National University of Lesotho

Analysis of Quthing River and Letseng-la-Letsie for Hydropower Potential

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A dissertation submitted in partial fulfilment
of the requirements for the degree of

Master of Science in Sustainable Energy

Offered by the

Energy Research Centre
Faculty of Science & Technology

February2020

Abstract

This dissertation presents the analysis of Quthing River and Letseng-la-Letsie for hydropower potential in Quthing district in Lesotho. Electrical power deficit in the country is more prominent in rural areas like Quthing District. This calls for assessment of electrical sources in the vicinity of rural area load centers to inform policies for electrical production so as to curb power deficit problem. Mountain Rivers like Quthing River with steep slopes or gradients naturally provide good head which needs to be assessed along with its flow rates. Furthermore elevated dams like Letseng-la-Letsie can also provide a natural good head which needs to be assessed alongside with its discharge rates. The assessment was carried out by employing catchment area method to asses flow rates since the abstraction points of the study areas were ungaged and lacks data. The maps in association with QGIS were used to evaluate heads of the study areas and lastly TURBNPRO was used to determine power outputs from the study areas.

The resultant net head for Quthing River was found to be 164.15 m while the net head for Letseng-la-Letsie was 159.23 m. The design flow rate of Quthing River was found to be 0.58 m^3/s while that of Letseng-la-Letsie was 0.116 m^3/s. The results from TURBNPRO showed that the power output for Quthing River turbine was 815 kW while the power output for Letseng-la-Letsie turbine was 221 kW. Using typical hydro-electric generators efficiency of 99% and typical capacity factor for Africa of 0.49, the capacity from Quthing River was found to be 807 kW with annual energy of 3.46 MWh. The capacity for Letseng-la-Letsie was found to be 0.22 MW with annual energy of 0.95 MWh.

Acknowledgements

Firstly, I would like to thank all the lectures for the great effort they took to capacitate me with multidisciplinary knowledge. You were not just lecturers but also counsellors. In a special way, I really thank Dr. L. Khaba and Dr. M. Makhele for unceasing guidance throughout the work of this thesis.

Secondly, I would also like to thank all my colleagues for unity and team spirit for the success of all team members.

Thirdly, but not the least, I would like to thank my wife and my children for sparing me some of the family time and the courage that they offered me.

Lastly but the greatest, I would like to thank my Lord Jesus Christ for the strength, courage and wisdom when the studies get tough.

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Chapter 1: Introduction

Quthing is one of the districts which have low access to electricity in Lesotho. This is due to the fact that Lesotho is currently (in 2019) capable of producing 66% of electricity used in the country. The other 44% of the electricity is imported from Mozambique and Republic of South Africa (RSA) to meet the country demand[1],[2],[3]. This deteriorates the poor economy of the country.

The common primary electrical power resources of RSA are coal which tend to pollute the environment dramatically[4].The environmental pollution is one of the factors that cause climate change. The climate change affects the community both socially and economically such that extreme flooding and droughts may influence migration of people or change their way of life [5]. It is therefore necessary for the country to conduct studies to analyse its electrical power resources in order to eventually overcome the thread of power security, environment pollution and economy deterioration.

1.1 Background

The global emerging economies are put under pressure of harnessing power using the natural resources. Quthing River and Letseng-la-Letsie are part of tributary sources to the biggest river in Lesotho called Senqu River which also known as Orange River in the Quthing district. Currently only the small portion of Letseng-la-Letsie (about 20% of the catchment area) is considered as a type of wetland under Ramsar convention (international convention with the objective of conserving and ensuring wise use of wetlands) implying that 80% percent can still be accessible for hydropower. This implies that Quthing River and Letseng-la-Letsie have few competing uses of their water resources yet their terrain is conducive for hydropower potential. It is therefore necessary for hydropower potential analysis to be carried out, within these catchments, to expand access to electricity for Quthing rural communities in the country.

1.2 Statement of the research problem

As an initiative to improve electrical power deficit in the country, Lesotho took an effort to earmark most of its rivers for hydropower generation. Most of the big rivers were considered for hydropower generation along with phase II of Lesotho highlands development Authority (LHDA). In addition to this, other rivers were considered for hydropower generation under Scaling-up

Renewable Energy Program (SREP). However, the generation capacities tabulated in SREP report are only indicative because specific weekly water flows were not provided[9]. This absence of flow rates can create a loop hole for the consultant should the study prove to be flawed. The study with only indicative results has low likelihood for the attraction of investors to continue with the project. Furthermore, the study with only indicative results increases the overheads of the project making it more expensive and impossible to start. This calls for the verification of results through analysis.

1.3 Significance

Though the indicative results of hydropower potential were provided, the hydropower output varies with flow rates which change frequently throughout the years. It is therefore necessary to investigate the instantaneous flow rates of the streams so as to provide flow duration curves and output power duration curves. The duration curves are most significant components which can provide the proper information concerning the choice of rated hydropower output.

1.4 Research objectives

The objectives of this research are: firstly, to explore and evaluate hydropower potential of Letseng-la-Letsie and Quthing River. This assessment is intended to provide reconnaissance information to support in the decision making of policy makers and developers (like Independent Power Producers) so that these developers will be able to develop power plants to solve the power deficit and decrease the amount of electricity imported. Secondly it indirectly contributes to fulfilment of Lesotho National Strategic Development Plan (increase clean energy production capacity and develop small-scale electricity generation models that are viable for communities, where connection to the national power grid is not cost-effective) and mobilise implementation of Lesotho Energy policy (Energy shall be universally accessible and affordable in a sustainable manner, with minimal impact on the climate).

1.5 Research questions

The research, particularly aims to answer the question of whether the indicated rated power in SREP falls within the acceptable range of Quthing River hydropower potential. The other question aimed is whether the hydropower will be implemented as Run-off River or involve the reservoir. Finally, the question of how to reduce degradation due to sedimentation and siltation will be addressed.

1.6 Outline

Apart from the introduction, Chapter 2 is the literature review in which background information on the subject matter is discussed. The chapter that follows the literature review is methodology, whereby the procedures used for determining flow rates, head and sizes of electrical and mechanical equipment are detailed. After methodology, results are presented in chapter 4 and their interpretation is detailed. The final chapter is the conclusion, whereby critical matters are summarized and recommendations for further work are made.

Chapter 2: Literature Review

2.1 Key parameters assessed

The kingdom in the sky (Lesotho) is blessed with huge volumes of white diamond (water) to the extent that some of it is sold to neighbouring countries. The other benefit that can be reaped from water is utilising it for developing hydropower stations in the country. In order to develop the hydropower project different levels of studies need to be conducted starting with desk-top study up to the project implementation stage. In this study the components of interest are analysed at the reconnaissance level. The first components to be analysed are the main input resources of hydropower plant which are head and water flow rate.

2.1.1 Flow rate assessment

Water flow of a river is directly related to the quantity of water moving off the watershed into the river. The flow may vary due to weather, such that it rises during rainstorms but decreases in dry periods. It also varies according to different seasons of the year, decreasing throughout summer months due to high evaporation rates and active growth of shoreline vegetation removing water from the ground. In United States, the lowest flow is experienced in August and September[10]. However, in Lesotho flow rates increase during summer months due to abundant rainfall but decreases in winter seasons due to low rainfall. The lowest flow is usually experienced in June and July while the highest flow is experienced during December and January.

There are many different ways or methods that can be used to assess the flow rate of hydropower plant. These range from the methods that use physical measurement tools at the site, to methods that use remote sensing measurement tools.

a) Salt method

The variability of the channel geometry parameters together with channel bumpiness makes it very difficult to measure or calculate the river flow rates in mountain Rivers. In mountain rivers, salt tracing method tend to be a better technique for measuring average flow rate of the river[11]. The Salt-dilution technique for measuring the flow rates has been previously used successfully[12].

The roughness of the river in mountains and henceforth the turbulence, makes it easy for the salt to dissolve in water resulting in proper measurements[11],[12].The technique is also known for its simplicity and quickness. In addition to that, the equipment used is a portable PH meter while the tracer is ordinary salt (sodium chloride) which is less costly and insignificantly pollutes the stream. The equipment and the tracer can easily be made available from most water resource centres[11],[12]. Though this method seemed to be appropriate for turbulent streams in the mountains and less costly, it can be costly for frequent (daily) measurements spanning a long period of time. This is mainly due to the salt consumption.

b) Float method

Float method is mostly applicable for large rivers for flow measurement. Regarding the measurement of flow rate through the open channel, this is one of the simplest methods. The concept entails the measurement of surface velocity of water using a floating object. The dimensions of the river width and average depth also need to be measured. The resultant flow rate is the product of velocity with both the river width and average depth of water. Though the method is simple, it is less accurate than salt method. Since the method works perfectly where the width of the river is constant, it is unsuitable for the mountain Rivers with uneven width. This renders method inappropriate for the study case area (Quthing River and Letseng-la-Letsie).

c) Weir method

A weir is a wall of a barrier built across the width of a stream which creates a low head dam. The barrier has got the opening with typical shape of rectangle, triangle or any other shape with which the area of the opening can be easily determined. With the definite area of the weir opening, the flow rate can easily be calculated.

The measurement of flow rate using a weir is based upon analysis of flow conditions as it passes over the weir crest. The simplest setup is experienced when a sharp-crested weir impounds a pool of still water. With this configuration the critical velocity is achieved as the flow passes over the crest. This critical velocity occurs when the critical depth of flow is two-thirds of the height of the pool above the weir crest. Since the critical depth of the flow is directly related to the critical velocity, the discharge in the channel can then be determined from the measurement of the height of water in the pool behind the weir. These relationships are derived from the Bernoulli equation[13]. The shortcoming of this method concerning Mountain Rivers like Quthing is heavy siltation which may offset the height of crest. In addition to that, this method is more expensive than float and salt method. The expenses are due to construction of weir.

d) Current meter method

In current meter method, the cross section of the river is divided into several vertical subsections. The area of each subsection is determined by measuring the width and depth of the subsection. The velocity of water is obtained by using a current meter. The flow rate in each subsection is then calculated by multiplying the subsection area by the velocity measured. The total flow rate is then determined by summing the flow rates of each subsection of the river[14].

The tools that can be used to measure subsection width include steel tape, cable or similar piece of equipment while depth can be measured using tools such as wading rod or by suspending a weight from a calibrated cable and reel system off a cableway, bridge or a boat. The velocity is measured either using vertical axis meter or horizontal axis meter. Both meters measure velocity by translating the linear motion of flowing water into rotational motion. As the meter rotates, it transmits an electronic signal on each revolution so that revolutions can be counted and timed. The velocity of water is therefore determined from the rate of the rotation of current meter rotor[15]. The common meter types are Price Type AA meter, WSC winter meter and Pygmy meter. United States Geological Survey (USGS) has used this method for decades [14].

e) Stream Stage rating curves

The most important concept for analysing the flow of water in a stream at any given moment is stage discharge relationship. The relationship between the stage and discharge for river and channel flow is determined by simultaneous measurements of stage (the level of water above some arbitrary point in the river) and flow rate. The flow rate can be established through the methods including the ones mentioned in 3.1.1 through 3.1.5. The stage-discharge relationship is dynamic and unique for selected station within the river. Mathematical equations can be used to determine these relationships[16].

This method works with a chart which can be developed by plotting the gauge heights and measured flows from relevant flow measurements. The gauge height (dependent variable) is plotted on the x-axis and the discharge (independent variable) on the y-axis. Thus, contrary to normal plots, the slope of the line is x/y[17].

The plots are done on logarithmic (log) paper since it has got advantages over other types of grids, rendering it to be the principal tool for graphic rating analysis. A log rating curve consists of curvature, slope, and an intercept that are relative to channel characteristics. The logarithmic curve can be straightened by adjusting the gauge-height scale, so that it can be represented simply by equation 1[17].

$$Q = P(G - e)^b \quad \text{--} \quad (1)$$

Where: b is the slope of the straight line.

e is the scale offset

G is the gauge height

P is the Q intercept which is equal to Q when (G-e) is equal to 1

Q is the discharge.

Slope greater than 2 indicates channel control while slope less than 2 indicates section control. The value of **e** for segment rating can be determined by trial and error whereby variety of trial values are added or subtracted from the numbered scales on the logarithmic grid until a straight-line rating is obtained. This process is illustrated in Figure 1[17].

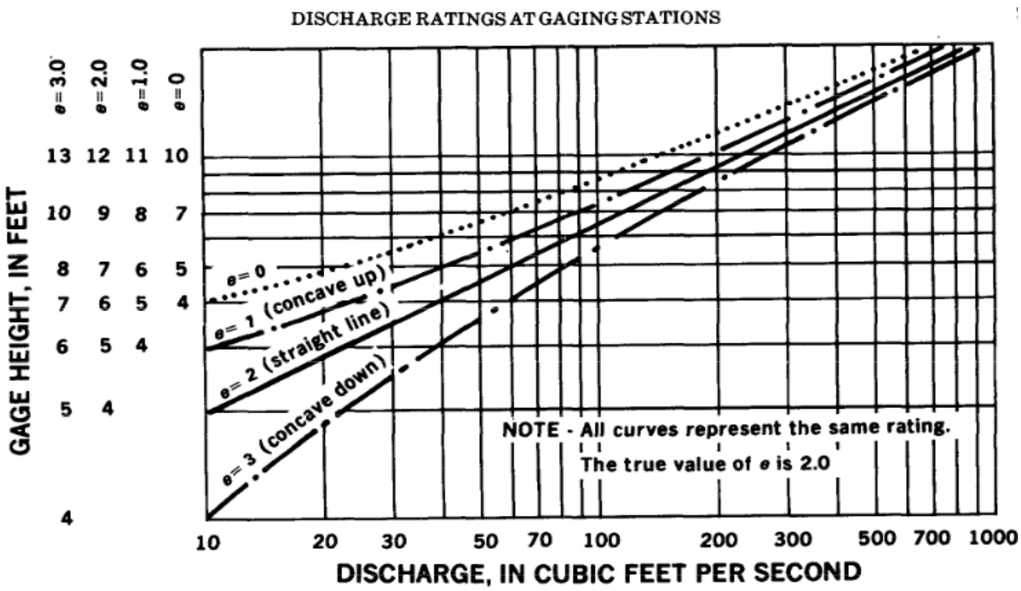


Figure 1:Hypothetical Rating curve shapes resulting from different gauge-height scale offset[17].

Alternatively, the offset, e, can be determined with a more direct method (Johnsons method). In this case the curve is straightened by subtracting the scale offset from each value of gauge height. The lower and upper bound coordinates are picked by using the normal logarithmic scales. The discharge at the midpoint is computed such as a square root of the product of upper and lower bound discharge [17]. Ultimately the offset is given by equation 2.

$$e = \frac{G_1 G_2 - G_3^2}{G_1 + G_2 - 2G_3} \quad \text{---} \quad (2)$$

The resultant graph derived from offset determined with a direct method is shown in Figure 2, indicating the solid curve which was straightened to assume the dotted line.

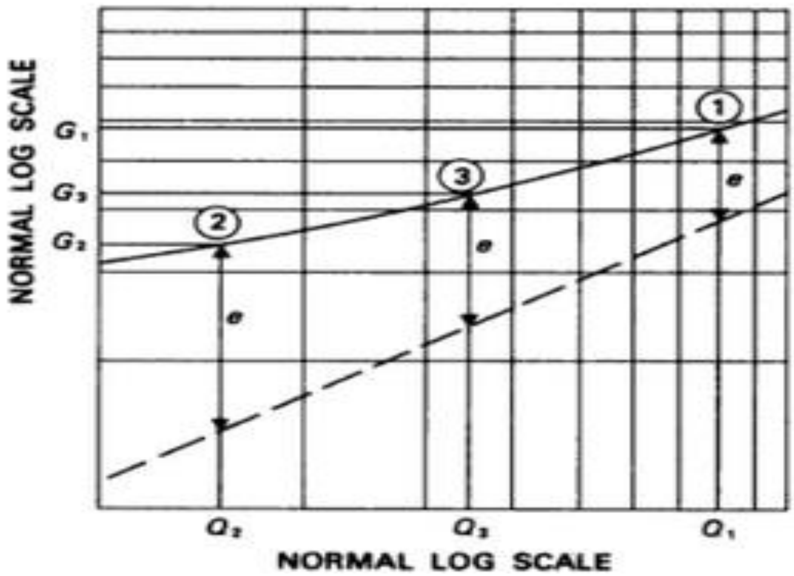


Figure 2: Stage Gauge curve determined by Johnson's method
[Source: Department of the Interior, U.S. Geological Survey]

2.1.2Ungauged Stream flow rates

The department of water affairs in the country, Lesotho, is entrusted with observation and maintenance of an extensive network of river gauges. The maintenance of river flow rates is however not very effective because most of the rivers do not have gauging stations. In spite of this, future water development resources projects and studies like hydropower projects will possibly require the analysis of water availability and quality for water supply at ungauged sites[19],[20].It is critically important therefore to employ the ability of estimation of flow in ungauged catchments.

a) Stream flow Statistics and Spatial Analysis Tools

Another technique is applying computer applications, from USGS, called StreamStats and BaSE. StreamStats, which is GIS program that allows users to easily obtain stream flow statistics, drainage-basin characteristics, and other information for user-selected sites on streams. BaSE can estimate daily mean stream flow by equating stream flow as a percentile from a flow duration curve for a particular day at an ungauged location with stream flow as a percentile from the flow duration curve for the same particular day at a reference stream gauge that is considered to be hydrologically similar to the ungauged location.

This is achieved by first delineating the ungauged stream using delineation tool in StreamStats. Once the delineation is complete the statistics of the basin characteristic are populated in StreamStats and then downloaded as a Microsoft Database file. BaSE will then match the downloaded database with the most hydrologically similar to the gauged site database file to act as a source of stream flow resources. The reference gauged site that is closer to ungauged site provides the same local weather conditions as the ungauged location. The final product is an excel report that includes stream flow data, exceedance probabilities, basin characteristics, and hydrographs for the ungauged site. The concern with this technique is that the reference site may be geographically distant from the ungauged site, hence localized summer thunderstorms are missed[22].

b) Rainfall-runoff Simulation and Model

The rainfall run off simulation method can also be used to determine flow rate at ungauged river basin. The typical example is the model which was used to simulate and model relations between rainfall and runoff in Karun River, South West Iran. The models were Hydrologic Engineering Centre-River Analysis System (HEC-RAS) and Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS).

