potential sites and estimating the potential of hydropower in those selected sites based on the slope of the area, availability of water and other factors such as accessibility, population, stream length, catchment area, watershed forests, availability of gauging stations, and network strength as shown in Table 6. Arc GIS version 10.7.1 was used to map the river network, rainfall stations and hydrometric stations as shown on Figure 6.

Table 6: Site selection criteria [Source: This study]

Sites		Accessibility (15%)	Population cluster (15%)	Stream length closeby (15%)	Catchment (25%)	Watershed - forest (25%)	Stations (5%)	Network Strength	Score
Ha Makebe	45 mins - 1hour, roads are good	5	3	3	3	1	0	Good	58
Lebakeng	8 hours, least accessible	1	3	2	4	2	0	Good	49
Mashai	6 hours, not great roads	3	5	3	4	3	5	Good	71
Matsoaing	8 hours, very good	4	4	3	2	5	5	Good	72
Sebapala	5-6 hours, roads good mostly	4	2	3	2	2	0	Good	51
Sehlonghong	7 hours, not great roads	3	4	3	4	4	0	Good	73
Tlhanyaku	10 hours, not great	3	4	5	2	2	0	Good	59
Tosing	5-6 hours, roads good mostly	4	1	4	2	2	0	Good	51
Ribaneng									
Ketane									
Sehlabathebe	8 hours, roads are decent, better than LBK								

From Table 6, the areas with the highest scores have been selected, being Mashai, Matsoaing and Sehonghong. Figure 6 shows the sites on a map plotted using GIS.

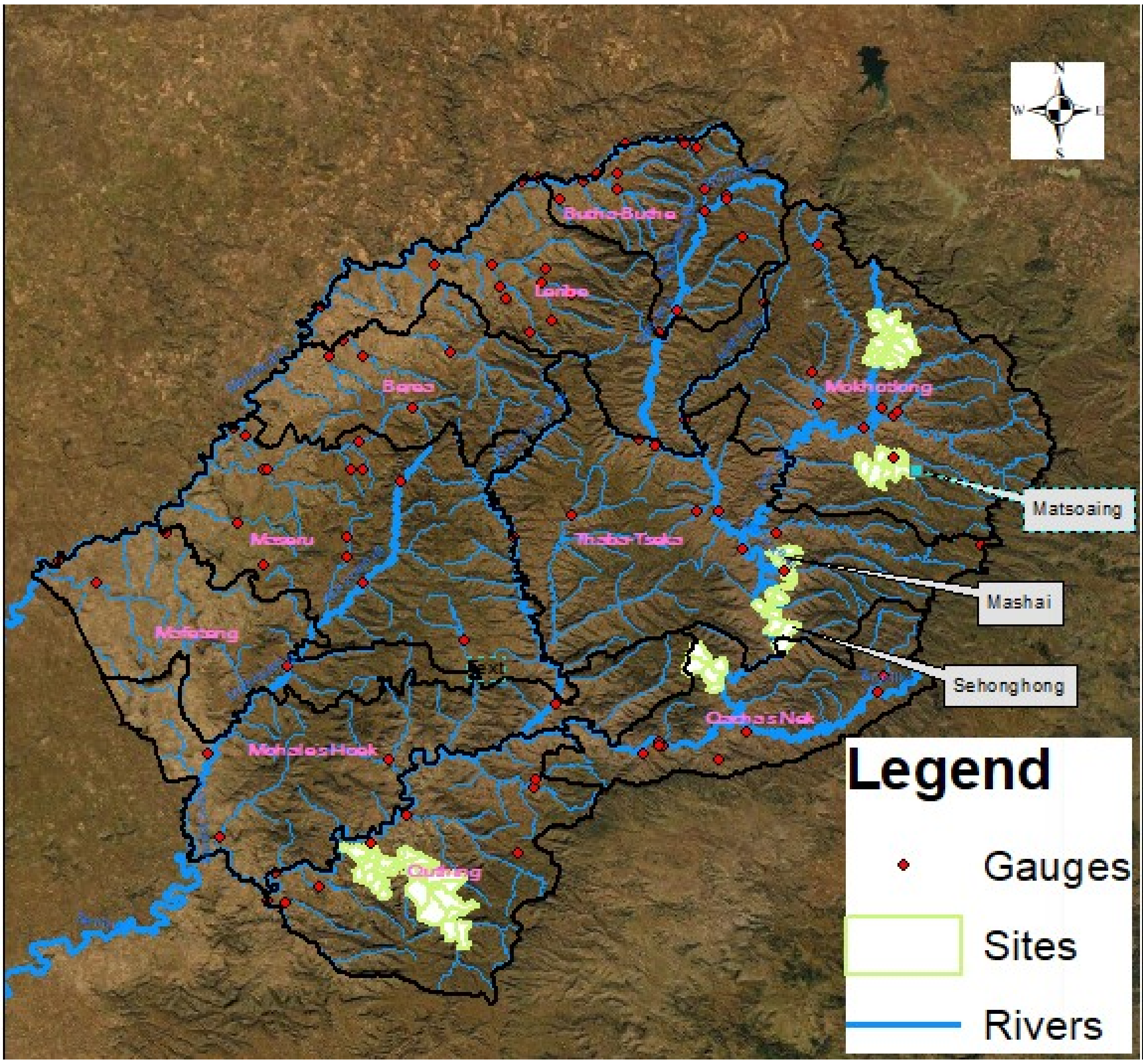

Figure 6: Study sites [Source: This study, created using Arc GIS)

3.1.1.1 Matsoaing

Matsoaing is found in the district of Mokhotlong with an estimated area 109.67 km^2. It is situated at the latitude of 29° 22' 59" S and longitude of 29° 4' 59" E. Matsoaing has a temperate highland climate with dry winters. The area has Sehonghong River passing through it, and it is also near Matsoaing River (tributary of the Sehonghong River), making it an attractive area to be assessed for hydropower potential.

3.1.1.2 Mashai

Mashai is located 47.7 km South East of ThabaTseka town with an estimated area of 41.78 km^2. Its geographical coordinates are 29° 38' 42.3" South and 28° 48' 35.8" East. The Mashai

River flows past this village which has a good head for run-off –river mini hydro which runs throughout the year

3.1.1.3 Sehonghong

Sehonghong is situated in the South East of the district of ThabaTseka with an estimated area of 90.19 km^2. Its geographical coordinates are 29° 48' 0" South and 28° 49' 0" East. It located in a rock-shelter that is 86 m long and 19 m deep. Sehonghong is approximately 1,800 m above sea level and is part of a sand stone projection of about 20 m above the Senqu/Orange River, there by having a fair head for run-off the river mini hydro power which can run throughout the year. The area's catchment receives precipitation in the form of rain in summer and snow in winter.

3.1.2 Data

The data used in this study is hydro-climatological data in the form of discharge or river flow data as hydropower generation depends on the availability of water.. Another set of data required is the spatial data in the form of Digital Elevation maps. The discharge data was obtained from the DWA and LHDA. The flow rates data for Sehonghong, Mashai and Matsoaing were obtained from hydrometric stations situated at Senqu at Komakoma, Mashai at St Theresa and Sehonghong at Ha Mamolibeli respectively. The data was processed in Microsoft Excel to generate hydrographs and FDCs.

The FDC shows the occurrence of different flow rates. It is developed by arranging all monthly average discharge observations in descending order of their magnitude and subdividing them in accordance with the percentage of time during which they are equalled or exceeded. Percentage exceedance, P, is done using the following equation:

$$P = \frac{flowrank}{totalnumberofobservations} * 100$$

Equation 3

For the assessment of possibility of hybridization, the renewable resources data (river flow rates, solar radiation and clearness index), energy demand data and components specifications are required. The river flow rates data was obtained from DWA and LHDA as explained above. The load data was obtained from the 1power design team after estimation of the energy demand from the households and village assessments that were undertaken during the baseline surveys. The solar resource data was retrieved from NASA by the HOMER software when correct coordinates of the areas are used. The specifications and costs of the required components were obtained from different suppliers' websites such as [94], [95] and [96].

3.1.3 Head/ falling height evaluation

The head is one of the important parameters in determination of potential hydropower because it determines the pressure of water across hydro turbine, i.e., the more head you have, the higher the water pressure across the hydro turbine and the more power it will generate. Head estimation was done using ASTER_GDEM within GIS software. First, the locations of the power house and the intake were identified and plotted in GIS using a simple method based on accessibility to the road for ease of maintenance. According to Kosa et al. [97], the differential elevation between the power house and the intake should be more than 20 m, while the distance between them should be less than 3 km in order to minimize head losses. The elevation differences between the two locations were then determined using the Digital Elevation Maps by finding the differences between the contour lines.