HEC-HMS is generally responsible for transforming the drainage paths and watershed boundaries into a hydrologic data structure that represents the watershed response to precipitation. HEC-HMS changes precipitation into channel runoff producing hydrographs. Once the hydrographs are produced, HEC-RAS models the river channel network on the bases of HEC-HMS derived hydrographs[23]. The shortfall of the model is that it considers only rainfall and runoff, thus other sources of water are neglected.

c) Watershed area ratio method

The method which has stood the test of time and most common for estimating daily flow in an ungauged catchment is the watershed area ratio method. The watershed area ratio method is mostly relevant to estimate flow in an ungauged catchment in situations whereby a nearby gauged watershed is present for use as a reference. In this method the flow at an ungauged location is estimated by multiplying the measured flow at the nearby reference gauged watershed by the area ratio of the ungauged to gauged watersheds[21] using formula 3:

$$Q_{ungaged} = Q_{gaged} \times \frac{A_{ungaged}}{A_{gaged}} \quad \text{--} \ (3)$$

Q in the formula represents the flow rate of a river and A is the area of the watershed. This is done with the assumption that flow rate scales directly with watershed area, meaning that the watershed area increases as the flow rate increases at some fixed rate per unit area. This ultimately means that the flow per unit area is the same at both the ungauged location and gauged reference location[20].

Considering the topology of the study area, the method which is suitable for flow rates measurement is stream stage gauge. It is the method which is deployed by department of Water affairs for Quthing River. The method is simple and allows for daily readings to be recorded easily. The Watershed area ratio method was deployed for estimating the flow rates of both Letseng-la-Letsie and Quthing River hydropower proposed intakes. The method is best for providing flow rates of ungaged watershed because of its simplicity and test of time (formerly produced acceptable results).

2.2 Condition of flow

The flow of water can be broadly classified into three conditions. These flow conditions are laminar, transition and turbulent. The criterion that is used to determine the condition of water flow is Reynolds number the ratio of inertia force to viscous force. The flow is laminar if the velocity is low and the movement of particles are in straight lines. The laminar flow is practically characterised by Reynolds number which is less than 2000. The flow is transitional if the velocity is unstable due to the onset of turbulence. Transitional flow is practically characterised by Reynolds numbers ranging from 2000 to 4000. The flow condition is turbulent if the velocity of water is high and the movement of the water particles is irregular. Turbulent flow is practically characterized by the Reynolds number which is more than 4000. Turbulent flow is the most common flow condition in conduits and pipes like penstocks [24].

After going through the reviews of flow rate assessment and flow conditions, it is also equally important to review the head assessment methods as detailed in section 2.3.

2.3 Head assessment

a) Altimeters

Altimeters are helpful for determining high head for hydropower stations feasibility studies. Basically, altimeters are used to determine the altitude on the basis of atmospheric pressure measurements. In essence, pressure altimeter is a barometer supplied with nonlinear calibration to indicate altitude as opposed to pressure. The range of errors for surveying altimeters falls within 3%. The method can be fast and useful on medium and high heads greater than 40m[25].However, since the altitude is pressure dependent with this method, it is possible that readings can vary by tens of meters due to sudden change in pressure yet the actual altitude did not change[26]. It is commonly known in Lesotho that temperature in mountains can suddenly change and hence change the pressure which ultimately affects measured height. This method is therefore not convenient for the study area.

b) Direct Distance Measurement

In this method a contractor's level on a tripod (surveyor's transit) or a level taped to a straight board can be used to measure head. Along with transit, a pole with graduated measurements is also required. The assistance of the second person is also needed for carrying out the measurements. The measurements are taken by making a series of vertical measurements using the transit level and the vertical measuring pole between points of interests. The ultimate height or head is determined by summing up all the series heights[27].The error of this method on steep slopes is within 5% while it ranges from 10% to 20% when applied to long gentle slopes[25]. Though this method is one of the accurate ones, it cannot be easily applied to rugged mountains like the ones where Quthing River runs due to series of measurements in terrain which is not conducive.

c) MAP

Beside the altimeter and direct distance measurement there are many other methods which use different tools for measuring head. They include: Water-filled tube and rods; Water-filled tube and pressure gauge; sighting meters (clinometers or Abney levels); Builders' levels (Dumpy) theodolite and others. The precautions that have to be taken, for all of these methods, are repeated measurements and calibration of the tools used. The use of map is exceptional since the precaution is to validate the correct study site identified. The accuracy of using the map depends on the quality and scale of map. The method is more applicable to high heads[25]. Maps can be accessed from land surveyors at some cost but the readily available one can be derived from Digital Elevation Model (DEM).

The methodology which can therefore be suitable for head assessment for the study area at reconnaissance level is map due to its advantages over other methods.

2.4 Hydropower Plants facilities

Hydropower plants can be classified according to the type of facility or system construction. Hydropower plants facilities are generally divided into storage hydropower plants, which has got a reservoir large enough to keep or regulate runoff significantly; Run-Of-River (ROR) hydropower plants, which may have a weir/barrage and pondage (i.e., small storage relative to flow) but generally not large storage; and Pumped-storage hydropower which provides peak-load supply, using water which is cycled between a lower and upper reservoir by pumps which use surplus energy from the system at times of low demand[28].

These hydropower facilities can often overlap. For example, storage hydropower facility can often involve a feature of pumping to supplement the water that flows naturally into the reservoir, and run-of-river projects may be implemented with some storage capability to modify head or increase duration of flow[28]. Furthermore, barrages can be include within the facility so as flush sedimentation using sluices[29].

2.4.1 Storage hydropower plants

The storage hydropower plant consists of a dam and a reservoir for impound water. The water is stored and released later when the need arises. The stored water in the reservoir provides flexibility for electricity generation on demand and reduces reliance on the variability of in-flow. The inflow to very large reservoirs can be stored for months or even years; such reservoirs are designed for seasonal storage, to provide water during dry seasons. The storage hydropower plants can be operated to supply both base-load power and peak-load power through their ability to be shut down and start-up again within short notice, with regard to the demand in the power system. This feature makes storage hydropower plants more flexible than ROR plants. With their ability to control water flows, storage reservoirs are often constructed for multipurpose, providing additional benefits such as irrigation, navigation, water supply, flood control, and recreation. The main advantage of hydropower plants with storage is the ability to store large amount of energy and respond to variable load requirements, from short term (daily peaking) to medium weekly and seasonal variability. The storage hydropower plants are becoming increasingly vital for storing energy from other intermittent renewable like solar and wind power [30].

The materials or resources that can be used to construct dam includes earth or rock fills concrete and stone masonry. The arrangement of materials to be used for the construction of the dam is determined or based on the topography of the site. Masonry dam is suitable for a narrow canyon, while an earth dam features well for a wide valley [31].Though this facility is flexible and provides multipurpose benefits, it is capital intensive to build a dam compared to ROR.

The typical structure of storage hydropower plant is shown in

Figure 3.

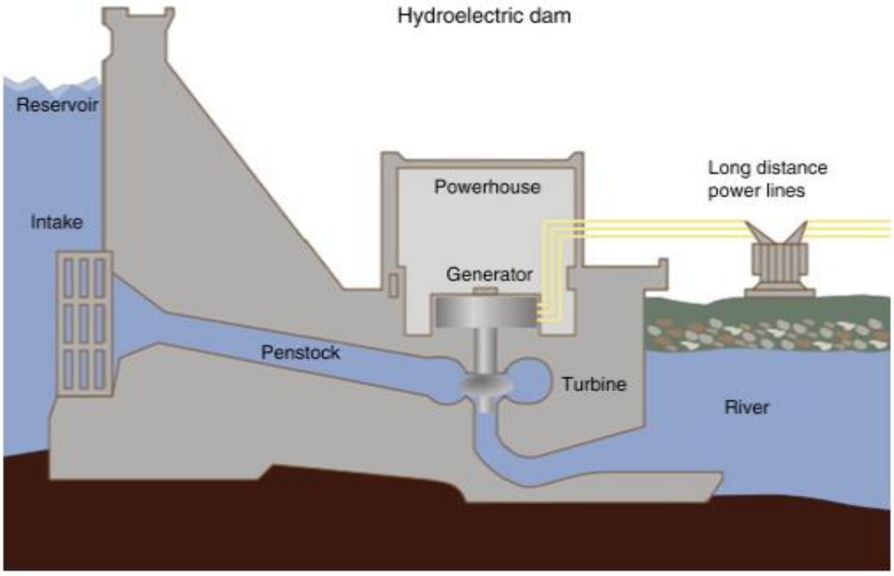


Figure 3: Storage hydropower plant
[Source: U.S. Energy Information Administration (EIA)]

2.4.2 Run-of-river hydropower Plant

In this facility, flowing water from a river is channelled through a canal or penstock to spin a turbine. A run-of-river (ROR) project typically has a little or no storage facility[32]. The typical picture of ROR is shown in

Figure 4.

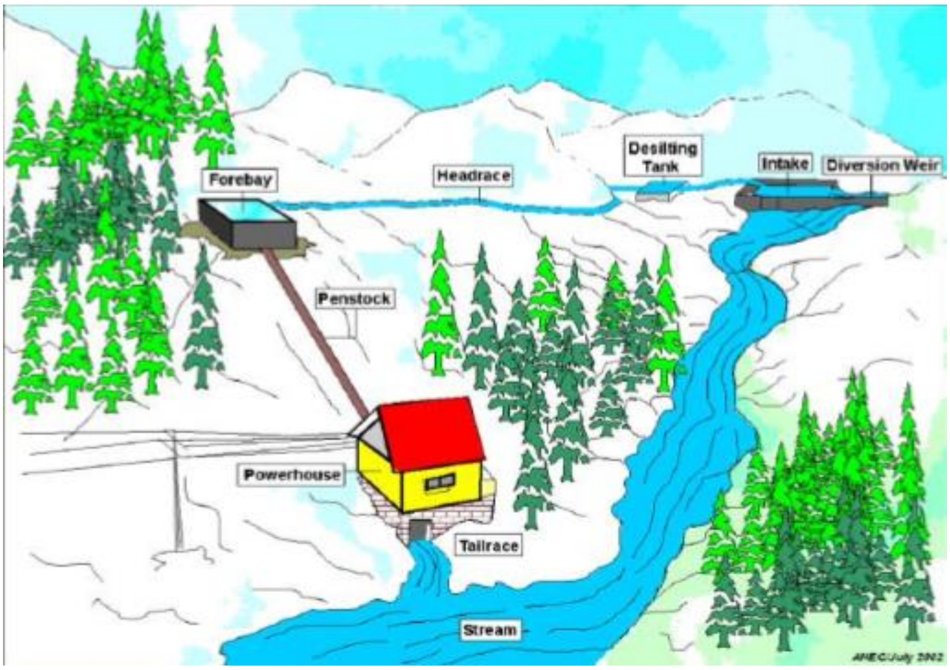


Figure 4: Run of River hydropower plant [Source: ResearchGate]

The first part of ROR facility is a diversion weir which is responsible for diverting water to the hydropower generation intake channel. The design of the diversion weir is based on the level of pond required, the length of weir and the amount of water withdrawal. For Mountain Rivers, the incoming sediment is also an important factor that needs to be considered when the type of diversion structure is selected. Weirs can also assist in providing information about the flow rates so that the regulation of water resources, pertaining to downstream species consumption versus power station consumption portion, can be maintained. Regarding environmental factors, weir can form a barrier which prevents migration of fish through headrace[33].

The water level at upstream is maintained by using bar-rages or weirs with movable gates. If the flow into the impoundment is more than the design discharge of the turbines, the excess flow is released downstream of the river by suitably opening the gates without increasing head water level further. Different types of weirs include: trench type, raised gravity type, bush and boulder and rubber dam type. Figure 5 shows different types of weirs[34].

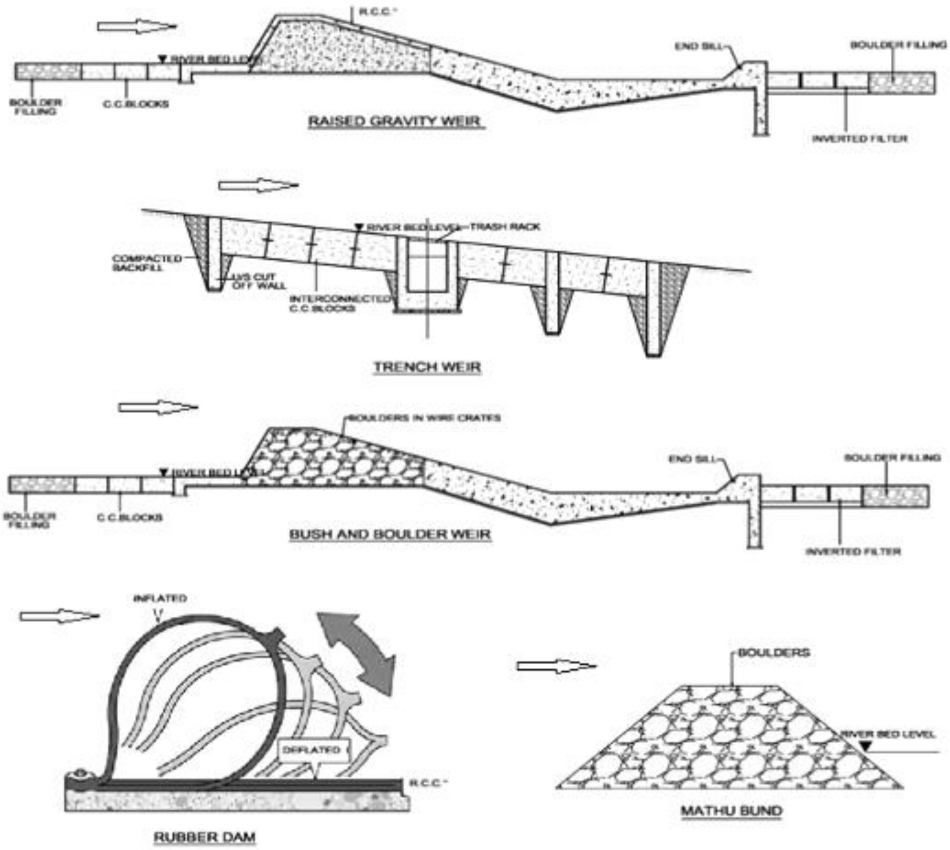


Figure 5: Types of weirs[34]

The second significant part is desilting tank which reduces siltation and sedimentation to the turbines. It actually traps and separate floating debris from water which may cause abrasion on hydraulic machines. The efficiency of desilting tank regarding sedimentation must be high for optimum operation of the plant[35].

The third part is the headrace. This is a canal or a conduit that carries water from desilting tank to the fore-bay. Different methods of constructions and different materials can be used to construct headrace. The availability of materials, manpower and site conditions (land slide, seepage crossing) determine the type and the design of headrace. The popular types of the canal headrace are stone masonry in cement mortar canal, earth canal, stone masonry in mud mortar canal and concrete canal. The common type of pipes which is used in conduit headrace is High Density Polyethylene (HDPE) pipes[36]. The span of headrace ranges from few meters to a kilometre.

The forth part is a forebay which is situated at the end of headrace. The forebay is a pool which has capacity to keep large volume of water. The forebay is normally elevated high so that penstock can draw water from high potential. The role of the forebay is to prevent air trapping by the water entering the penstock, since the entry of air into the penstock may cause cavitation. It consists of air vet which is responsible for the release of air [36].

The fifth part is a penstock which is used for channelling water from forebay to power house, particularly to the turbine. The material which makes up penstock should carefully be selected to meet unique characteristics such as water hammer conditions and the corresponding allowable stress in the penstock shell. The site with high head would generally require a penstock which is made of steel and steel strength has to be determined. For the low head site the materials such as wire wound stave, banded wood stave, plastic, fibreglass, concrete and mild steel can be appropriate[37].The working pressure or head determines the thickness of the penstock.

As the penstock operates, there is possibility of developing of cracks, holes and other problems. To identify and repair these problems, penstock needs to be serviced and inspected more often. During planned maintenance, sluices are used to close water through penstock. Alternatively, the protection of penstock is carried out using devices such as automatic butterfly valve and air valve. The butterfly valve shut off water through the penstock rapidly when it ruptures. The air valve maintains air pressure inside the penstock at equilibrium with atmospheric pressure outside in order to prevent collapsing of the penstock [38].

Since the hydropower facilities can often overlap, the Run of River with some storage is adopted for this study such that a storage component would be implemented for raising the head and for provision of sustainability of water retention.

2.5 Electromechanical Equipment

The equipment which is responsible for producing electricity is both mechanical and electrical. The main ones are turbine, Generator and transformer. The generator and turbine are normally located in power house. The power house is located at low altitudes compared to intake so that generating equipment inside would be able to convert potential energy at intake into effective electrical energy.

The first equipment in the power house is turbine. Its main function is to convert kinetic energy into mechanical energy to turn the rotor of the generator. Turbines are classified into two broad types which are impulse turbine and reaction turbine. Reaction turbines operate well for low and medium heads. The blades of the reaction turbine are driven by both pressure energy and velocity head. The example of reaction turbine is Francis Turbine. On the other hand, impulse turbines are suitable for high head. In impulse turbine, the velocity of water jet drives the wheel as the water pressure is changed into kinetic energy. The example of impulse turbine is Pelton turbine. Turbine must be maintained well with anti-corrosive agents and coatings to prevent failure due to cavitation and silt erosion [39]. The topology of the study area consists of steep gradients contributing to high heads. It is therefore suitable to employ impulse turbine and particularly Pelton turbine. Since it is very common, much simulation software including TURBNPRO adopted it.

The second major equipment in the power house is a generator. This is power equipment which converts mechanical energy from the turbine into electrical energy. There are two main types of generators. The two types are synchronous A.C. generator and asynchronous A.C generator. In synchronous generator permanent magnets are used to create excitation rather than a coil to create excitation field. The asynchronous generators draw their excitation from the power grid. Normally salient pole synchronous generators equipped with automatic voltage regulator(AVR) are used for low speed [40]. Thus, for high speed turbines non-salient pole synchronous generators are used.

Chapter3: Methodology

3.1 Study area

The sustainable hydropower plant is the one which has got the component of storage. The storage is generally a dam, which is placed across a river to create a reservoir or a pondage (for small hydropower plant). Letseng-la-Letsie is a natural lake forming elevated tributary to Quthing River catchment. Since the elevated lake can form a reservoir and provide a good head, it felt significant to analyse the hydropower potential for Quthing river catchment and its sub-catchment (Letseng la Letsie).

3.1.1 Letseng-la-Letsie

Letseng-la-Letsie catchment is in the district of Quthing. The area of the catchment is approximately 40 square kilometres. The area of more than 8 square kilometres, which is about 20% of the catchment area, is considered as a type of wetland. More than half, 4.32 square kilometres, of the wetland area has been declared as the wetland of international importance under Ramsar convention (international convention with the objective of conserving and ensuring wise use of wetlands)[41].

The climate at Letseng-la-Letsie varies depending on the seasons. During summer the temperatures reaching 26^{0}C can be experienced in January. In winter the temperatures can drop as low as -5^{0}C. The average rainfall throughout the years is approximately 800 mm. More than 80% of this rainfall can be experienced during summer time, starting from October to march. In winter the frequent snowfall can be experienced in this area[42].