Since this work does not design the hydropower systems, but just assesses the available hydropower potential at those selected areas, the net heads are calculated only for maximum power, i.e., estimated power production before the turbine shaft as:

$$H_f = \left(\frac{1}{3}\right) * h \qquad \text{Equation 4}$$

Where H_f represents the head losses and h is the gross head.

The net head (h_{net}) is given by the difference between gross head and head losses, i.e.

$$h_{net} = h - H_f \qquad \text{Equation 5}$$

3.1.4 Estimation of hydropower potential

The flow rates data from DWA and LHDA was processed in Microsoft Excel to produce the FDCs which were then used to determine the discharge with large enough probability (between 30% and 70%, by the rule of thumb). Using the flow below 30% probability may lead to over sizing because such flows rarely happen, while using the one above 70% may lead to under sizing of the system. The gross hydropower potential for each site was determined under the influence of gravity using the following equation:

$$P = 9.81\rho Q h_{net} \quad \text{Equation 6}$$

Where P is the power in kW, ρ is the density of water, Q is the flow rate in m^3/s and h_{net} is the net head or the vertical drop calculated for maximum power production before the turbine shaft.

3.1.5 Simulation, Optimization and Sensitivity analysis of a possible hybrid system using HOMER software

In order to benefit from renewable energy technologies, it is important to assess whether the proposed Renewable Energy Systems will be feasible and profitable. The study used HOMER Pro software version 3.11.2. HOMER helps in finding the combination of components that can serve the load at the lowest life-cycle cost. HOMER's primary role is to simulate the long-term operation of micro-power systems. Its two high level roles of optimization and sensitivity analysis rely on the simulation role results.

The simulation process determines how a particular system configuration, a combination of components and a particular operating strategy would behave in a given settings over a period of time. HOMER can simulate a wide variety of micro-power systems comprising of solar PV panels, wind turbines, hydro turbines, generators, battery bank, ac-dc converter, electrolyser and a hydrogen storage tank. Simulation process serves two purposes; first it determines whether the system is possible, and second it estimates the life-cycle cost for ease of comparison of different system configurations which form the basis for the optimization process.

The optimization process on the other hand determines the best possible/optimal system that meets the load at the lowest total NPC. In the optimization processes different system configurations are simulated, infeasible ones discarded, feasible ones ranked according to total NPC, with the lowest total NPC as the optimal system configuration. The optimal value of each decision variable (a variable over which a designer has control), is determined in the optimization process. Such decision variables include: the size of the PV array, the number of batteries, the size of the generator, the presence of the hydro system, the size of the ac-dc converter, etc. The results of the optimization help the modeller find the optimal system out of many feasible systems.

Under sensitivity analysis, this is where HOMER reveals how sensitive the outputs are to changes in inputs. A range of input values for variables that are not decision variables are entered for a single input variable. Examples of such variables include the grid power price, the fuel price, the interest rate and the lifetime of the PV array. The sensitivity analysis helps the system designer to deal with uncertainty, meaning for one sensitivity variable; different values that cover the likely range can be entered.

For this study, potential energy demand for the three study areas and specifications of the planned PV system were obtained from 1Power design team. To obtain the potential energy demand for the areas, baseline studies have been undertaken by the team, which included village and household assessments. The kind of information required from the assessments include population, number of households, road accessibility, business opportunities, types of houses, cost of other energy sources, etc. All this information is used to make evaluations and estimations of energy consumption and peak demand to generate load profiles.

Another set of inputs is the specifications of components to be used for the hybrid solar-micro-hydropower plant, their performance characteristics, installation costs and operation and maintenance costs. Such requirements for the solar PV system were obtained from the 1power design team. For the hydropower system, generic components were used based on the peak demand while the costs were estimated based on previous studies.

The last set of inputs is the availability of renewable energy resources at the study areas. The river flow rates were obtained from DWA and LHDA while the solar resource data was retrieved from NASA by the HOMER software.

3.1.5.1 Defining the primary load

The load profiles obtained from 1Power design team were entered into HOMER to produce the daily, seasonal and yearly profiles and also estimate the average and peak demand.

Chapter 4: Results and discussions

This chapter presents and discusses the results of hydropower potential assessment for the three sites together with the results of assessment of the possibility of integration of solar and micro hydro to form a hybrid system. Availability of water resources in the form of stream flow data and water head are the starting point to the estimation of hydropower potential. The design flow (Q) was calculated in Microsoft Excel using the stream flow data and the water head (h_{net}) was determined using DEM in GIS interface and Equation 6 was used to determine the hydropower potential (P). The chapter also presents and interprets the hybridization results from HOMER software, in which the NPC and LCOE have been used as the main selection criteria for the optimum system. NPC is the present value of all costs of installing and operating the energy system for a lifetime minus all the revenues that the system earns for that particular lifetime while the LCOE is the average cost per kWh of useful electrical energy produced by the system.

4.1 Hydrographs, average flow rates and Flow Duration curves

The data for the derivation of the hydrograph for Sehonghong was from the hydrometric station at Senqu River at KomaKoma area for the period of January 2010 to September 2019 while for Mashai River, the data was from St Theresa Hydrometric station for the period of August 2012 to July 2018, and for Matsoaing, the data was from Sehonghong River at Ha Mamolibeli hydromedric station for the period of January 2010 to February 2019. Figure 7, Figure 8, and Figure 9 show the daily flow rates for Sehonghong, Mashai and Matsoaing.

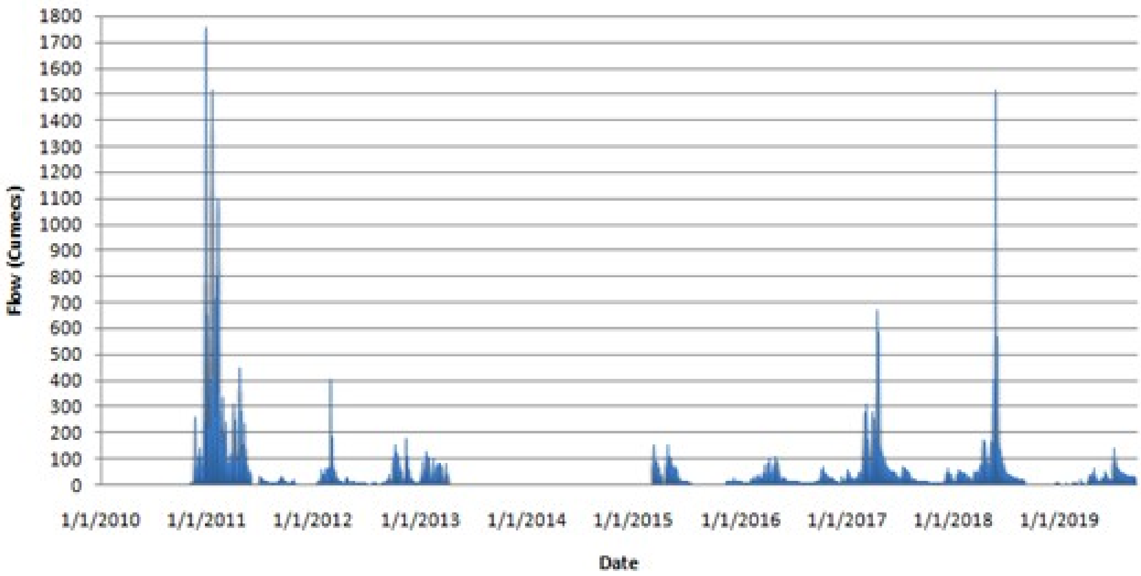

Figure 7: Hydrograph for Sehonghong (Senqu River at Komakoma)

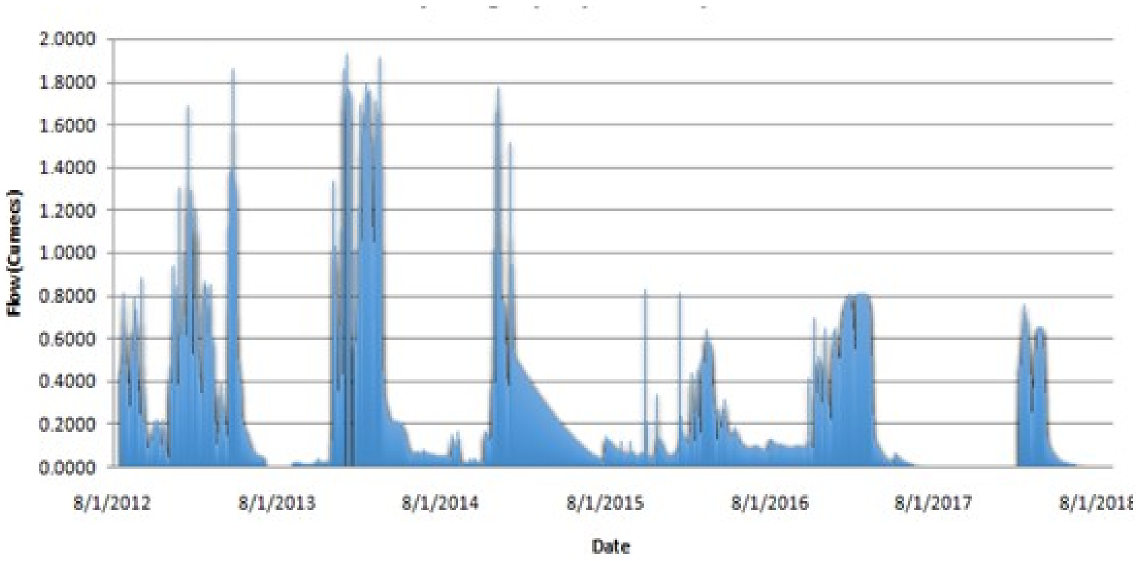

Figure 8: Hydrograph for Mashai(Mashai River at St Theresa)

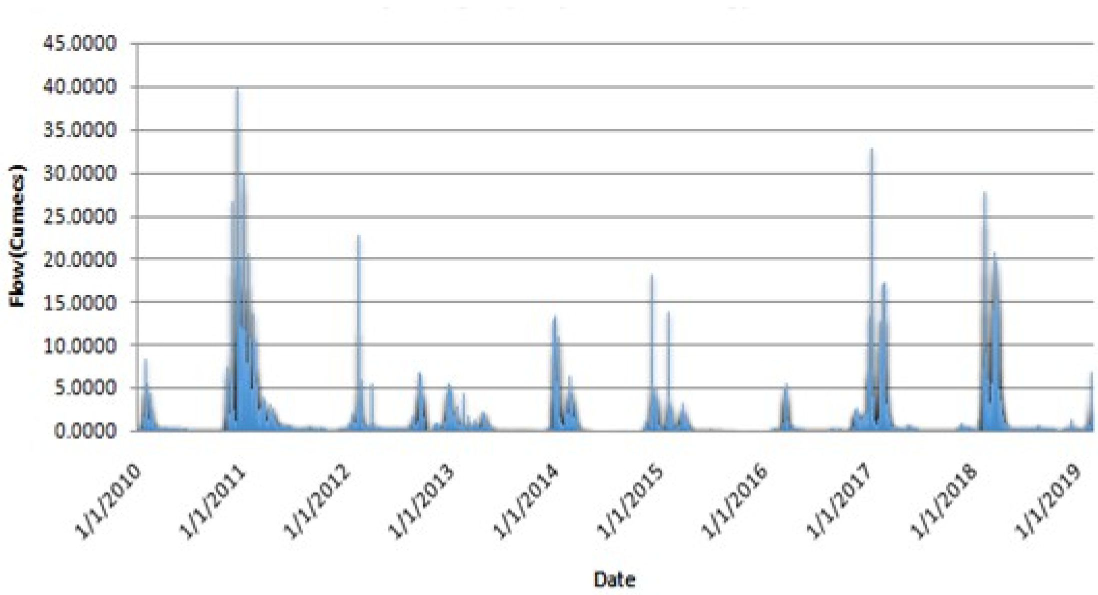

Figure 9: Hydrograph for Matsoaing (Sehonghong River at Ha Mamolibeli)

From Figure 7, Figure 8, and Figure 9, it is observed that the daily flow rates for Sehonghong, Mashai and Matsoaing can go as high as 1,700 m^3/s, 1.98 m^3/s and 40 m^3/s respectively. These flow rates are experienced in times of heavy rain falls or floods while during times of droughts, 0 m^3/s flow rates are experienced in all the three locations. Since the daily flow rates fluctuate depending on the seasons or months, it is important to depict the monthly average flow rates to have an idea of how the hydropower systems may perform in different months/ seasons. Figure 10, Figure 11, and Figure 12 show the monthly average flow rates for the three areas.