It is therefore evident that water resources of this catchment area are due to summer rainfall which last approximately for half of a year. Another water resource is the contribution of wetlands which never cease to store and release water appropriately. The snowfall in winter provides yet some water resources. Lastly, there is one river (Mohlakeng River) which is the tributary to this catchment area[42].

3.1.2 Quthing River

Quthing River is found in the district of Quthing, in the south-East of Lesotho. It is one of the main tributary to the great Orange River close to the border of Lesotho with South Africa. This river runs in the mountain with steep slopes. It has a catchment area of approximately 614 square kilometres. This catchment area has got the maximum altitude of 2850 metres while the minimum altitude is 1880 metres above sea level. Due to its steep gradient, the extensive soil erosion is experienced along the river channel. The soil erosion results into heavy sediment transport by the river within the catchment [43].

The climate of Quthing River catchment area follows the same pattern as that of Letseng-la-Letsie. The character of the river is such that high-peaked floods are experienced in summer, during rainy seasons. The low base-flow occurs during the dry periods [43]. However, it is common for the frost and snow to occur during winter period (May - July). Sometimes the frost can last even to the end of September. It therefore follows that water resources to Quthing River are tributary springs, Letseng-la-Letsie, heavy rain fall in summer and defrosting of snow. **Error! Reference source not found.** shows the map for both study areas.

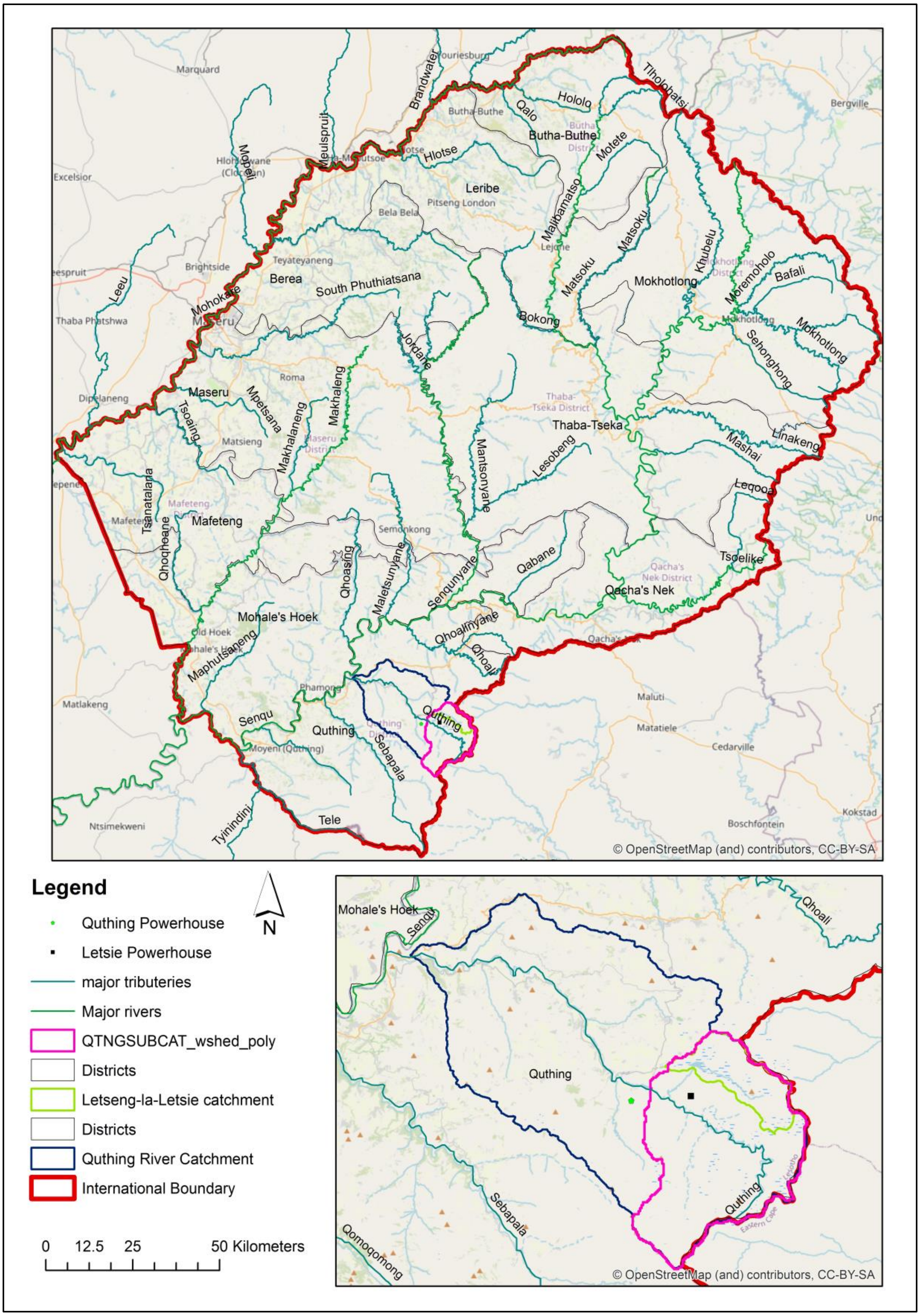


Figure 6: Study Area

[**Source: Department of Water Affairs Lesotho GIS**]

Beside the study area the methodology followed, for the analysis of hydropower potential for both Quthing River and Letseng-la-Letsie, can be summarized through the flow chart shown in Figure 7.

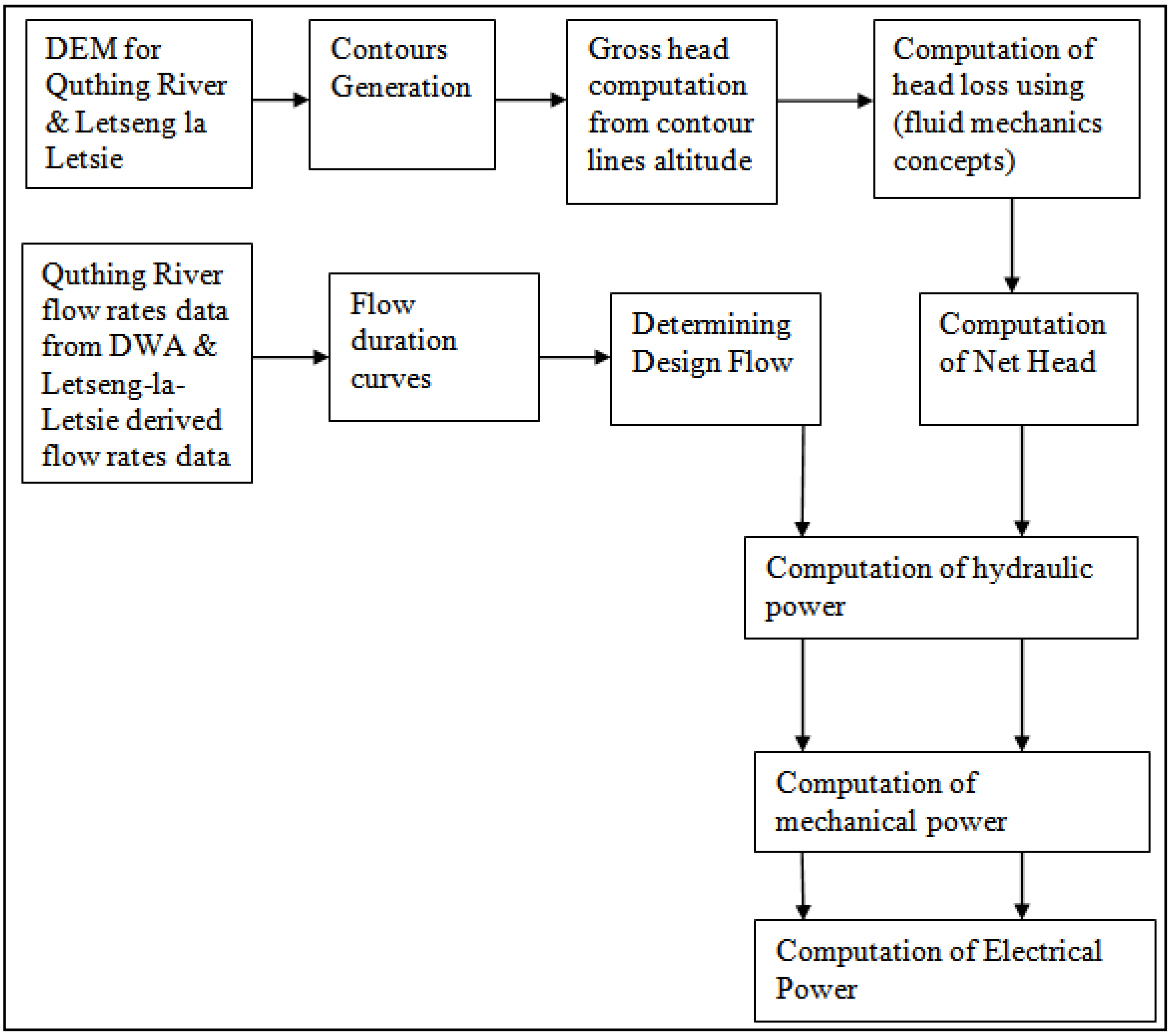


Figure 7: Methodology Flowchart

3.2 Head assessment

The assessment of head can be achieved through different methods as discussed in literature review. The methodology used in this analysis is map due to its advantages over the others. In this methodology the site was first identified using Google maps within the program of Google Pro. This tool has the features which render the site exploration to be easy because the site can be identified easily by applying the coordinates of the site if known or by just navigating along the area until the site of the interest is identified. One of the study sites (Letseng-la-Letsie), located using Google, is shown in

Figure 8.

Figure 8: Letseng-la-Letsie site [Source: Google Map]

Once the site is located, through Google maps, it was then identified in (QGIS). To identify the site, the feature of QGIS which is called quick map was used to launch Open Street Map (OSM) layer. While within the OSM interface, the study site was then identified from the map. The study site within QGIS 3 is shown in

Figure 9.

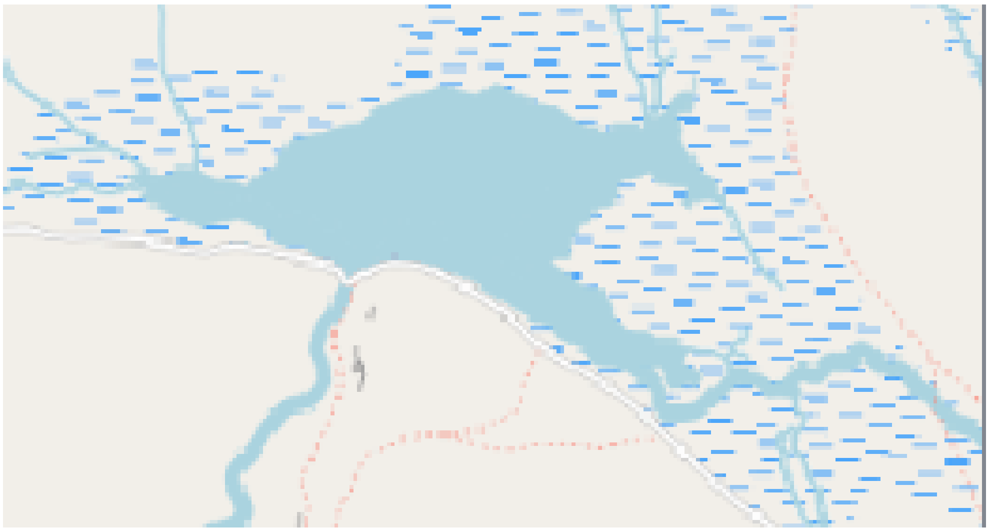


Figure 9: Letseng-la-Letsie site in OSM
[Source: QGIS and AsterGDEM]

The correct coordinate reference system (CRS) is necessary to be selected so that the exact spatial characteristics of the study site are achieved. The CRS for the study site was searched in Google and the information was provided in conjunction with World Geodetic System (WGS), Universal Transverse Mercator (UTM) and European Petroleum Survey Group (ESPG). The CRS for the country was therefore given as WGS 84/UTM zone 35N with ESPG: 32635. The correct projection was then defined for the site in QGIS. With the reference defined, the Digital Elevation Model (DEM) was downloaded using Shuttle Radar Topography Mission (SRTM) downloader plug-in.

Though most of downloaded DEM comes with more than one tile, which requires merging process, DEM for the Letseng la Letsie manifested with one tile.

Since the downloaded tile was still in geographic projection (latitude and longitude) it had to be projected again. Once re-projected, the DEM was converted into raster tagged image file format which could be processed to unfold other information including contours providing altitudes and reliefs of the study site. Thus, gross head of Letseng-la-Letsie can be determined from contours in Figure 10.

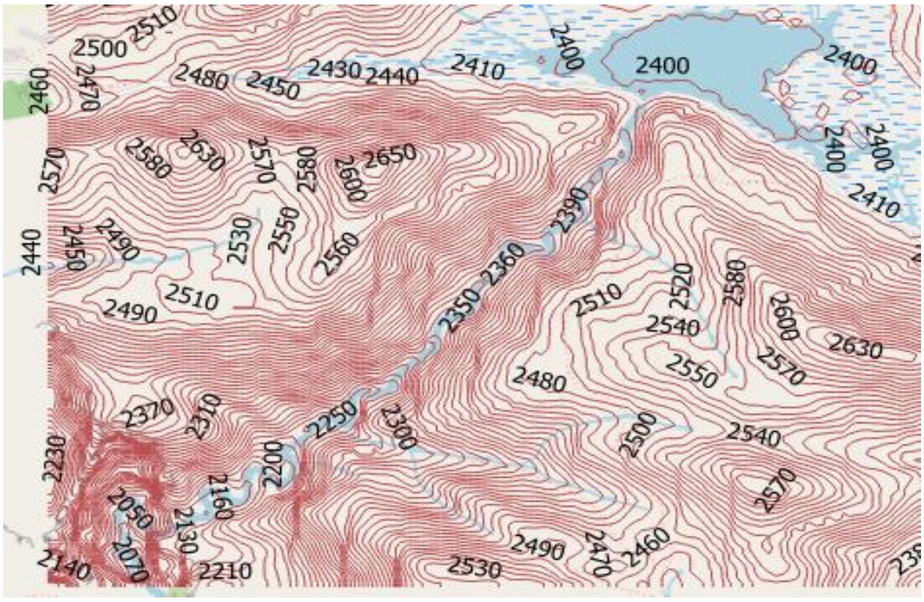


Figure 10: Contour Lines of Letseng-la-Letsie
[**Source: This study (derived using QGIS and AsterGDEM)**]

The net head could then be determined from the gross head by using equation 4 to equation 9. According to Warnick et al, the optimum diameter of penstock, in terms of rated discharge, can be determined using equation 4

$$D = 0.72Q^{0.5} \text{ --- (4)}$$

The longitudinal or frictional head losses can be determined using equation 5 as follows:

$$h_f = f \times \frac{L}{D} \times \frac{v^2}{2g} \text{ --- (5)}$$

The local losses are given by equation 6

$$h_{loc} = k \bullet \frac{v^2}{2g} \quad \text{-- (6)}$$

The friction factor can be determined from moody chart using relative roughness and Reynold's number. Equation 7 shows relative roughness whereas equation 8 shows Reynold's number.

$$relative\,roughness = \frac{\varepsilon}{D} \quad \text{--- (7)}$$

$$R_e = \frac{vD}{\mu}(m^2 / s) = \frac{\rho vD}{\mu}(Ns / m^2)\ or\ (kg / ms) \text{------------------------ (8)}$$

From equation 4 to 8:

Q is flow rate

L is length of penstock

D is diameter of penstock

v is velocity of water

ρ is density of water

μ is kinematic viscosity of water

k is pipe loss coefficients

Once the Reynold's number is determined different approximation equations can be used to determine the friction factor depending on whether the condition of water flow is laminar, transitional or turbulent. However the common way is to use Moody chart as adopted in the next chapter (results and discussions).

Ultimately the net head is given by equation 9 as follows:

$$h_n = h_g - (h_f + h_{loc}) \quad \text{-- (9)}$$

Where: h_g is the gross head.

The net head for Quthing River can similarly be determined by applying equation 2 to equation 7 while the gross head can be derived from the Q-GIS generated contours shown in

Figure 11.

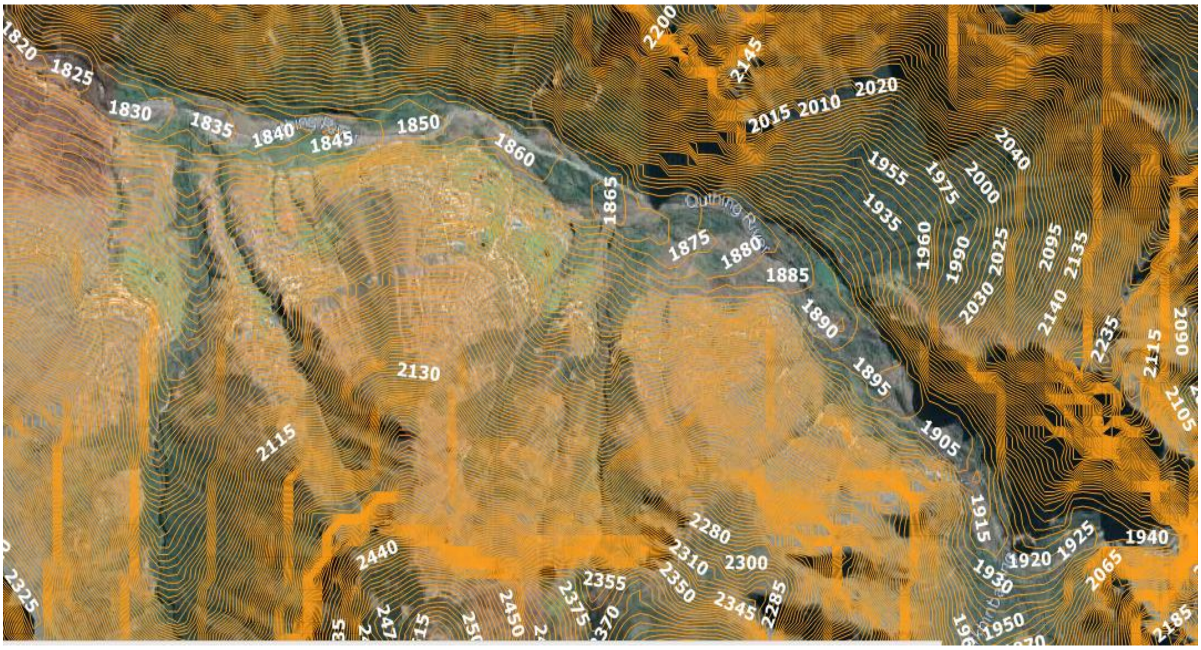


Figure 11: Contour lines of Quthing River

[**Source: This study (derived using QGIS and AsterGDEM)**]

3.3 Flow rate assessment

The data for flow-rate, of Quthing River, was collected from the department of water affairs (DWA). The observation was made from the hydrologic measuring station situated at the place called Hoko in Quthing district. The time series of flow rates and dates was then conducted to produce the hydrograph. Using the same information, the graph of monthly average flow rates through the March 1990 to September 2018 was also produced.

The data was further processed to produce flow duration curve (FDC) to give more significant information concerning analysis of hydropower potential. Flow duration curve is important because it shows the frequency of observations or occurrence of various flow rates. It is a cumulative frequency graph developed by arranging all discharge observations in the descending order of their magnitude (with reference to flow column) and subdividing them in accordance to the percentages of time during which specific flows are equalled or exceeded (% exceedance column)[44]. Equation for percentage exceedance (P) with reference to table 1 is given by equation 10:

$$P = \frac{flow\ rank}{total\ number\ of\ obeservations} \times 100 \text{ --------------------------------- } (10)$$

The procedure elaborating for preparation of flow duration curve is shown in table 1.

Table 1: Sample data series for flow duration

Observations in months	Flow (cumecs) (m^3/s)	Flow in Descending order	Flow ranks	Flow frequency Accumulation	Flow Percentage Exceedance
Jan	1	13	1	0.083	8.3
Feb	4	11	2	0.17	17
March	7	9	3	0.25	25
April	3	8	4	0.33	33
May	0	7	5	0.42	42
June	9	6	6	0.5	50
July	6	5	7	0.58	58
Aug	2	4	8	0.67	67
Sept	8	3	9	0.75	75
Oct	5	2	10	0.83	83
Nov	13	1	11	0.92	92
Dec	11	0	12	1	100

Power curve is then synthesized from the flow duration curve produced. Power is the product of density, acceleration due to gravity, head and flow rate. The three parameters which are density, acceleration due to gravity and head are normally considered constant. However, the temperature of water varies and this affects the density of water and its viscosity. In spite of this, hydrometric observations from resource centre were made without temperature readings and therefore average temperature of 10^0C was assumed. The power curve was therefore produced as the function of flow rate percentage exceedance. Equation11 was used to produce the power curve.

$$P_{hydraulic} = \rho g H Q \, (W) \text{ -- } (11)$$

Where: ρ is density of water

g is acceleration due to gravity

H is the head

Q is the flow rate

3.4 Mechanical Power

Since only part of kinetic energy is used to drive the turbine(converted into mechanical energy) while the remaining part of kinetic energy is used for driving exhausted water through the draft tube, the efficiency of a turbine is not 100 %. The output power curve of the turbine was therefore produced using equation 11 scaled down by turbine efficiency as presented in equation 12

$$P_{mechanical} = \eta\rho gHQ\,(W) \text{ --(12)}$$

The efficiency of a turbine is not constant but also varies with flow rate. Equation 13was used to produce the efficiency curve.

$$\eta = \eta_{rated} \times \sqrt{\left(\frac{Q}{Q_D}\right)} \text{ -- (13)}$$

Where:

Q_D is design flow rate

η is efficiency of turbine

3.5TURBNPRO Interface

The power determined through the analysis detailed in section 4.2 is power due to flowing water. The modelling approach can be used to determine the mechanical power from the study area. The application that was used for modelling is called TURBNPRO. It has a simple user friendly interface where input parameters can be applied into the model.

The input parameters applied for turbine configuration are rated discharge in m^3/s (determined at 60 % from flow duration curve), net head at rated discharge in meters, site gross head in meters, site elevation in meters, desired unit setting to tail water in meters, efficiency priority at maximum output, Electrical system frequency, minimum net head and maximum net head. The values of these input parameters were applied for both Quthing River and Letseng-la-Letsie study areas.

3.6 Generator Specifications

The specification of the generator which produces electrical power output has to be determined. These specifications include speed, frequency and rotor pole pairs, voltage and number of phases. The speed of the generator rotor is equivalent to the speed of the runner of the turbine. This speed is generally low revolutions per minutes. In order to achieve the frequency of either 60 Hz or 50Hz, the number of poles of the generator rotor has to be many. Equation 14 is used to determine the number of poles of the rotor

$$f = \frac{np}{60} \quad \text{---} \quad (14)$$

Where:

n is speed of the rotor in RPM

f is frequency in Hz

p is pairs of poles

Equation 14 is applicable to both types of synchronous generator rotors being salient pole synchronous generator rotor and non salient pole rotor.

The next chapter, after methodology, is results and discussions in which outcomes are explained.

Chapter 4: Results and Discussions

4.1 Hydrographs and Average flow rates

The availability of water harnessed for hydropower generation is the starting point of analysis of streams for hydropower potential. From the data set of Quthing River flow rates measurements made from March 1990 to November 2018, the catchment area ratio method was used to display the availability of water for potential hydropower intake. The method was used due to unavailability of flow rates observations within vicinity of the intake. The catchment area of Quthing River is 614 km^2 while catchment area at Quthing abstraction point 202 km^2 while. The two areas scale to catchment area ratio of 3:1. Using this ratio the hydrograph of Quthing abstraction point is presented in Figure 12.

The data for Letseng-la-Letsie hydropower generation was also derived from the data set of Quthing River flow rates measurements made from March 1990 to November 2018. The catchment area ratio of 15:1, for Quthing River to Letseng-la-Letsie, was used to develop the hydrograph for Letseng-la-Letsie as shown in Figure 13.

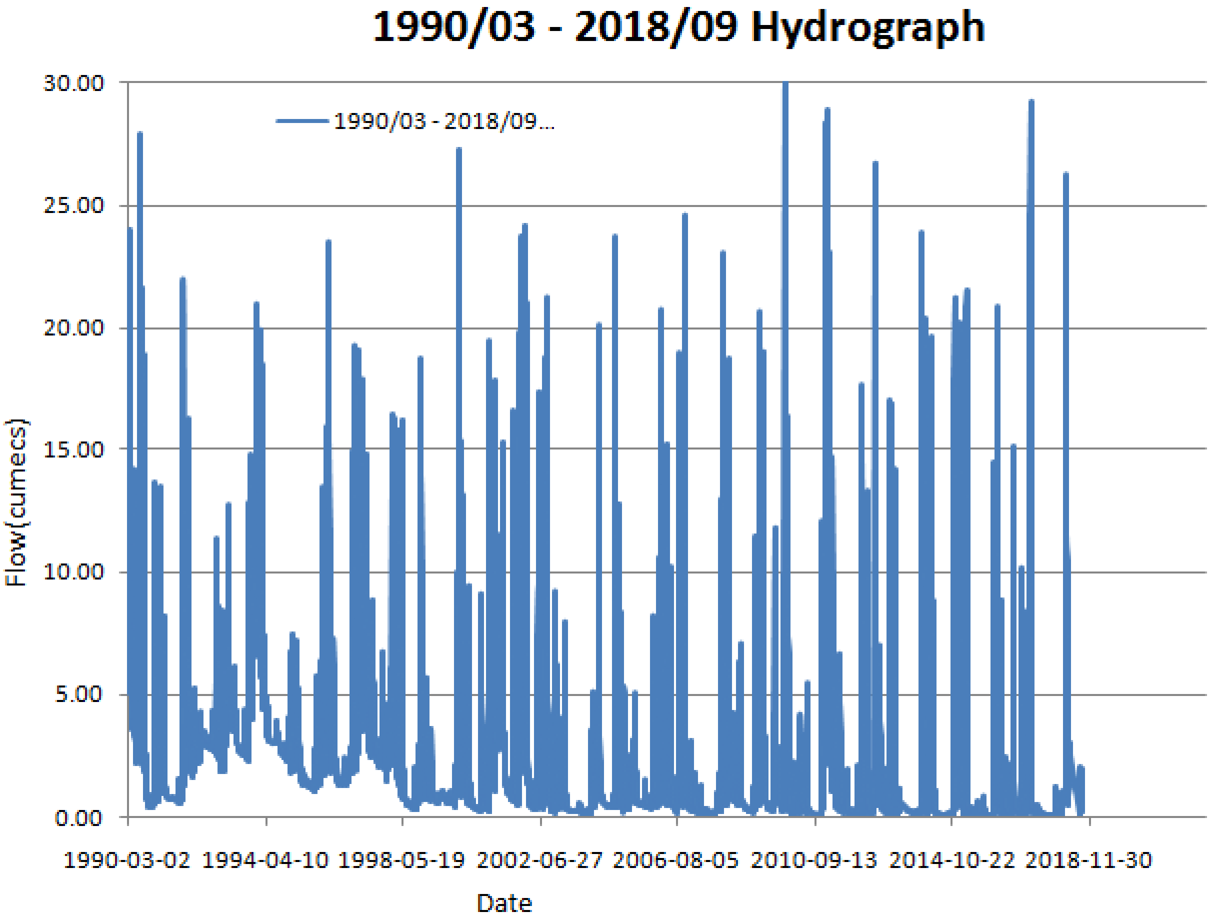


Figure 12: hydrograph of Quthing River (1990/03 – 2018/09)

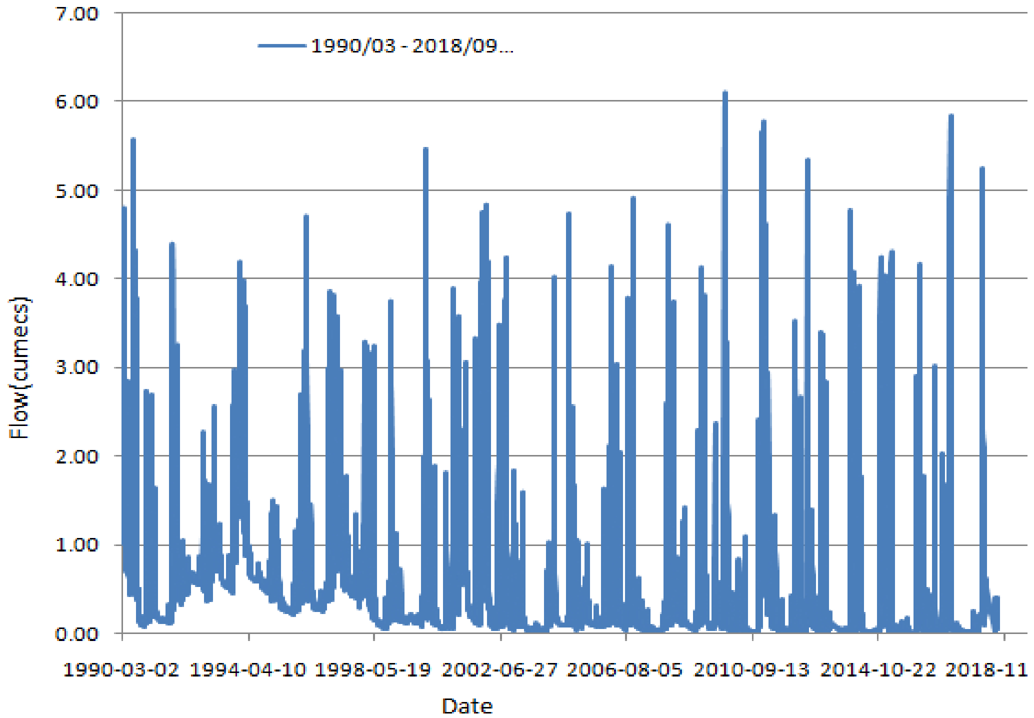


Figure 13: hydrograph of Letseng-la-Letsie(1990/03-2018/09)

It can be seen that the daily flow rates of Quthing River can go as high as 30 m^3/s during the years and seasons of abundant rain as shown in Figure 12, while from Figure 13 it can be seen that the daily flow rates of Letseng-la-Letsie can increase to $6.07m^3/s$ during the same seasons and years. In times of drought in the country, the daily flow rates of both Quthing River and Letseng-la-Letsie fall down as low as $0m^3/s$. Furthermore the average daily flow rates of Quthing basin in the span of years from 1990 to 2018 is $3.46m^3/s$ whereas average daily flow rates of Letseng-la-Letsie is 0.69 m^3/s.

The daily flow rates are generally fluctuating with respect to the climate of the country which can be characterised by the months. Figure 14 and Figure 15 shows the monthly average flow rates of Quthing River and Letseng-la-Letsie for 1990 to 2018.

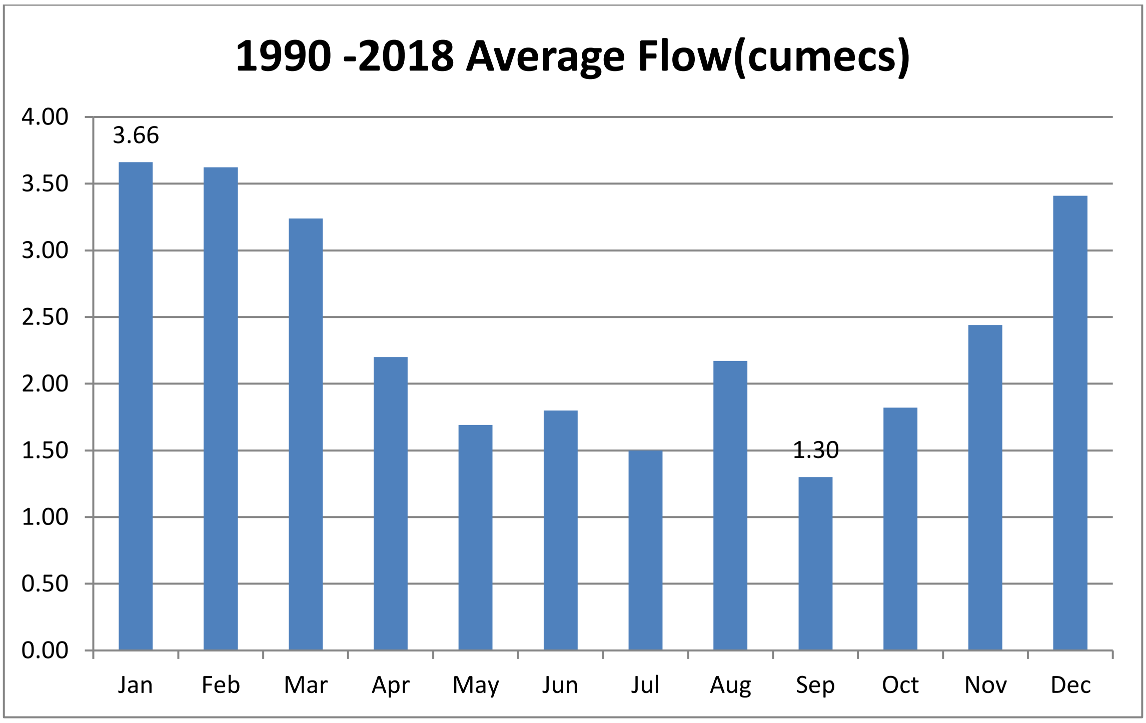


Figure 14: Quthing River Monthly Average flow rates

Just like Quthing River, the daily flow rates of Letseng-la-Letsie are generally fluctuating with respect to the climate of the country which can be characterised by the months. Figure 15 shows the monthly average flow rates of Letseng-la Letsie from 1990 to 2018.

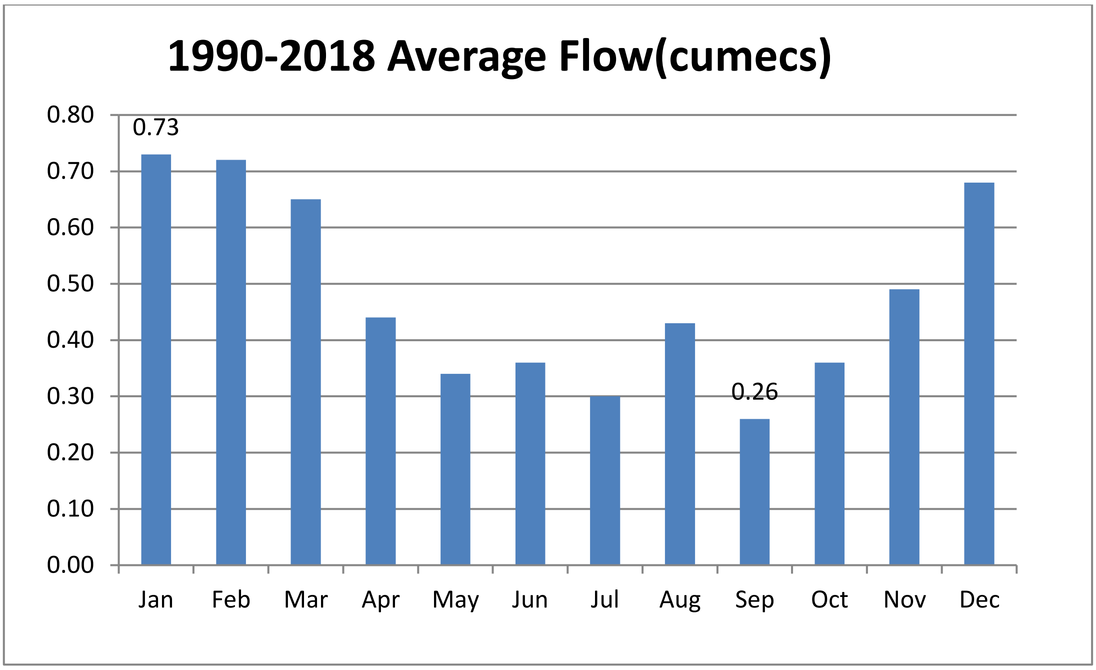


Figure 15: Letseng-la-Letsie Monthly Average flow rates

According to Figure 14 and Figure 15, it is evident that highest average flow rates are experienced in the month of January being 3.66 m^3/s and 0.73 m^3/s for both Quthing River and Letseng-la-Letsie respectively. The lowest flow rate in Quthing River and Letseng-la-Letsie occur in the month of September with an average flow rate of 1.30 m^3/s and 0.26 m^3/s respectively. This gives an indication that if more than one generation units are installed, for Quthing River, it would be possible to generate more power within January and February and least in September.

This is just an indication because the maximum flow rate, average flow rate and the minimum flow rate of the stream do not provide enough information for the analysis of hydropower potential of the river. The firm decision for hydropower potential is derived from flow duration curve.