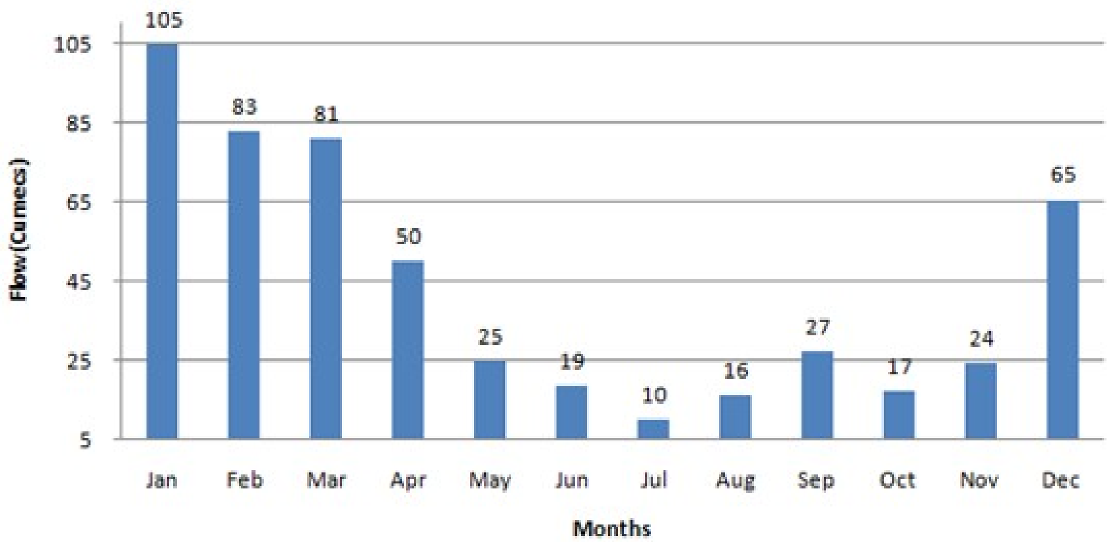

Figure 10: Monthly Average flow rates for Sehonghong- Senqu River at KomaKoma

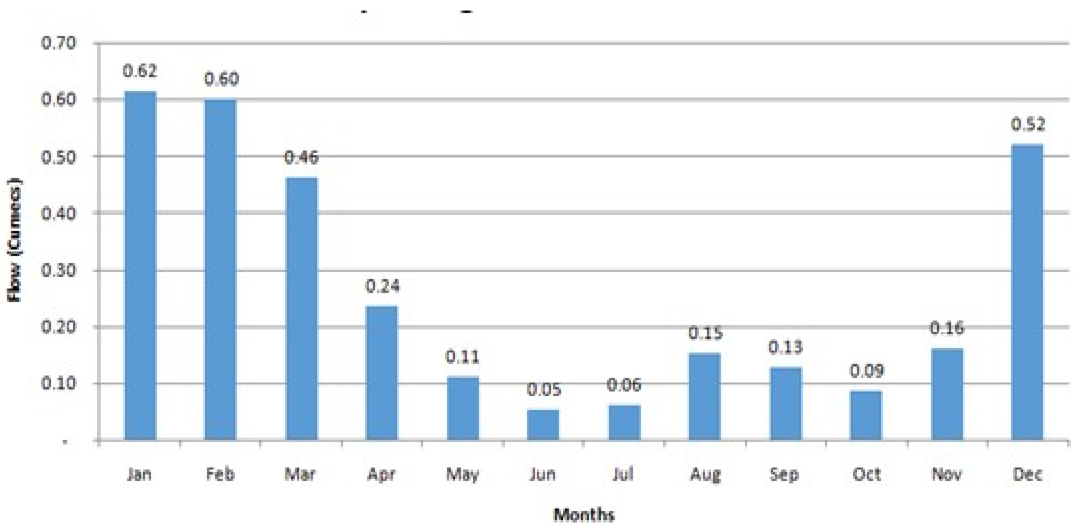

Figure 11: Monthly average flow rates for Mashai- Mashai River at St Theresa

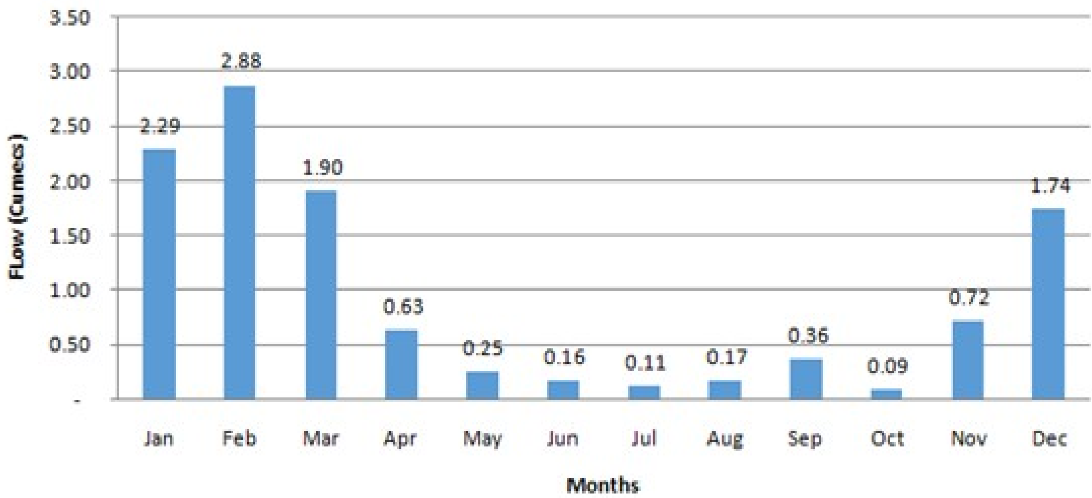

Figure 12: Monthly average flow rates for Matsoaing- Sehonghong River at Ha Mamolibeli

It is evident from Figure 10, Figure 11 and Figure 12 that higher flow rates are experienced in the months of December, January, February and March, which are the months that the country experiences good rains or even floods in most parts of the country. The lowest flow rates are experienced in winter, autumn and spring, which are mostly the dry seasons of the country; July, August and October for Sehonghong, June, July and October for Mashai and

June, July, August and October in Matsoaing. The above hydrographs give an idea of extremes of high and low flow rates but does not give what happens in between. To get such information, the Flow Duration Curve (FDC) is a better tool to use. The FDC gives the percentage of time that a certain flow rate is equalled or exceeded.

Flow rates that happen in between 0 percent and 10 percent of the time, i.e., between Q_0 and Q_{10} are considered high flow rates, in which Q_0 to Q_1 would be extreme flood events. It is important that hydropower systems are designed to cope with such extreme flows. Flows from Q_{10} to Q_{70} would be the 'medium' range of flows and one would want their hydropower system to operate efficiently right across these flow rates [98]. Flow rates from Q_{70} to Q_{100} are the 'low flows' when hydropower systems will just be operating but at a low power output. Moving further to the right on the FDC, hydro systems will begin to shut down due to low flow. Thus, the Q_{95} to $Q_{100}$are considered as the low-flow or drought flows. Figure 13, Figure 14 and Figure 15depict the FDCs for Sehonghong, Mashai and Matsoaing, respectively.

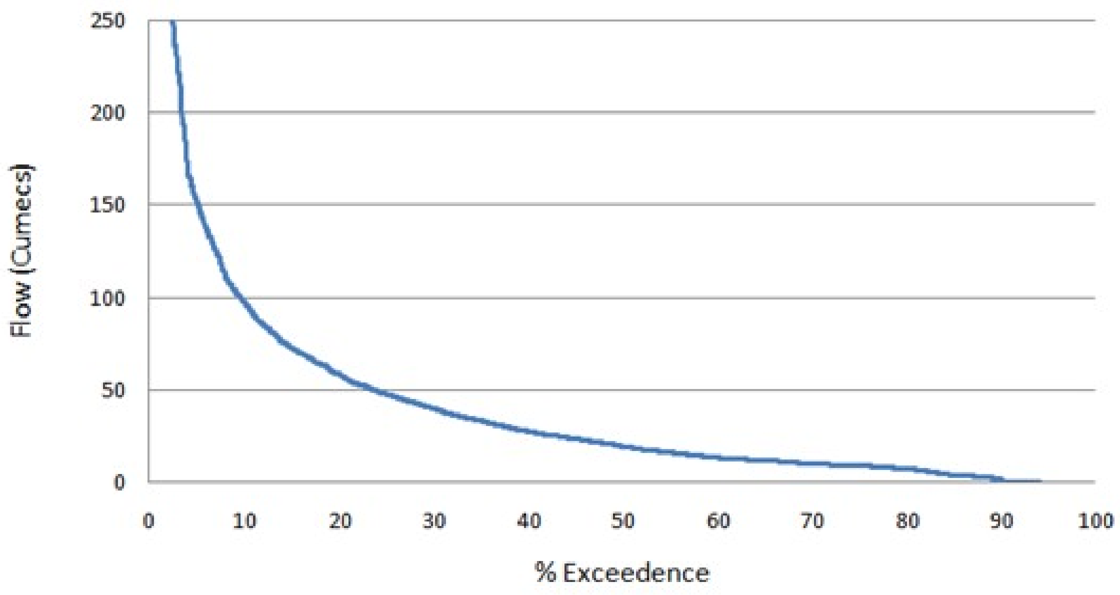

Figure 13: Flow duration Curve for Sehonghong (Senqu River at Sehonghong)

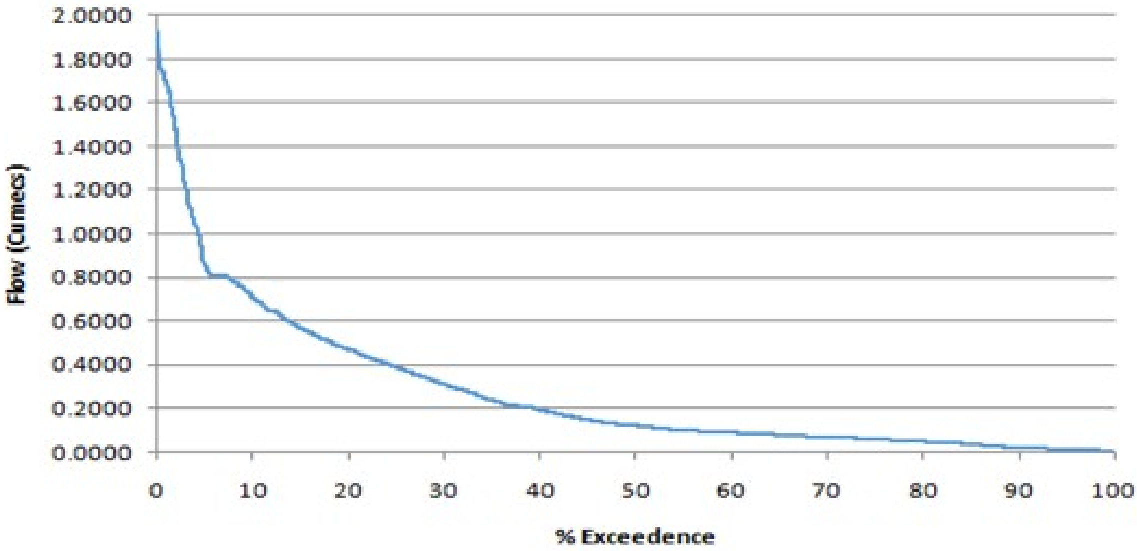

Figure 14: Flow Duration Curve for Mashai (Mashai River at St Theresa)