4.2 Flow Duration Curves

The graphical information which is appropriate and detailed for the analysis of rivers regarding hydropower potential is from flow duration curve. With the feature of showing the portion of the time for sustainability of a definite flow rate, FDC makes it easier for design flow rate and firm flow rate to be selected. Using the typical flow rates and % exceedance from Appendix 1

flow duration curves for both Quthing River and Letseng-la-Letsie were generated as shown in

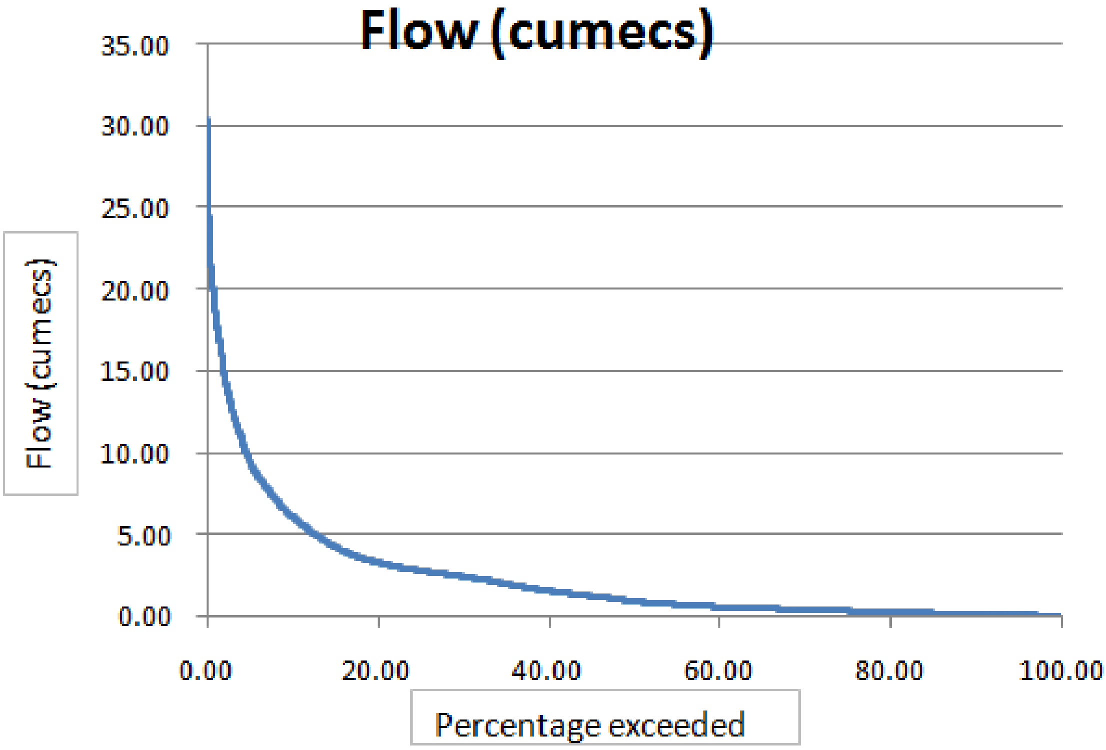


Figure 16 and Figure 17 respectively.

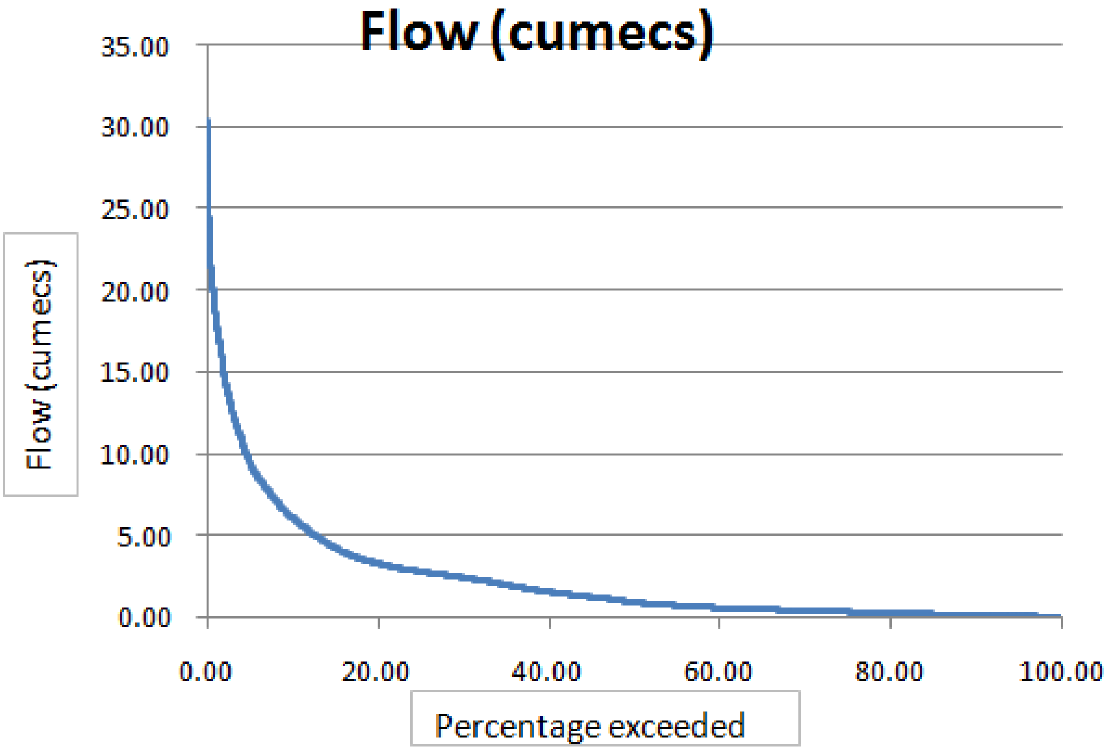


Figure 16: Quthing River FDC

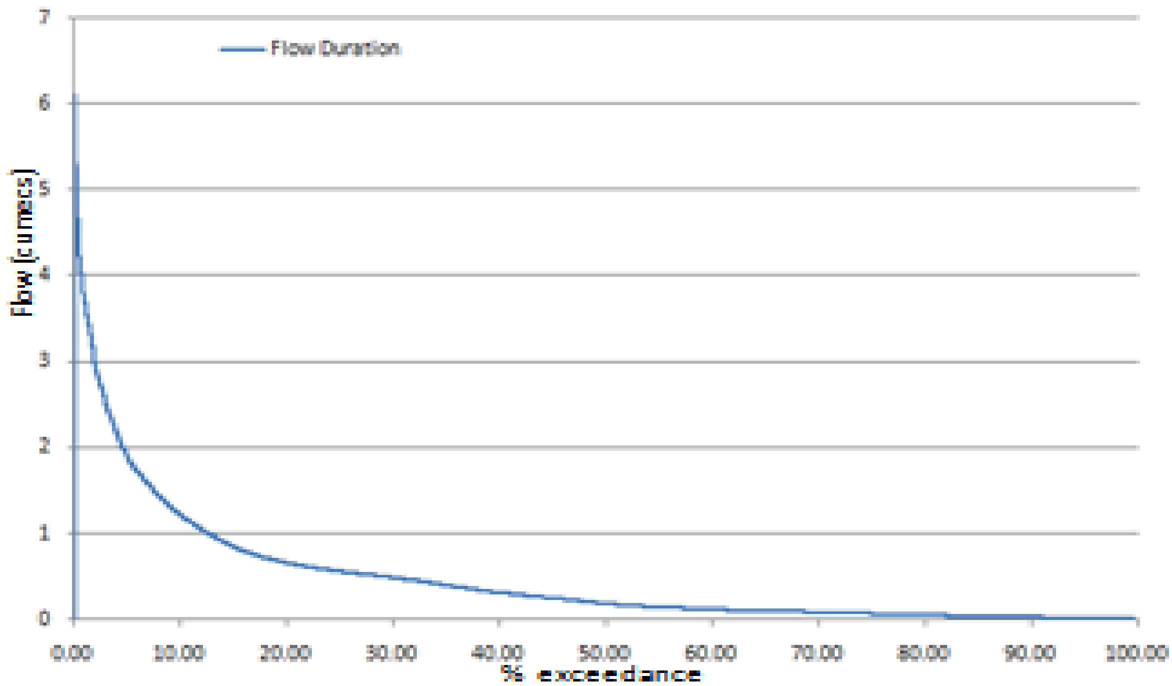
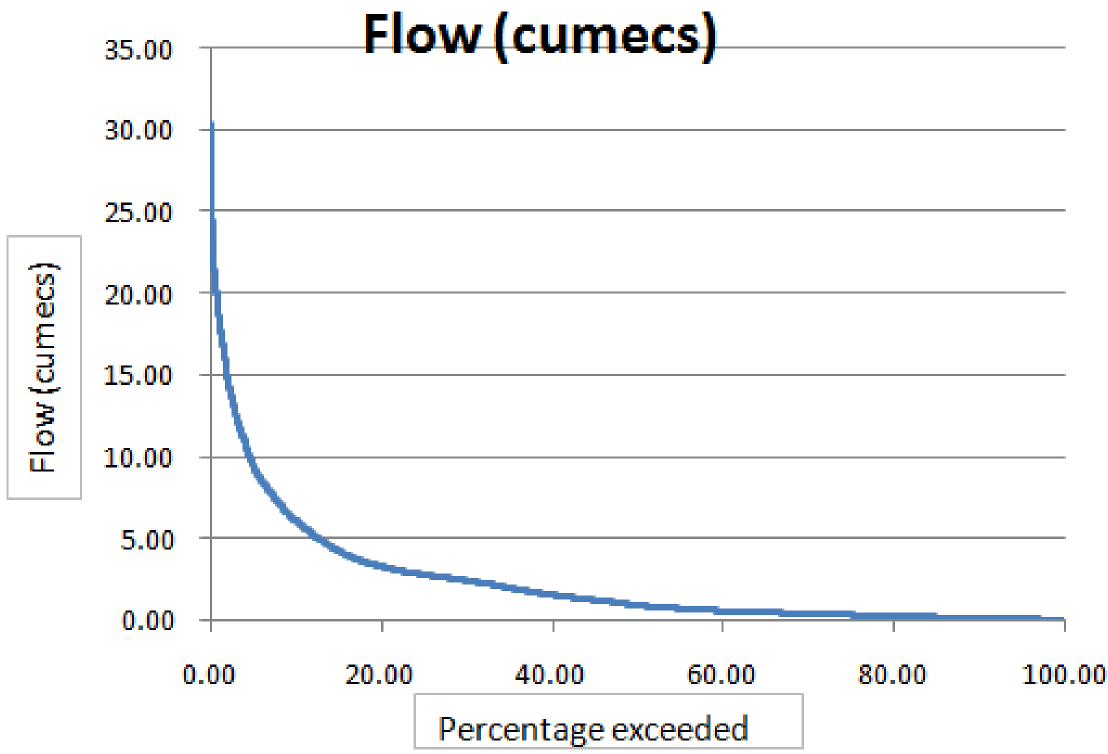
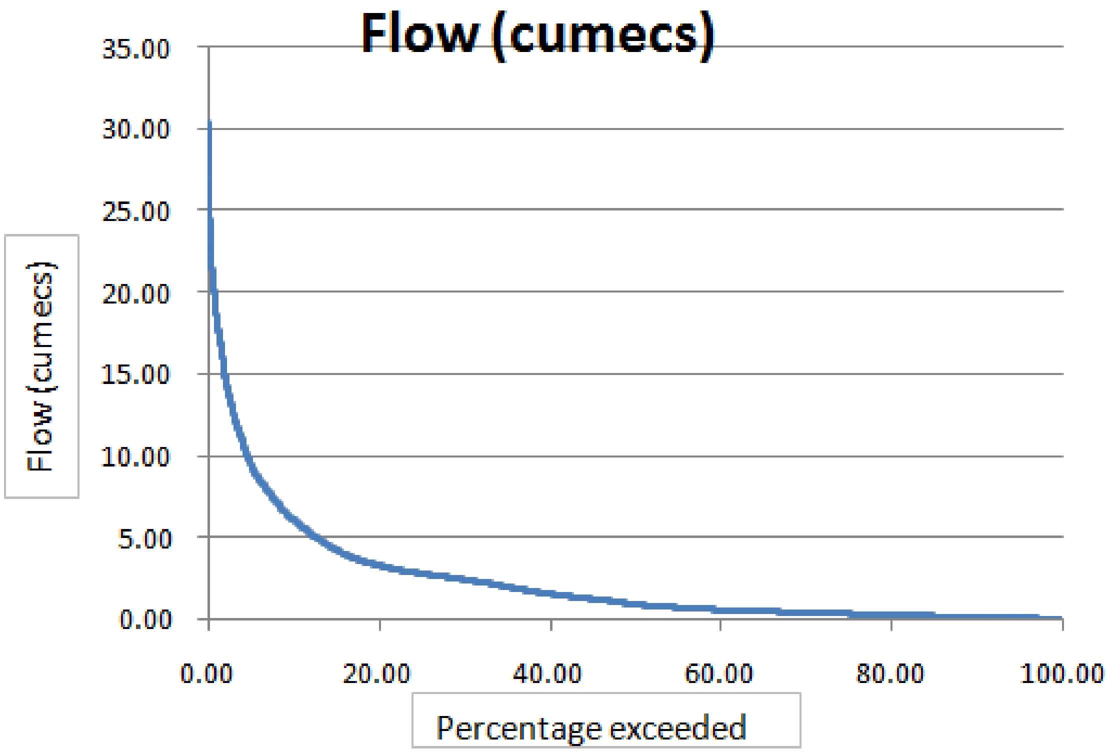


Figure 17: Letseng-la-Letsie FDC



From both

Figure 16 and Figure 17, it is evident that, the percentage exceeded of 0m³/s is 100%. This means that there is 100% chances of getting of 0m³/s or higher each time the flow rate observation are taken. The percentile of interest, regarding hydropower potential from FDC, is firm flow rate and design flow rate. The firm flow rate is normally chosen at 95% upwards.



From

Figure 166, the firm flow rated at (Q_{95}) for Quthing River is 0.10 m^3/s while the firm flow rate for Letseng la Letsie is 0.019m^3/s, as per Figure 17. The design flow rate (Q_D) is normally selected based on the usage of the power from the proposed power station. Quthing district is located in the rural region of Lesotho. According to the study from "Grid electrification challenges, photovoltaic electrification progress and energy sustainability in Lesotho" [45] and "Electricity supply cost of service study: load forecast report"[46], people in rural areas use approximately less than 20% of electrical power while other sources of power take more than 80%. It can therefore follow that electricity is used less than 20% of the time in rural areas. This implies that Q_D can be selected at 20% but catering for scalability due to development, it is more appropriate to select the design flow rate at 60%. The design flow rate ($Q_D = Q_{60}$) with reference to

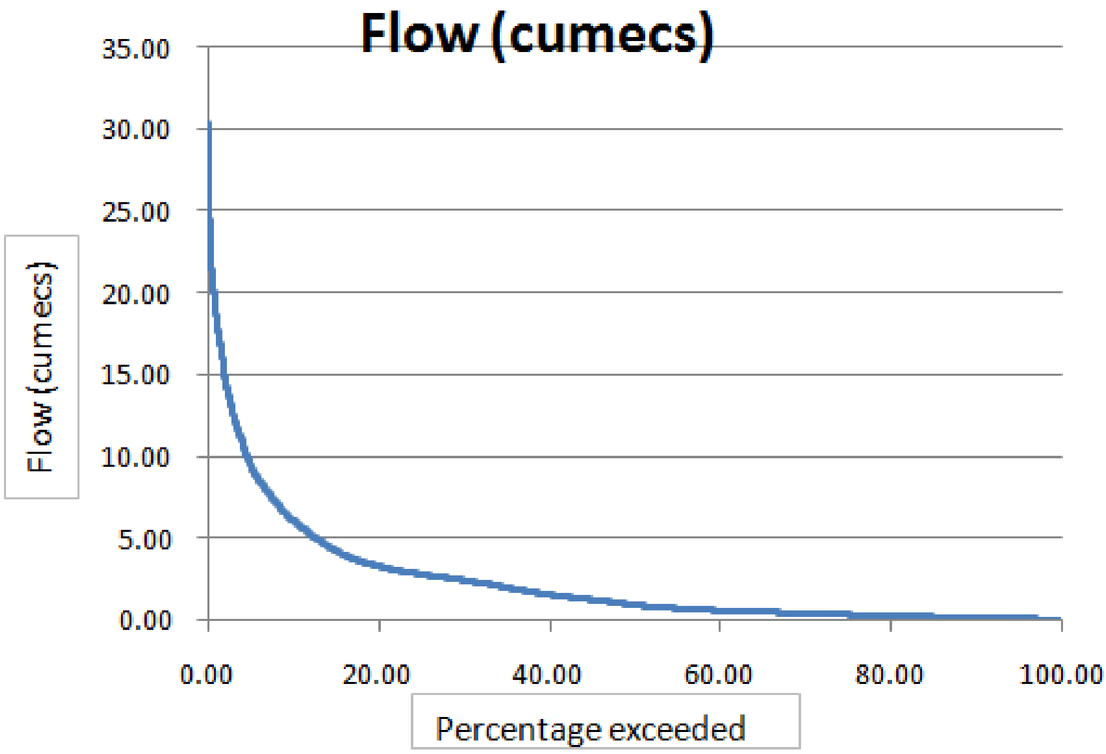


Figure 16, will therefore be 0.58 m^3/s while Figure 17 reveal the design flow rate (Q_D) for Letseng-la-Letsie as 0.116 m^3/s.

The next step after discussing the resultant design flow is to determine the resultant head.

4.3Net head

The net head, for Quthing River and Letseng-la-Letsie, can be calculated starting with equation 4. With the design flow rate of 0.58 m^3/s, the diameter of the penstock for Quthing River will be 0.55 m and the resultant cross-sectional area will be 0.24 m^2. The diameter of the penstock for Letseng-la-Letsie with design flow rate of 0.116 m^3/s, will similarly be determined as 0.24m with the cross-sectional area of 0.045m^2.

Since the temperature of water in Quthing River can be assumed to be at 10^0C, the kinematic viscosity of water will therefore be 1.3065x $10^{-6} m^2/s$ with reference to Appendix 2.The Reynold's number for Quthing River, according to equation 8, will then be 1.02×10^6 . The Reynold's number for Letseng-la-Letsie will accordingly be 4.73×10^5. This shows that flow for both catchments is turbulent because Reynold's numbers are greater than 4000. The relative roughness for Quthing River penstock, considering commercial steel with surface roughness (ε) of 0.045 mm in accordance to Appendix 3, can be determined from equation 7 and results to 0.000082. Applying the same approach the relative roughness for Letseng-la-Letsie can be determined and results to 0.0001875.

With relative roughness of 0.000082 and the Reynold's number of 1.02×10^6, the friction factor (*f or λ*) for Quthing River can then be determined from moody in

Figure 18.

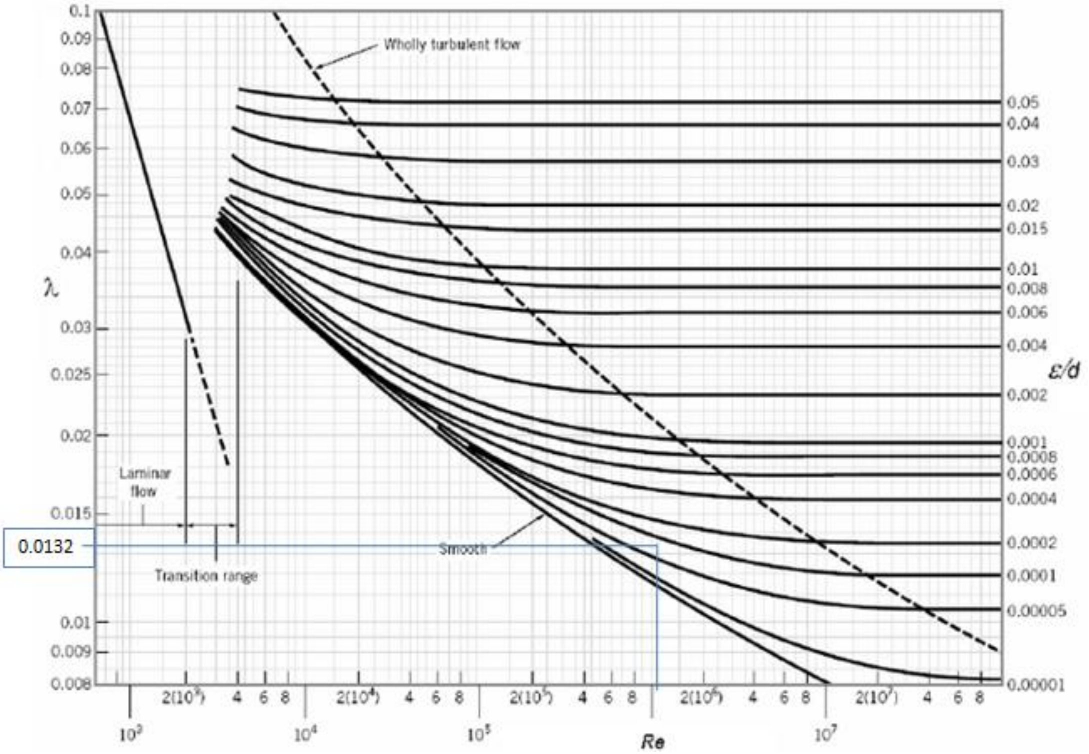


Figure 18: Friction factor for Quthing River [Source: ResearchGate]

Similarly with relative roughness of 0.0001875 and the Reynold's number of 4.73×10^5, the friction factor (*f or λ*) for Quthing River can then be determined from moody chart in Figure 19.

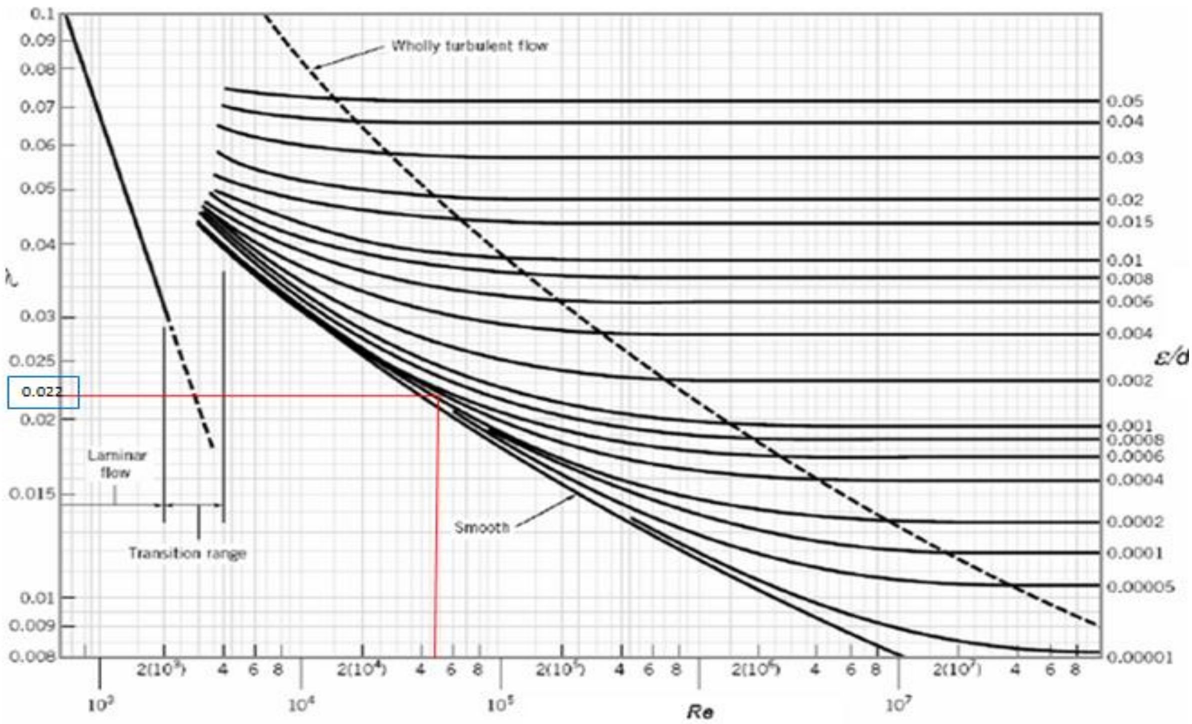


Figure 19: Friction factor for Letseng-la-Letsie[Source: ResearchGate]

From

Figure 18 it can be seen that the friction factor is approximately 0.0132 for Quthing River. Figure 19 shows that the friction factor for Letseng-la-Letsie is approximately 0.022. With friction factor determined, the net head can then be calculated and Figure 20 is used to illustrate the concept.

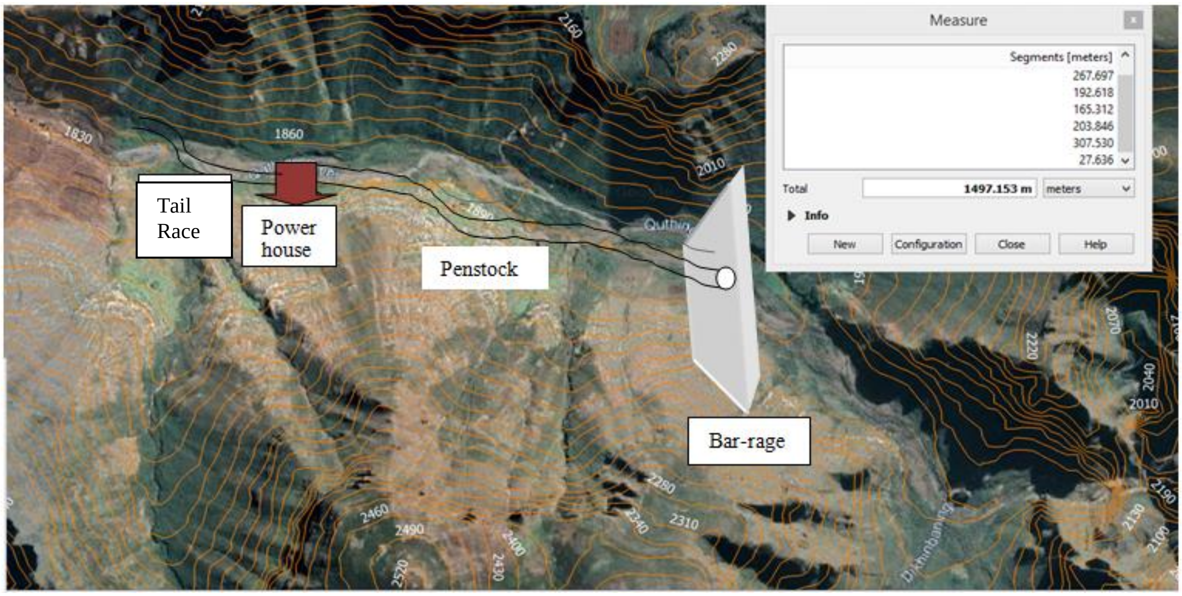


Figure 20: Quthing River Hydropower Layout
[**Source: This study(derived using QGIS and AsterGDEM)**]

The bar-rage is inserted to create a pondage and to raise the altitude of intake from 1890 m to 2010 m such that gross head (vertical height between intake and power) will be the difference between 2010 m and 1840 m. The length of the penstock is approximately equal to the distance between power house and intake at the bar-rage which is 1497.15 m. Assuming a penstock of long radius of 45^0 which is flanged, pipe loss coefficients (k) will be 0.2 according to Appendix 4. The head for Quthing River is then calculated through equation 9 giving cross head of 170m and the head of 159.23m. Applying the same concept, the head for Letseng-la-Letsie can be calculated and the resultant cross head will be 250 m with the net head of 216.37 m.

4.4 Power curves

The powers that can be developed from Quthing River and Letseng-la-Letsie are directly proportional to the flow rate of water. The equation which is used to determine the amount of power is the common one given in equation 11. Assuming that density of water is kept constant at1000 kg/m^3; acceleration due to gravity is kept constant at 9.8 m^2/s, the net head is determined as 159.23 m and the rated flow as 0.12 m^3/s. The hydraulic power developed from Quthing River can be shown in graphical form as in Figure 21 and as computed in Appendix 1.

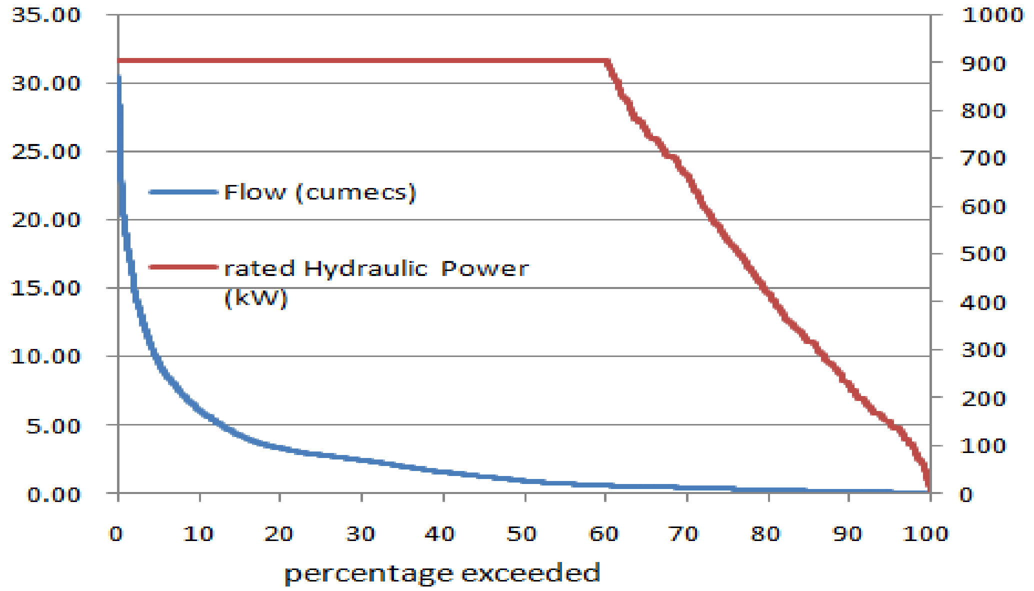


Figure 21: power curve for Quthing River

While the hydraulic power that can be developed from Letseng-la-Letsie with head of 216.37 m and rated flow of 0.116 m^3/s can be shown in Figure 22 and as determined in Appendix 1.

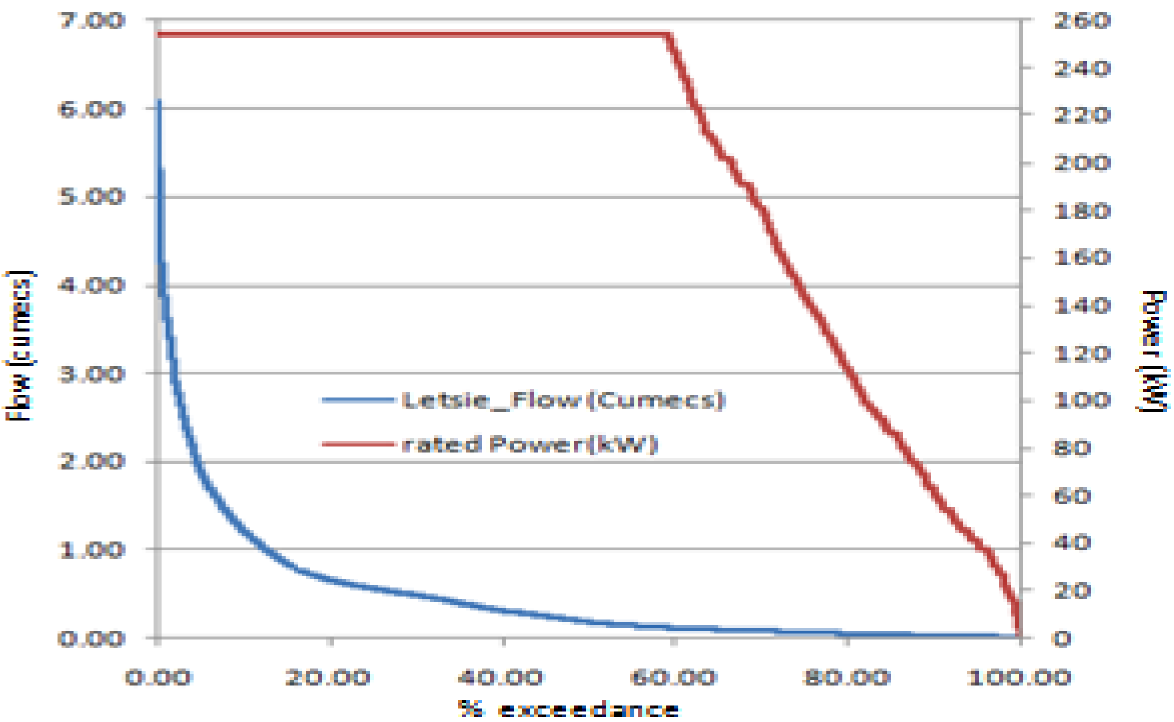


Figure 22: power curve for Letseng-la-Letsie

From Figure 21 and Figure 22 it can be seen that Powers from Quthing River and Letseng-la-Letsie at Q_{60} are 906 kW and 246.22 kW respectively, in accordance to equation 11. The graphs reveal that as long as flow rates are equal or greater than design flow rates (0.58 m^3/s and 0.116

m^3/s), the powers remain constant at 906 kW and 246.22 kW respectively (see also Appendix 1). On the other hand, when flow rates drop below the design flow rates the powers decrease gradually. This gradual decrease is experienced from Q_{60} to Q_{100}. The rated hydraulic power is also determined at Q_{60} similarly to design flow.

The power due to kinetic energy need to be converted into mechanical power before it can be used to harness electrical power.

4.5 Mechanical Power

The power development illustrated on power curves (Figure 22 and Figure 22) are due to flowing water to the turbine thus input powers driving the turbine. Since determined net heads for Quthing River and Letseng-la-Letsie were 159.23 m and 216.37 m respectively, the high head (impulse turbine) was selected and in particular, the Pelton turbine was selected using turbine selection chart shown in Appendix 5. Another important factor is that the typical efficiency of the turbine is 90 % but the efficiency drops below 90 % as the flow rate drops below design flow or as percentage exceedance goes beyond design percentage exceedance. Figure 23 and Figure 24 show the variation of power and efficiency with flow rates percentage exceedence as determined in appendix 1.

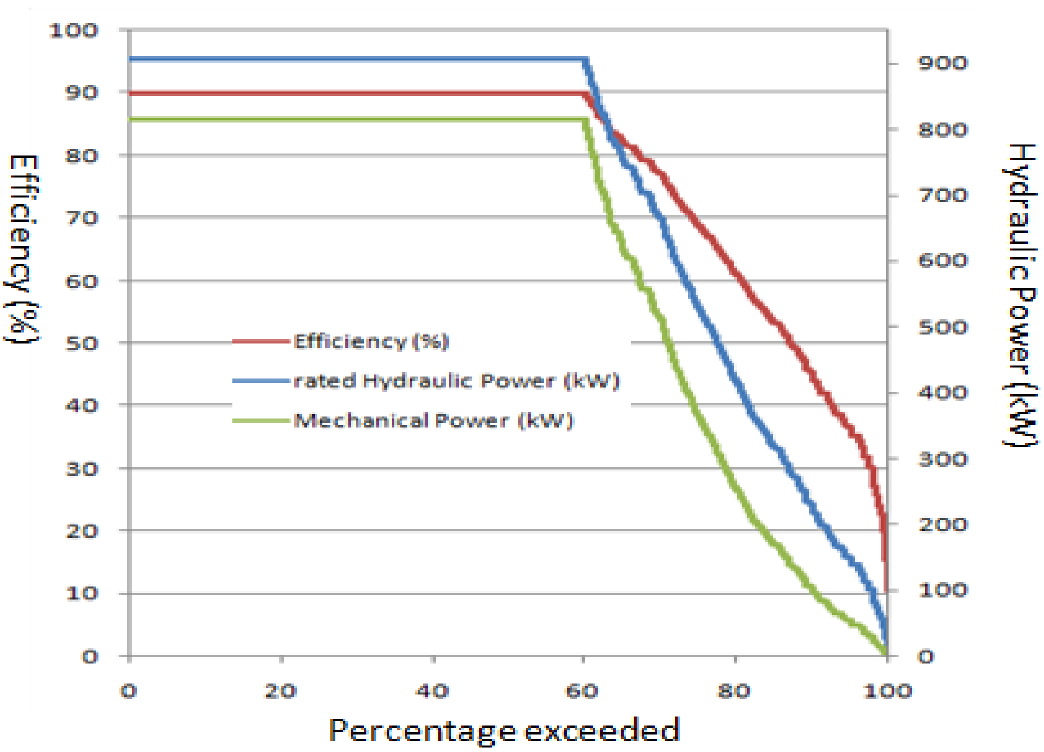


Figure 23: Quthing River Power and Efficiency curves

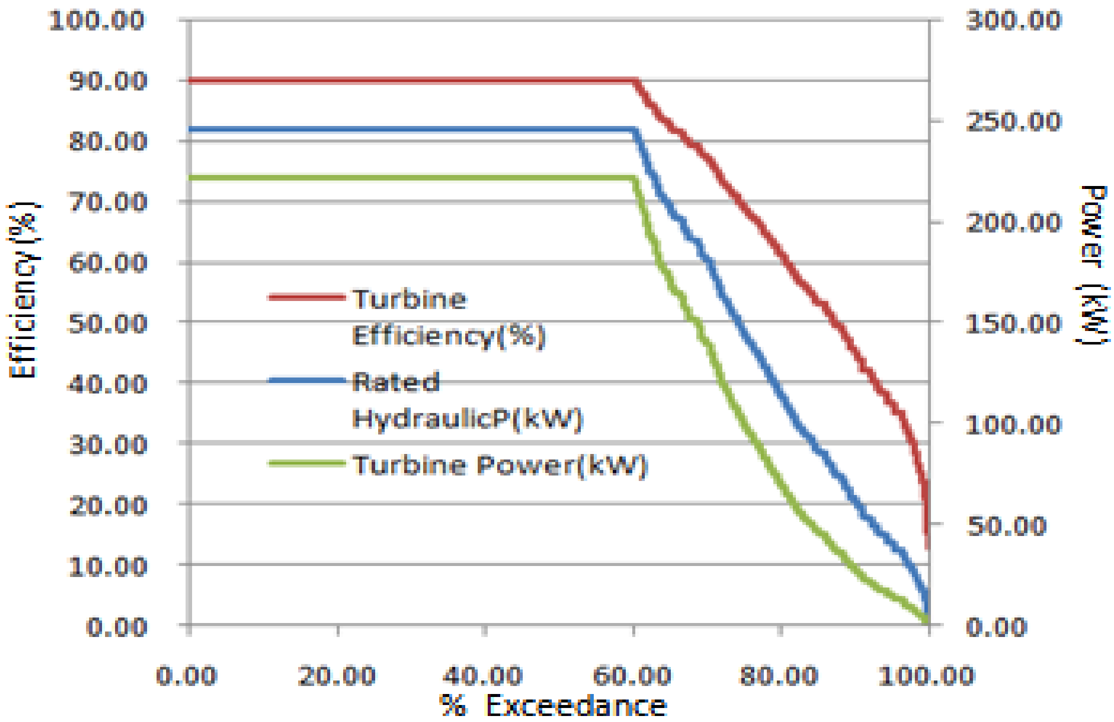


Figure 24: Letseng-la-Letsie Power and Efficiency curves

Figure 23 and Figure 24 show that the output power of the turbine is the replica of the input power to the turbine. Both powers remain constant at their maximum values as long as flow rate is equal or above design flow at Q_{60}.