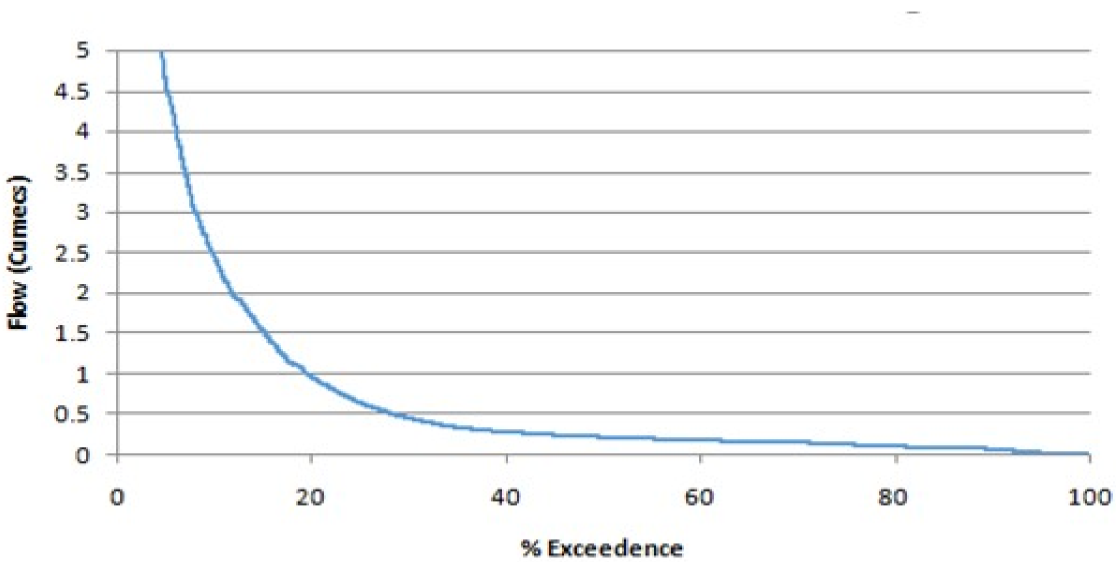

Figure 15: Flow Duration Curve for Matsoaing (Sehonghong River at Ha Mamolibeli)

According to Nasir [99] and [98], in order to ensure that the hydropower plant operates most of the time whenever there is flow, it is best to use the mean flow rate or at least the flow rate between 10 % and 70% exceedance as the design flow. The chosen design flow rates are 47.57 m^3/s, 0.27 m^3/s and 1.05 m^3/s for Sehonghong, Mashai and Matsoaing, with the percentage exceedance of 21.1%, 32% and 16.5% respectively.

4.2 The head

The determination of head was done after careful placement of intake and powerhouse as explained in section3.1.3. Figure 16, Figure 17 and Figure 18 show the schematic layout of the systems for Matsoaing, Mashai and Sehonghong respectively. For Matsoaing (Figure 16), the intake is at 2,150 m elevation while the power house is located at 2,125 m. For Mashai (Figure 17), the intake is at 1,825 m while the power house is at 1,800 m. As can be seen from Figure 16 and Figure 17 there is no other contour line between the two contour lines where the intake and the power house are placed; meaning the gross head is equal to the contour interval of the topographic map, which is 25 m for both Matsoaing and Mashai.

It is a different case with Sehonghong (Figure 18) because a different topographic map of 10 m contour interval was used. The reason for using a different map is that Sehonghong seemed to be a little flat on the map, and the map with smaller contour interval had to be used. The intake is placed at 1,710 m while the power house is at 1,700 m, giving a gross head of 10 m. To get the net heads, Equation 4 and Equation 5 were used. The resultant net heads were found to be 16.67 m for both Matsoaing and Mashai and 6.67 m for Sehonghong.

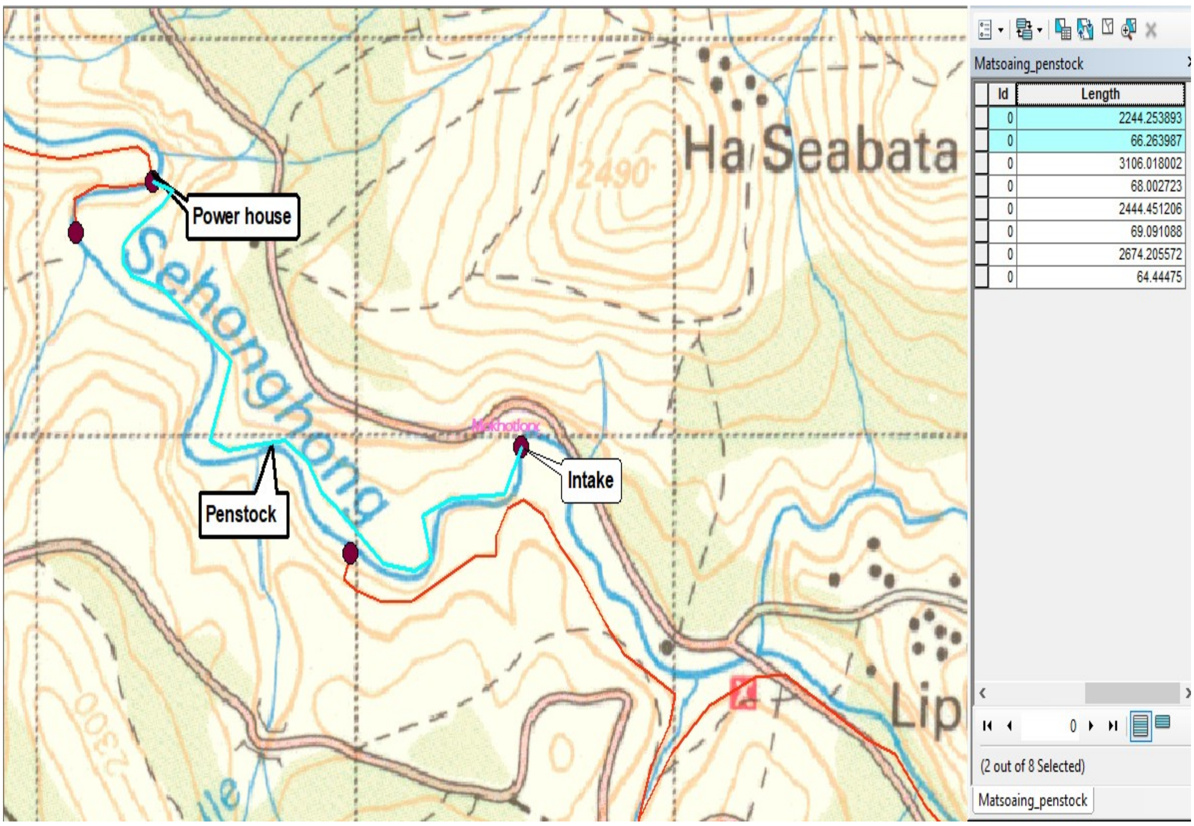

Figure 16: Contour lines and system layout for Matsoaing

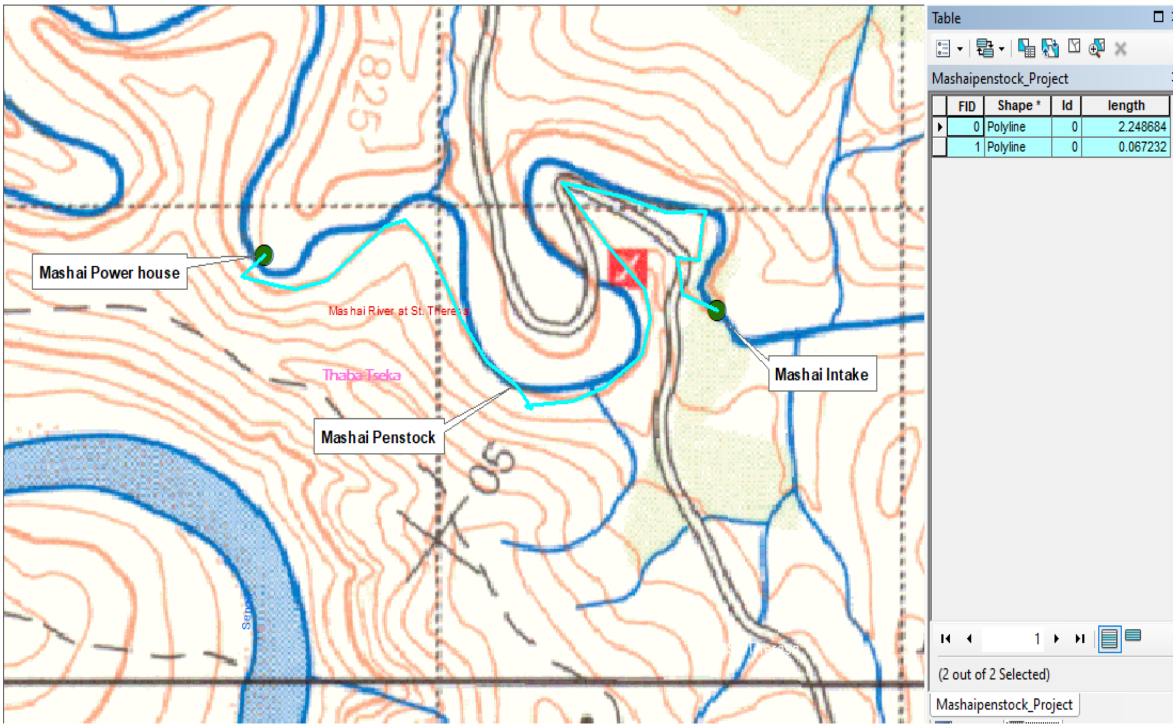

Figure 17: Contour lines and system layout for Mashai

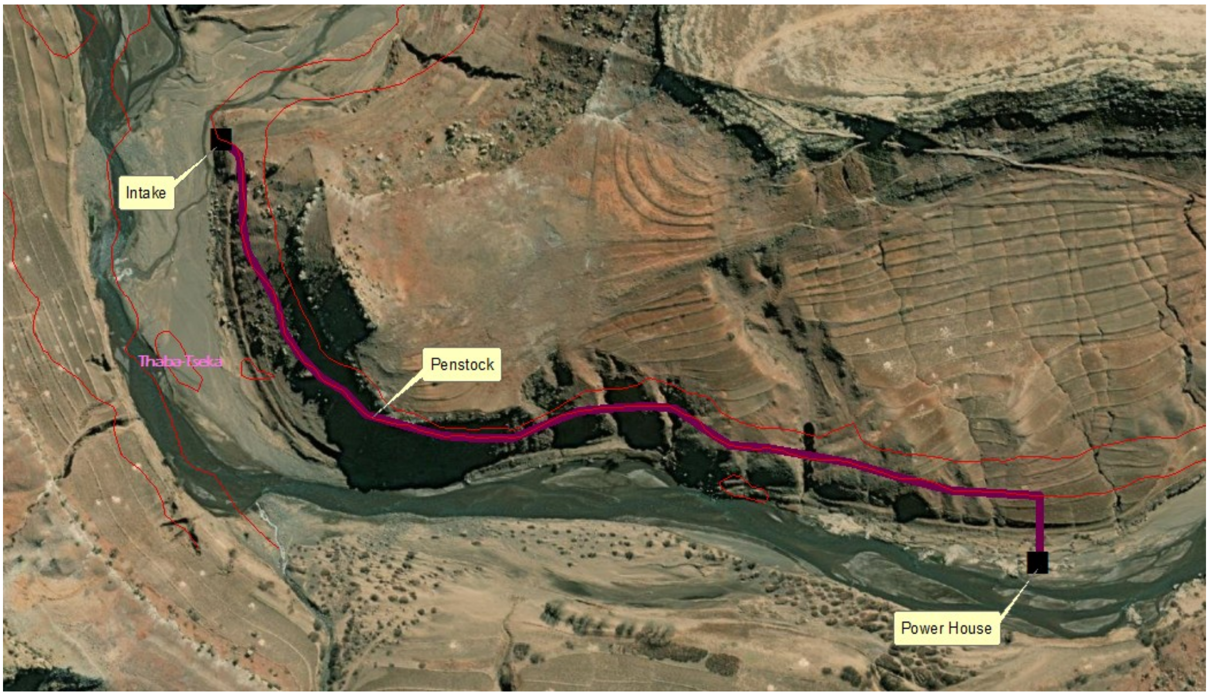

Figure 18: Contour lines and system layout for Sehonghong

4.3 Maximum Electrical Power

To find the potential maximum power that can be produced from the three sites, Equation 6 was used for computation of power at each site. The maximum power that can be produced at Matsoaing, Mashai and Sehonghong is 171.71 kW, 44.15 kW and 3,112.63 kW, respectively.

4.4 Hybridization feasibility through HOMER software

This section presents and discusses the feasibility results of the three hybrid systems for the three areas based on the economic and technical performance of the systems. The purpose of investigating the feasibility of hybrid systems in those areas is because the renewable energy resources (solar and hydro in this study) are intermittent; the sun is not available at night and during cloudy days while the water resource is not available during drought. So, project developers are interested to know how the system will be able to perform using these renewable resources for proper planning of the systems. The following sub-sections will discuss the primary load, simulation and optimization results.

4.4.1 The primary load

The daily demand profiles for all the months as generated from the 1Power survey were used to generate the daily, seasonal and yearly profiles. The average energy demand to be met by Matsoaing system is 78.92 kWh/d with a peak load of 8.45 kW as depicted in Figure 19. The daily profile shows that the pick demand will be in the morning between 6am and 9am and again later in the evening between 6pm and 9am these are the times when residents are at home using electric appliances for different purposes. The seasonal profile shows that the seasonal peak iis reached in July, which is the coldest month of the year and residents normally use energy for space heating. The load factor is 0.39 and is not good as it means the load is not using the system that efficiently; the peak is reached occasionally while the system is idling for most of the time.

The average demand for Mashai is 103.41 kWh/d with peak load of 10.34 kW as shown in Figure 20 while for Sehonghong the average demand is 154.75 kWh/d with a peak load of 15.41 kW. The daily and seasonal profiles for Mashai and Sehonghong follow the same pattern as that of Matsoaing. The load profile is however 0.42 for both areas, which is relatively better as compared to Matsoaing.