It can be seen from Figure 23 and Figure 24 that efficiency drops as percentage of time exceeded goes beyond Q_{60}, where the flow rate drops below rated flow (see also appendix 1). These relationships are going to be analysed further with TURBNPRO application software model within this section.

The initial input data for the software is rated discharge determined from flow duration curve, net head at rated discharge, gross head of the site, electrical system frequency, efficiency priority at maximum output, minimum net head and maximum net head. The application interface for applying these input data, of the turbine are shown in Figure 25 and Figure 26 for both Quthing River and Letseng-la-Letsie respectively.

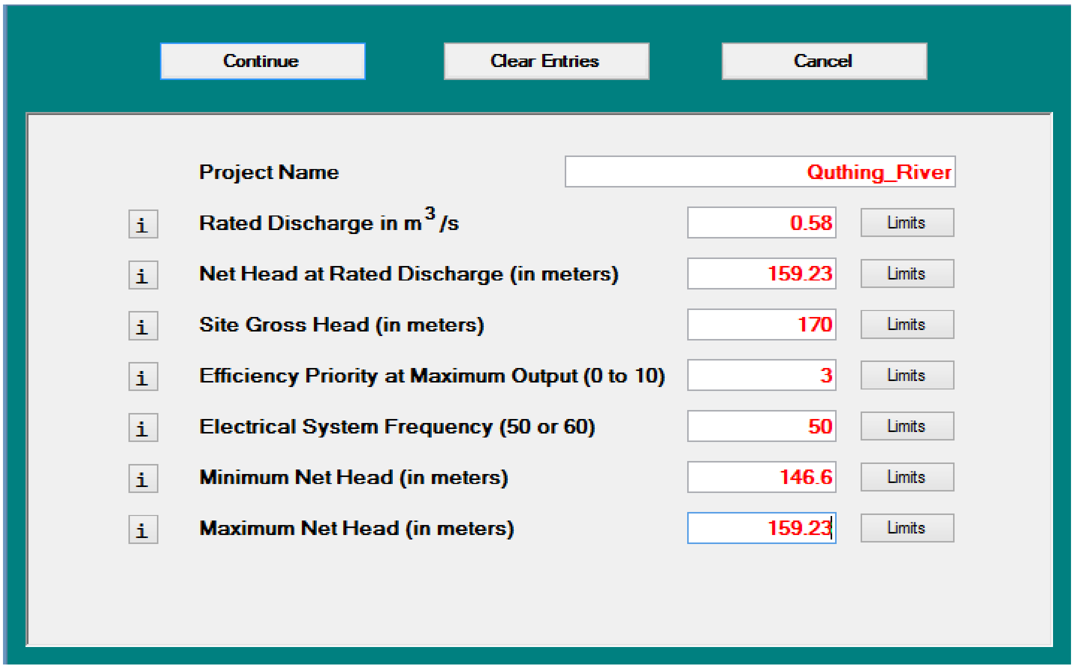


Figure 25: Quthing River Turbine input data

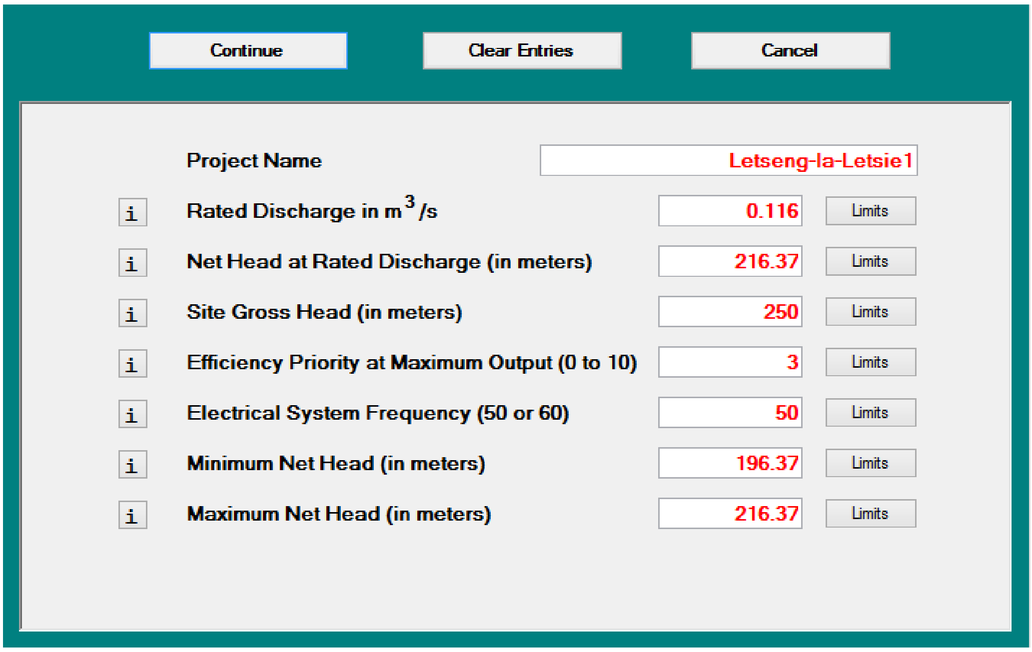
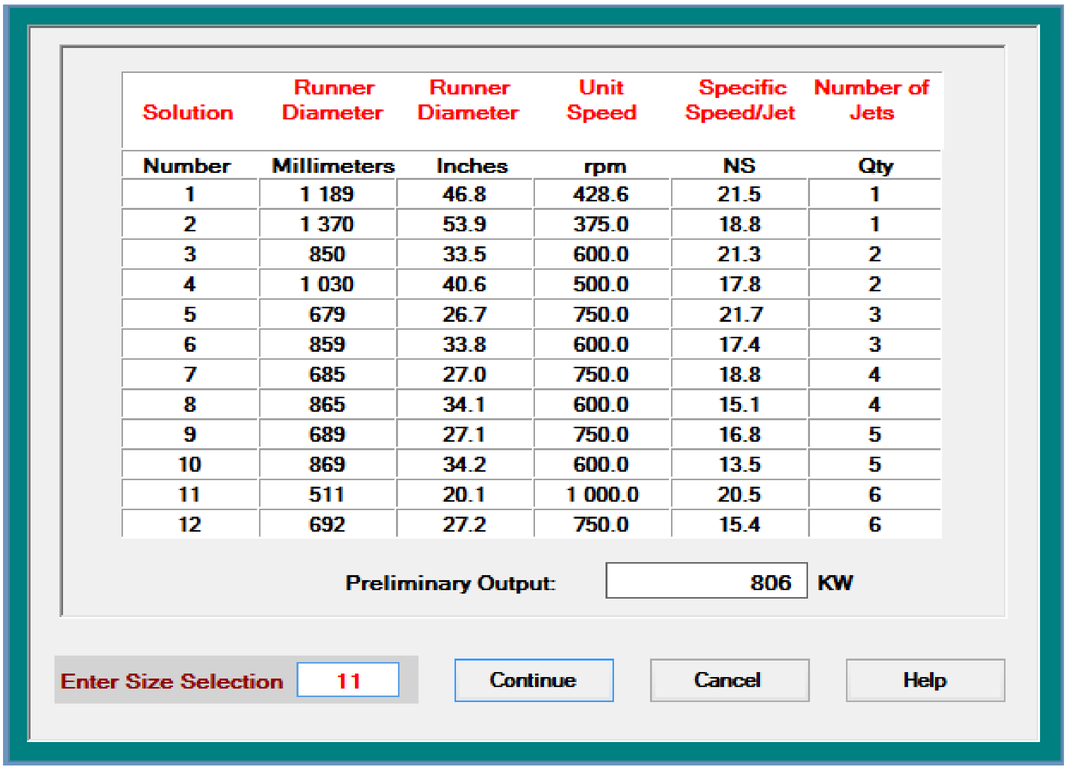


Figure 26: Letseng-la-Letsie Turbine input data

With the initial input parameters applied to the turbine size interface as in Figure 25 and Figure 26 the output results are as shown in Figure 27 to Figure 42.

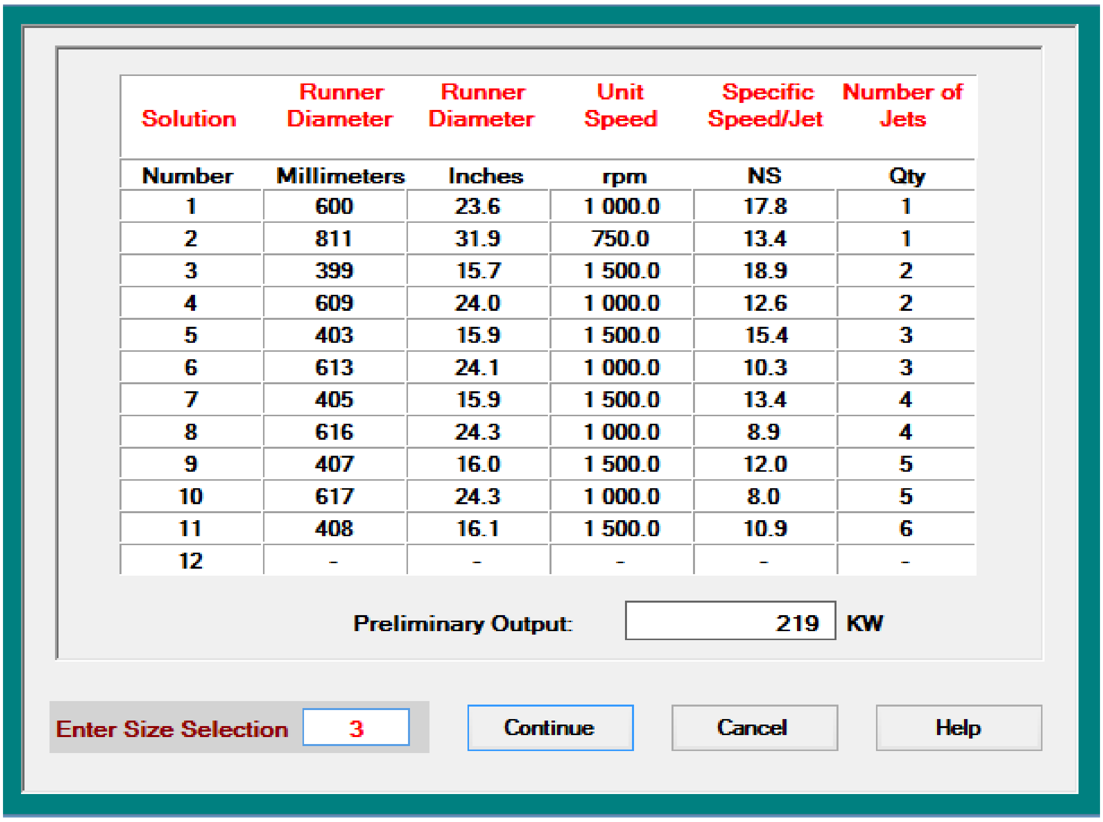


Solution	Runner Diameter	Runner Diameter	Unit Speed	Specific Speed/Jet	Number of Jets
Number	Millimeters	Inches	rpm	NS	Qty
1	1 189	46.8	428.6	21.5	1
2	1 370	53.9	375.0	18.8	1
3	850	33.5	600.0	21.3	2
4	1 030	40.6	500.0	17.8	2
5	679	26.7	750.0	21.7	3
6	859	33.8	600.0	17.4	3
7	685	27.0	750.0	18.8	4
8	865	34.1	600.0	15.1	4
9	689	27.1	750.0	16.8	5
10	869	34.2	600.0	13.5	5
11	511	20.1	1 000.0	20.5	6
12	692	27.2	750.0	15.4	6

Preliminary Output: 806 KW

Enter Size Selection 11 | Continue | Cancel | Help

Figure 27: Quthing River Turbine Solution Possibilities



Solution	Runner Diameter	Runner Diameter	Unit Speed	Specific Speed/Jet	Number of Jets
Number	Millimeters	Inches	rpm	NS	Qty
1	600	23.6	1 000.0	17.8	1
2	811	31.9	750.0	13.4	1
3	399	15.7	1 500.0	18.9	2
4	609	24.0	1 000.0	12.6	2
5	403	15.9	1 500.0	15.4	3
6	613	24.1	1 000.0	10.3	3
7	405	15.9	1 500.0	13.4	4
8	616	24.3	1 000.0	8.9	4
9	407	16.0	1 500.0	12.0	5
10	617	24.3	1 000.0	8.0	5
11	408	16.1	1 500.0	10.9	6
12	-	-	-	-	-

Preliminary Output: 219 KW

Enter Size Selection 3 | Continue | Cancel | Help

Figure 28: Letseng-la-Letsie Turbine Solution possibilities

Figure 27 and Figure 28 show the alternative options of Pelton turbine with regard to input parameters relating to Quthing River and Letseng-la-Letsie respectively. The options are characterized by different possible turbine sizes and speeds within a range of suitable specific speed designs. In this analysis solution number 11 was selected for Quthing River because it offered the turbine with a smaller diameter implying less expensive turbine. Solution number 3 was selected for Letseng-la-Letsie because it offered smallest diameter runner as per criteria for Quthing River. In addition to provision of smaller diameter, both solutions offered a turbine with high speed, 1000 rpm and 1500 rpm, for both Quthing River and Letseng-la-Letsie respectively. High speed is important because the magnitude of induced electromotive force (emf) increases with the speed of the turbine or generator rotor. The preliminary output of the turbine for Quthing River is 806 kW while the input hydraulic power is 906 kW. The preliminary output of the turbine for Letseng-la-Letsie is 219 kW with the input hydraulic power of 246.22 kW. This implies the preliminary turbine efficiency of 89% for both Quthing River and Letseng-la-Letsie.

After selecting the turbine size, the turbine will need to be configured with regard to axis orientation (horizontal or vertical); shaft arrangement (engaging of shaft/bearings or overhang runner on generator shaft) and efficiency modifier.

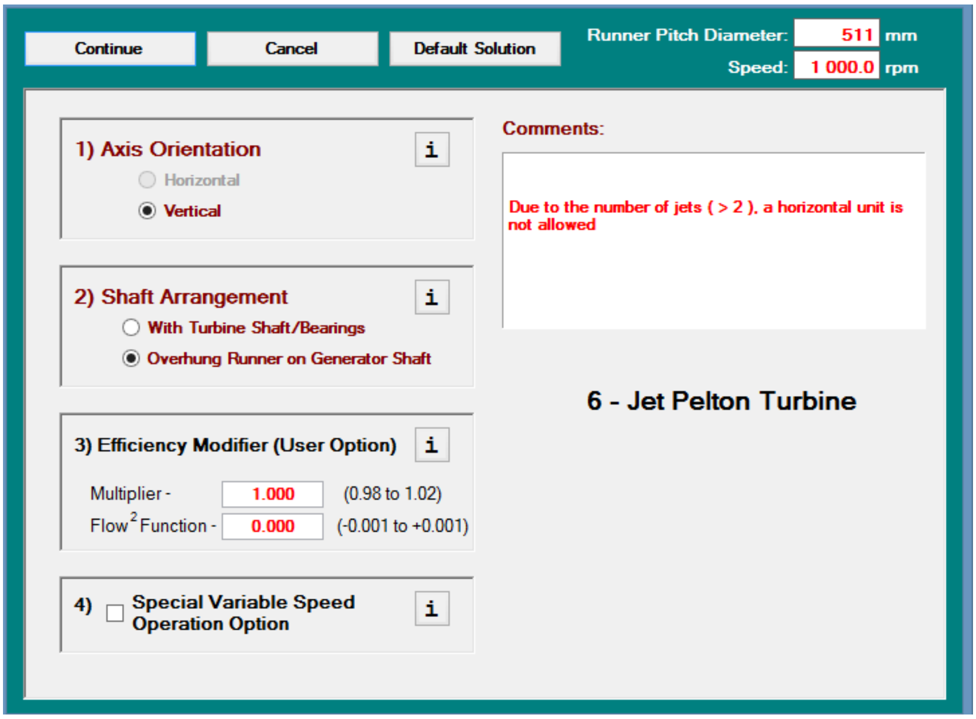


Figure 29: Quthing River Pelton Turbine configuration

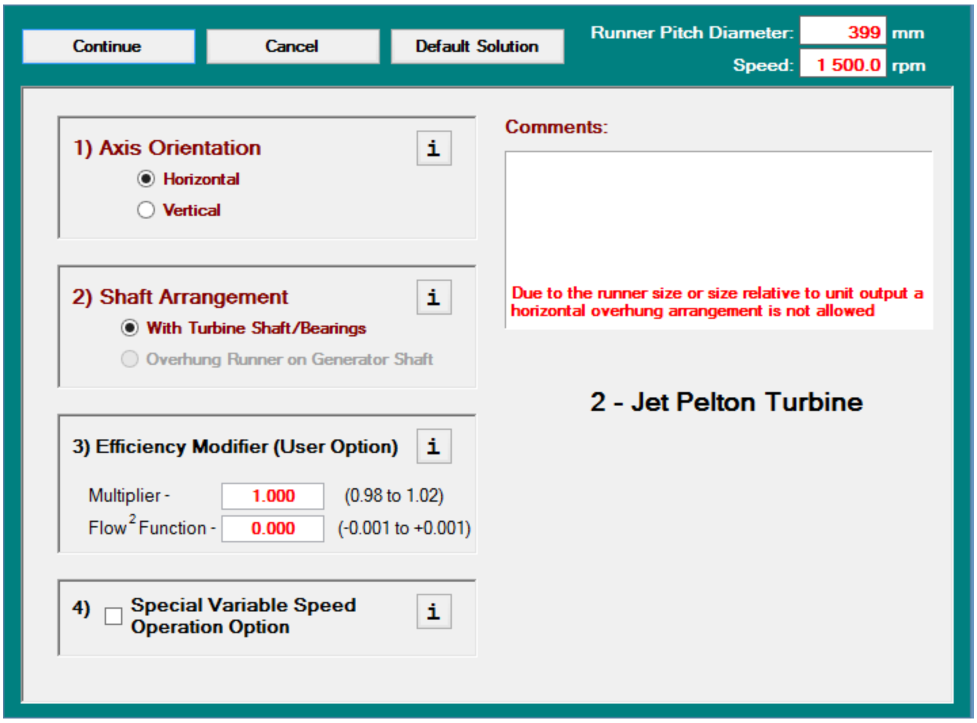


Figure 30: Letseng-la-Letsie Pelton Turbine configuration

Figure 29 shows the configuration of the turbine, for Quthing River, with the pitch diameter of 511 mm, unit speed of 1000 rpm and 6 water jets. The configuration for Letseng-la-Letsie is shown in Figure 30 with pitch diameter of 399 mm, unit speed of 1500 rpm and 2 water jets. The resultant recommendation for Quthing River turbine, is to use vertical axis orientation due to many water jets (vertical orientation is used for more than two jets) while the orientation recommended for Letseng-la-Letsie is horizontal axis due to less number of water jets (two jets). The recommended shaft arrangement, for Quthing River, is to overhang runner on generator shaft due to size limits. The shaft arrangement recommended for Letseng-la-Letsie, is to use configuration whereby the turbine runner will be mounted onto separate turbine shaft supported by bearings. The efficiency of the turbine for both Quthing River and Letseng-la-Letsie does not need to be modified because the head losses and henceforth flow rates analysis were carefully carried out during penstock analysis. If the gross head had been used, the efficiency modifier would have been used to cater for losses.