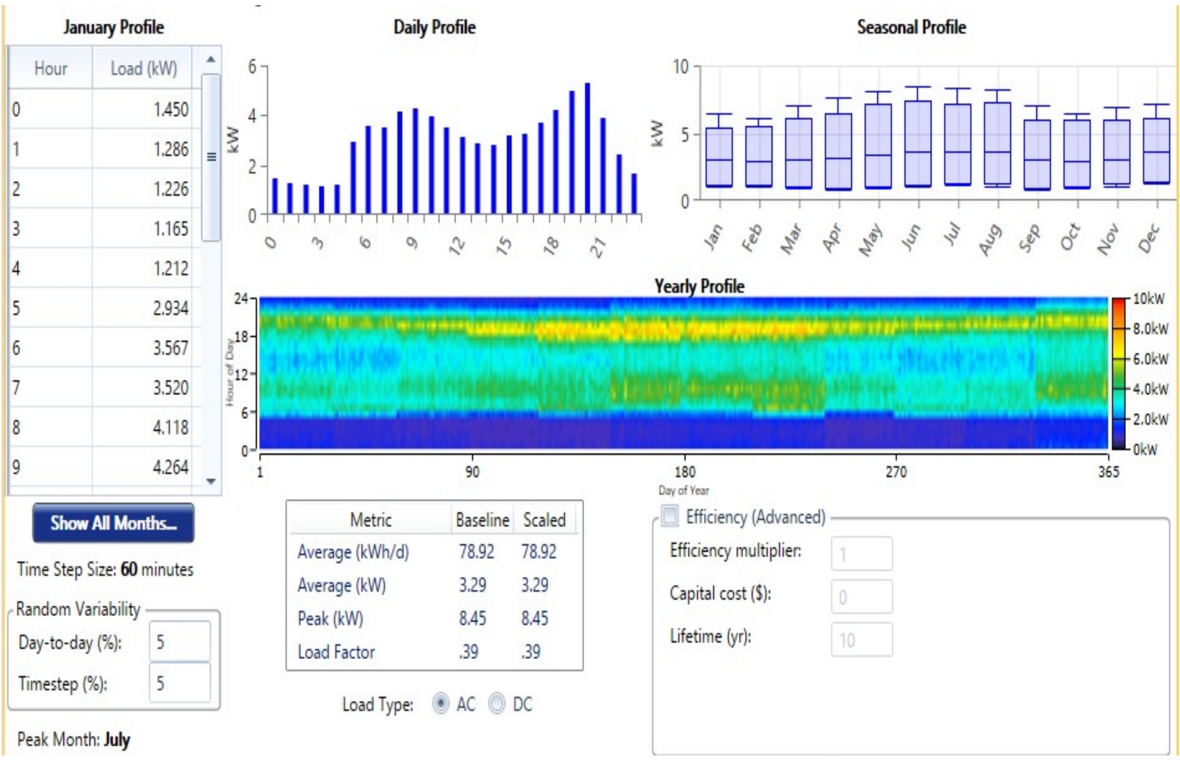

Figure 19: Daily, seasonal and yearly load profiles for Matsoaing

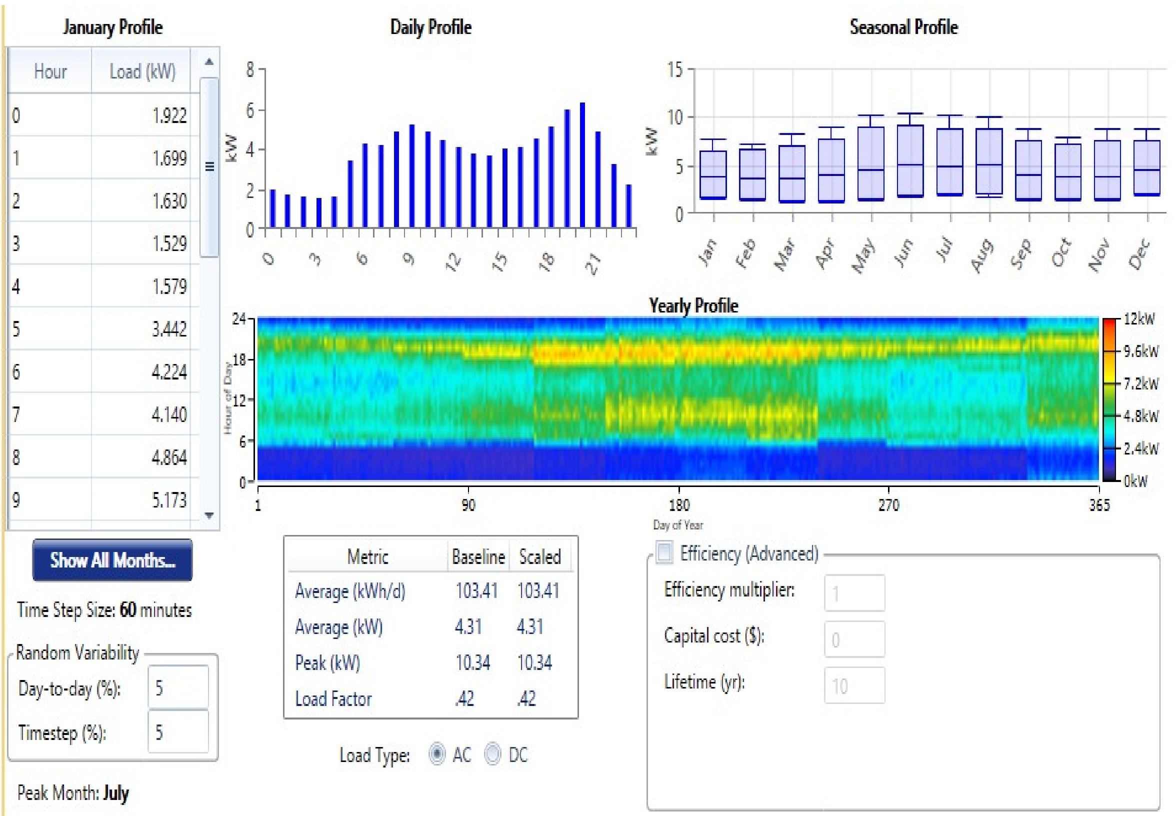

Figure 20: Daily, seasonal and yearly load profile for Mashai

Figure 21: Daily, seasonal and yearly load profile for Sehonghong

4.4.2 Simulation results

4.4.2.1 Matsoaing simulation results

Based on the input components specifications, fuel costs, capital costs and sensitivity parameters, the simulation results produced the following results as shown in Figure 22. The optimum system is a hybrid solar-hydro system which comprises of 24 kW generic flat plate, 10 kW diesel generator, 5 kW hydro turbine and 48 kW converter. The diesel generator is included to ensure reliability in the event where there is no sunlight, and it is during the dry season. The Net Present Cost is the main selection criteria for the optimum system. The Net Present Cost for the optimum system is $79,184 while the LCOE is $ 0.184. HOMER has ranked the feasible systems; the system with the lowest NPC and lowest LCOE is ranked as the most profitable system.

PV (kW)	Gen10 (kW)	LI ASM	Hyd5 (kW)	PRET48K (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
9.00	10.0		35.3	48.0	LF	$0.184	$79,184	$3,348	$29,200	84.0	2,029
12.0	10.0	70	35.3	48.0	CC	$0.288	$123,652	$3,177	$76,226	94.0	778
24.0		140	35.3	48.0	LF	$0.464	$199,349	$4,044	$138,974	100	0

Figure 22: Simulation results for Matsoaing hybrid solar-hydropower system

It can be observed from Figure 23 that the hybrid system will produce 293,957 kWh/year, and out of that, 5.50% will come from the solar PV system, 1.56% will be from the diesel generator while a bigger portion of 92.9% will be from hydropower. However, hydropower will not produce in July and October which are normally dry months in Lesotho. During those months, it is when the importance of hybrid system is realized. If the system was of hydro only, it means there would not be any power production during those dry months, but this system seems to have zero (0) unmet load due to the two resources supplementing each other. The hybrid system will have a renewable fraction of 84.0, meaning the system will operate more from renewable sources and less from the diesel generator.

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Production	kWh/yr	%
Generic flat plate PV	16,177	5.50
Generic 10kW Fixed Capacity Genset	4,596	1.56
Hydro	273,184	92.9
Total	293,957	100

Consumption	kWh/yr	%
AC Primary Load	28,805	100
DC Primary Load	0	0
Total	28,805	100

Quantity	kWh/yr	%
Excess Electricity	265,137	90.2
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value
Renewable Fraction	84.0
Max. Renew. Penetration	6,250

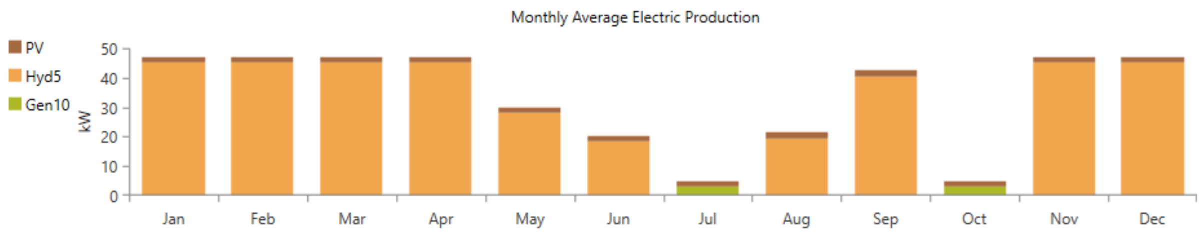

Figure 23: Electricity production results for Matsoaing hybrid system

4.4.2.2 Mashai simulation results

The Mashai hybrid solar-hydro system comprises of 24 kW generic flat plate, 10 kW diesel generator, 1 kWh/276 Ah battery storage, 5 kW hydro turbine and 48 kW converter. The optimum system includes the Solar PV, hydro and diesel generator as shown by the ranking of the feasible systems in Figure 24 (the top most system). Using the Net Present Cost as the main selection criteria for the optimum system, the NPC for the optimum system is $ 375,411 while the LCOE is $ 0.666.

					PV (kW)	CAT-20 (kW)	LI ASM	Hyd5 (kW)	Conv (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
					24.0	16.0	168	39.7	14.0	CC	$0.666	$375,411	$14,431	$159,953	94.3	708
					12.0	16.0		39.7	14.0	CC	$5.57	$3.14M	$206,813	$49,300	55.4	6,636

Figure 24: Simulation results for Mashai hybrid solar-hydropower system

It can be observed from Figure 25 that the hybrid system will produce 242,666 kWh/year, and out of that, 17.8% will be from the solar PV, 0.892 % will be from the diesel generator while a bigger portion of 81.3% will be from hydropower. During the months of June and July, the system will generate from solar and diesel generator only. Those are the months when the country experiences drought. However, there will be zero (0) unmet load. The hybrid system will have a renewable fraction of 94.3, which is still high enough.

Production	kWh/yr	%
Generic flat plate PV	43,283	17.8
CAT-20kVA-50Hz-PP	2,165	0.892
Hydro	197,217	81.3
Total	242,666	100

Consumption	kWh/yr	%
AC Primary Load	37,744	100
DC Primary Load	0	0
Total	37,744	100

Quantity	kWh/yr	%
Excess Electricity	203,193	83.7
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value
Renewable Fraction	94.3
Max. Renew. Penetration	4,466

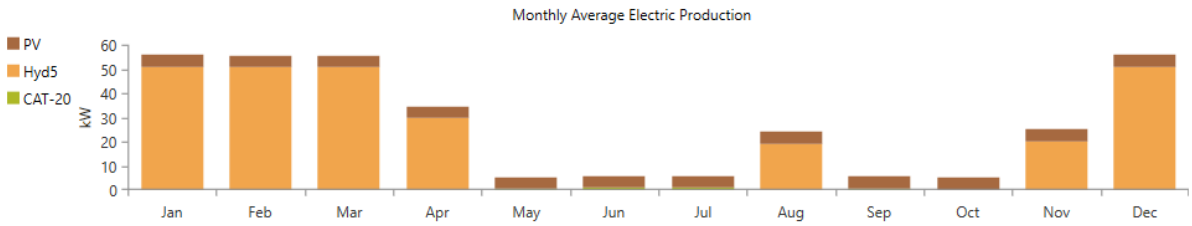

Figure 25: Electricity production results for Mashai hybrid system

4.4.2.3 Sehonghong simulation results

The Sehonghong hybrid solar-hydro system comprises of 24 kW generic flat plate, 1 kWh/276 Ah battery storage, 10 kW hydro turbine and 25 kW converter. The optimum system includes the Solar PV, hydro, the battery storage together with the converter as shown by the ranking of the feasible systems in Figure 26 (the top most system). Using the Net

Present Cost as the main selection criteria for the optimum system, the NPC for the optimum system is $ 369725,960 while the LCOE is $ 0.483.

PV (kW)	CAT-20 (kW)	LI ASM	Hyd10 (kW)	Leon25 (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours
24.0	16.0	84	3.66	25.0	CC	$0.438	$369,725	$12,361	$185,166	95.0	921	181
24.0	16.0		3.66	25.0	CC	$2.98	$2.51M	$159,195	$138,050	52.5	10,634	5,974

Figure 26: Simulation results for Sehonghong hybrid solar-hydropower system

It can also be observed from Figure 27 that the hybrid system will produce 83,353 kWh/year, and out of that, 52% will be from the solar PV, 3.37% will be from a diesel generator while 44.6% will be from hydropower. Both resources (solar and hydro) will be available throughout the year; but will be limited in June and July. That is when the country normally experiences drought and the sunshine hours are short, so there is a need for a backup generator. There will be zero (0) unmet load with renewable fraction of 95%.

Production	kWh/yr	%
Generic flat plate PV	43,357	52.0
CAT-20kVA-50Hz-PP	2,807	3.37
Hydro	37,189	44.6
Total	83,353	100

Consumption	kWh/yr	%
AC Primary Load	56,485	100
DC Primary Load	0	0
Total	56,485	100

Quantity	kWh/yr	%
Excess Electricity	24,688	29.6
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value
Renewable Fraction	95.0
Max. Renew. Penetration	529

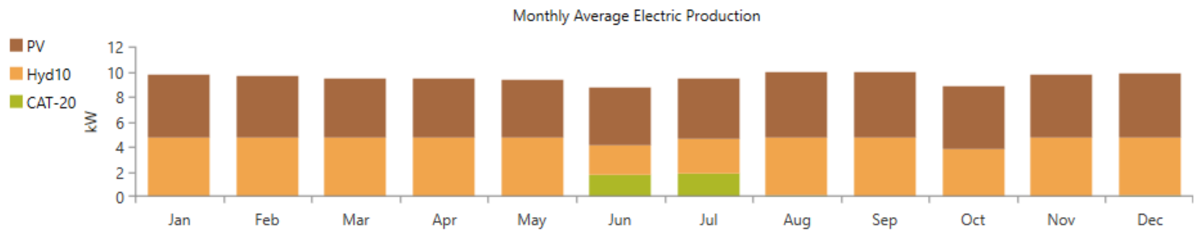

Figure 27: Electricity production results for Sehonghong hybrid system

Chapter 5: Conclusions and recommendations

5.1 Conclusion

The study investigated the availability of water resources at three (3) sites earmarked for solar mini grids development for potential integration of micro-hydro power with solar mini grids to form a hybrid system. Three (3) sites were selected based on the availability of water resources, population size, accessibility, catchment area and availability of hydrometric stations. The selected sites were Matsoaing, Sehonghong and Mashai.

In chapter one of the study, the background of the study was provided together with the problem that needs to be addressed and the questions that the study aimed to answer. The chapter further set out the scope of the study. Chapter two reviewed the available literature; both theoretical and empirical and identified methodologies and techniques used in the field. The objective of this chapter was to establish similarities and differences in the methodologies and identify gaps that the current and future studies need to fill. In chapter three, the methodology used has been outlined together with data used, its sources and collection and analysis methods. The assumptions and limitations of the study have also been described in chapter three. Chapter four presented and interpreted the study results, linking them with the literature and objectives of the study.

The results demonstrated that the average discharges for Matsoaing, Sehonghong and Mashai were found to be 1.05 m^3/s, 47.57 m^3/s and 0.27 m^3/s, respectively while the available heads based on the locations of the intake and power house were found to be 16.67 m for both Matsoaing and Mashai, and 6.67 m for Sehonghong. Based on the average flow rates and available heads, the maximum hydropower that can be produced in Matsoaing, Mashai and Sehonghong is 171.71 kW, 44.15 kW and 3,112.63 kW, respectively.

The study went further to assess the possibility of hybridization of micro-hydro power with solar mini grids, and the results revealed that hybridization is possible in all three sites. With the hybrid systems, there will be power generation throughout the year, even when one of the resources is unavailable, i.e., when it is cloudy or during dry season. This is revealed by the zero (0) unmet load in all the study sites. Hybridised power systems are therefore reliable, cost-effective and sustainable way of providing electricity to the areas. This is because inherently, the places have enough water supply and head which could potentially produce enough electricity to the areas.

The methodology and results obtained in this study could serve as a basis for the creation of hydroelectric information system for the country, which could be employed as a decision making tool in renewable energy matters. The approach could be adopted to support electrification decentralization and thus guarantee energy security in Lesotho.

5.2 Recommendations

Considering this study, additional or future work to assess the hydropower potential should include:

- An assessment of the impacts of climate change combined with several scenarios of land use at different climatic horizons. In addition, other aspects should be considered in future research to identify potentially exploitable hydropower generation sites, namely, economic feasibility, social profitability, legal/geopolitical constraints, and water use conflicts.
- As the literature has revealed, FDC is an important method in hydrological calculations for the estimation of water resources for hydropower planning. Although the data provided by the DWA and LHDA suffice for this study, it is recommended that future studies should consider improving the reliability of the FDCs by verifying the observed FDC with the simulated FDC through rainfall run-off models.

- Additionally, since Lesotho has a huge number of graduates within the engineering departments, it would be worthwhile for government and policymakers to consider absorbing this skill to generate green energy; investing in solar and hydro energy using specialized skills that already exist in the country. Whilst water engineering is still a rare skill, the current skills would suffice to run an efficient hybrid station. Initially, the capital costs would be hefty however would be written off by the recurring benefits to communities and potential commercial sites which would come to be.
- The government of Lesotho as a signatory to 2030 Agenda for Sustainable development, has a responsibility to contribute to the attainment of goal 7; ensure access to affordable, reliable, sustainable and modern energy for all. It should embark on off-grid electricity generation to reduce dependence on the EDM and ESKOM imported electricity. This will in the long-run reduce the electricity cost and carbon emissions since electricity would be greener for the country. Lesotho has potential in the solar, hydro-powered and wind energy production due to the terrain (for hydro stations), altitude (wind power) and sunshine all year round (for solar energy) which could make it an independent electricity producer in Southern Africa.
- It is recommended that further feasibility studies be conducted in other areas of the country on possibility of hybridization of micro-hydro power with solar mini grids to inform planning and development of renewable energy projects to ensure that the majority of remote rural communities get access to electricity.
- Lastly, the study recommends that the Energy Research Centre and Ministry of Energy and Meteorology should pilot mini grids in the areas already studied to inform further implementation. Piloting can be done to generally generate evidence on the challenges and merits of the country to generate green energy.

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