The configurations selected for Quthing River were therefore vertical axis orientation; shaft arrangement with turbine shaft/bearing and efficiency modifier of one. The configurations selected for Letseng-la-Letsie were horizontal axis orientation; shaft arrangement with turbine shaft/bearing and efficiency modifier of one. The solution information summary is shown in Figure 31 to Figure 40.

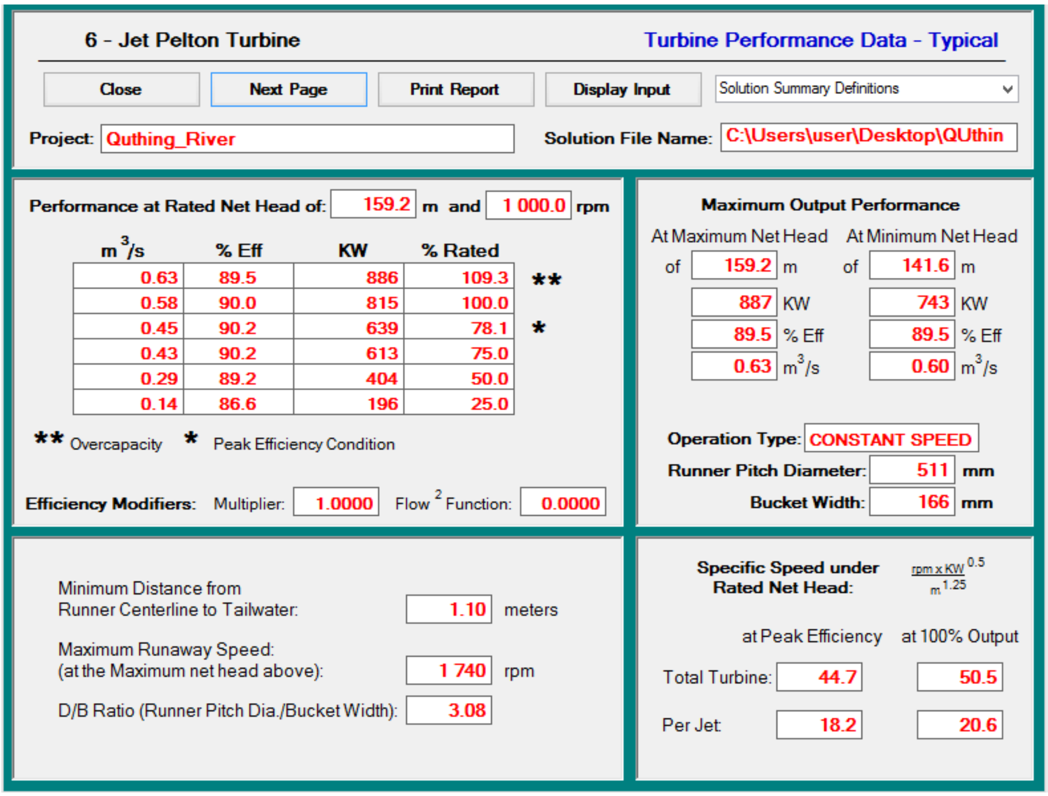


Figure 31: Quthing River Turbine Typical performance data

From Figure 31 it can be seen that performance of the turbine for Quthing River; at design flow rate of 0.58 m^3/s, rated net head of 159.2 m and speed of 1000 rpm; is 89.9% efficient. The power output at this efficiency is 815 kW. The output can be increased by overdriving the turbine with flow rate greater than designed which is 0.63 m^3/s but the turbine would be used at overcapacity. The turbine can be operated at its peak efficiency by driving it with input flow rate of 0.45 m^3/s.

The maximum output performance reveals that; with efficiency of 89.5%, flow rate of 0.63 m^3/s and the maximum head of 159.2 m, the output would be 887 kW. The output at minimum head of 141.6 m would be 743 kW with efficiency of 89.5% for flow rate of 0.6 m^3/s. The specific speed at peak efficiency output (639 kW) is 44.7 rpm while the specific speed at 100% output (815 kW) is 50.5 rpm. This implies that if the turbine is operated at peak efficiency more power output is reached with lower turbine specific speed. The ultimate mechanical power is 815 kW as per design flow rate.

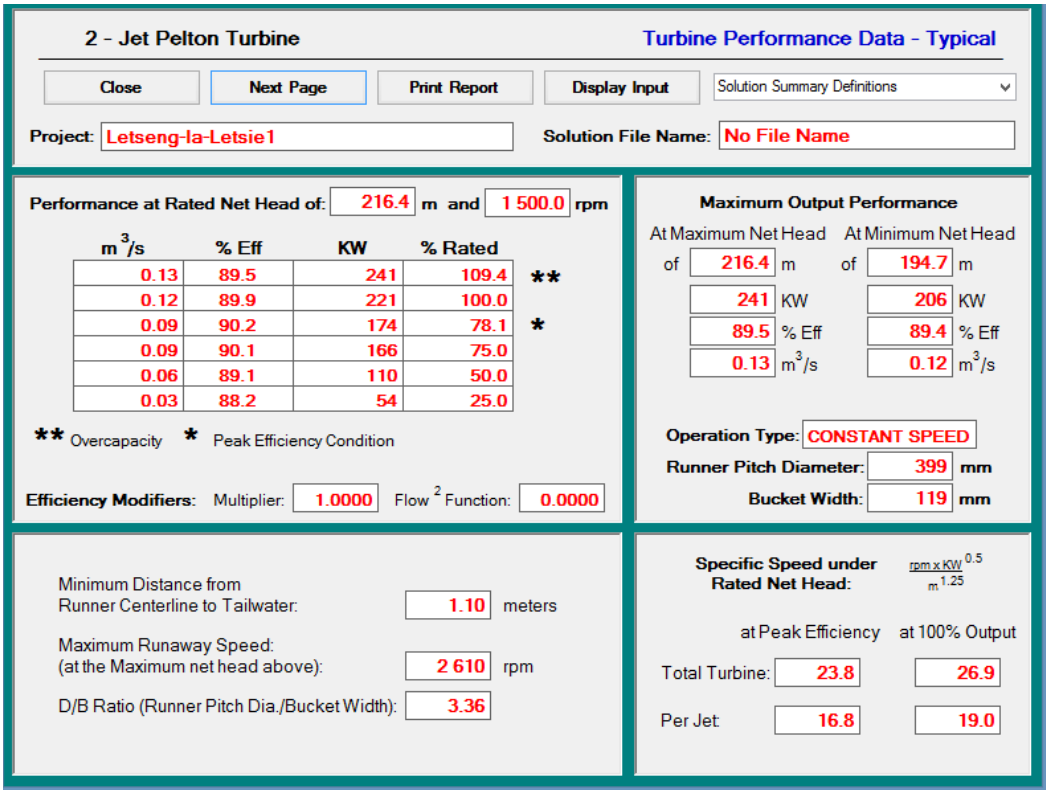


Figure 32: Letseng-la Letsie Turbine Typical performance data

Figure 32 shows that performance of the turbine for Letseng-la-Letsie; at design flow rate of 0.12 m^3/s, rated net head of 216.4 m and speed of 1500 rpm; is 89.9% efficient. The power output at this efficiency is 221 kW. Overdriving the turbine with flow rate of 0.13 m^3/s can increase the output to 241 kW but the turbine would be used at its overcapacity. The turbine can be operated at its peak efficiency by driving it with input flow rate of 0.09 m^3/s.

The maximum output performance reveals that; with efficiency of 89.5%, flow rate of 0.13 m^3/s and the maximum head of 216.4 m, the output would be 241 kW. The output at minimum head of 194.7 m would be 206 kW with efficiency of 89.4% for flow rate of 0.12 m^3/s. The specific speed at peak efficiency output (241 kW) is 23.8 rpm while the specific speed at 100% output (221 kW) is 26.9 rpm. This implies that if the turbine is operated at peak efficiency more power output is reached with lower turbine specific speed. The ultimate mechanical power is 221 kW as per design flow rate.

Since the turbine is located inside the power house it is necessary to have a picture of its mass, length, width and height so that its installation and mounting in power house can well be catered for during design stage of the power house. Figure 33 and Figure 34 give the details of the dimensions of the turbines for Quthing River and Letseng-la-Letsie respectively.

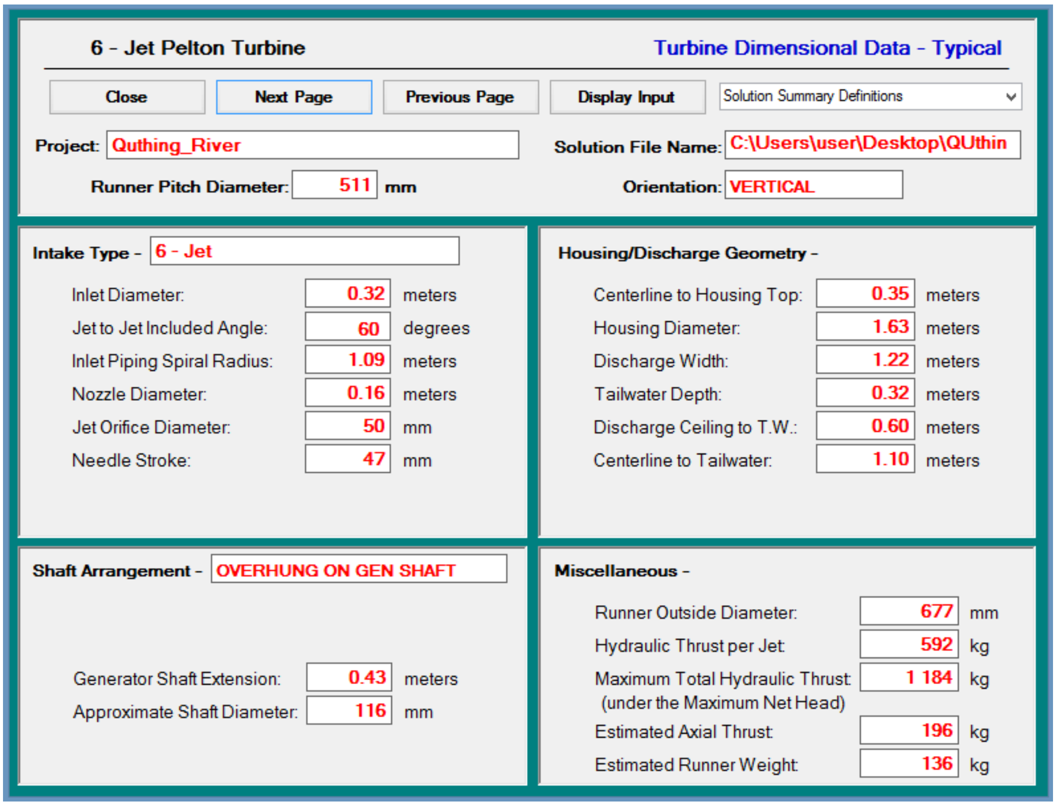


Figure 33: Quthing River Turbine Dimensional Data

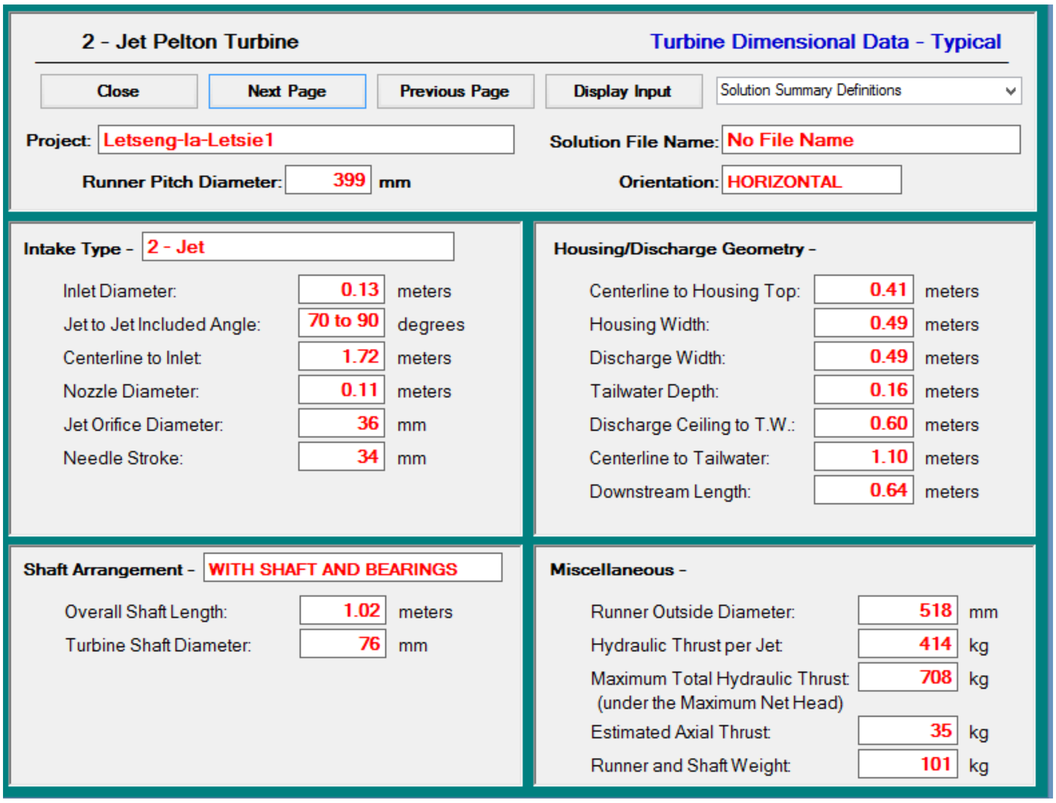


Figure 34: Letseng-la-Letsie Turbine Dimensional Data

Figure 33 and Figure 34 show that, the first part of turbine dimensional data focuses on the intake of the turbine. These give the details of the intake jets. The details show that cross section of the jets is bigger at the beginning from inlet diameter of 0.32 m for Quthing and 0.13 m for Letseng-la-Letsie. The cross-sectional area of the water channel reduces down to ultimate jet orifice diameter of 0.05 m for Quthing River and 0.036 m for Letseng-la-Letsie. This information logically relates to pressure accumulation from the turbine intake to firing of the jets. Miscellaneous information focuses more on the weight which can give rough idea for designing slabs and foundations of the power house.

The information of dimensional data is not enough for working with power equipment like turbine. Technical drawings of the equipment are necessary for engineers and technicians to make informed decision concerning the equipment being dealt with. Figure 35 through Figure 40 show typical technical drawing of Pelton turbine.

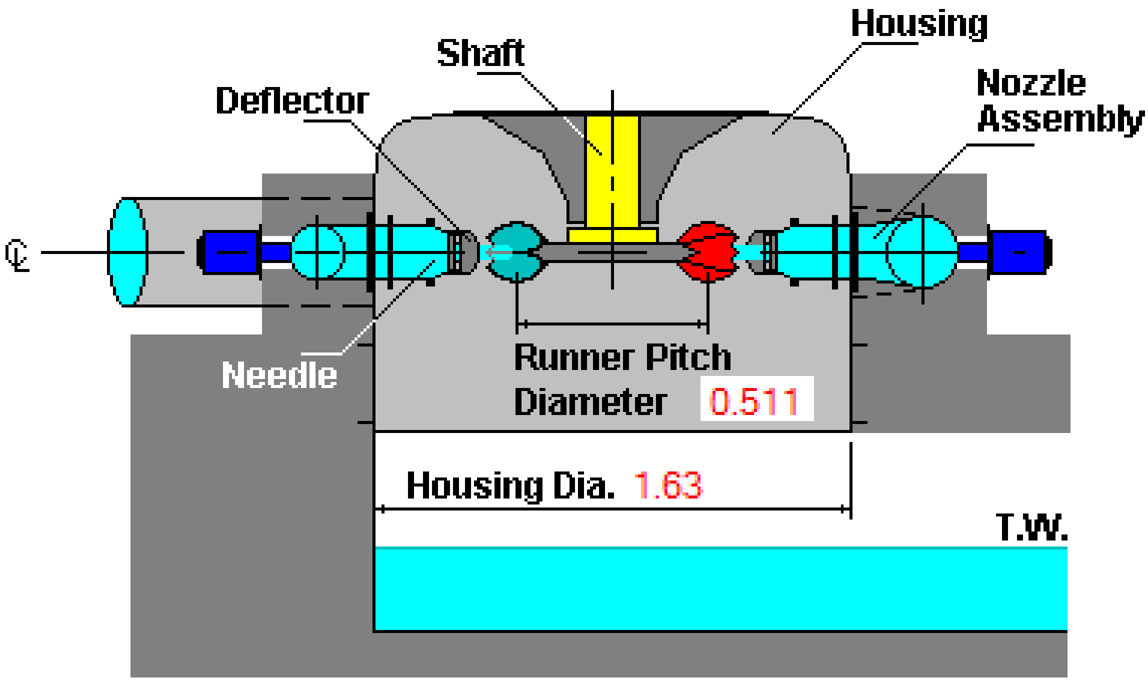


Figure 35: Quthing River Section view of Pelton Turbine

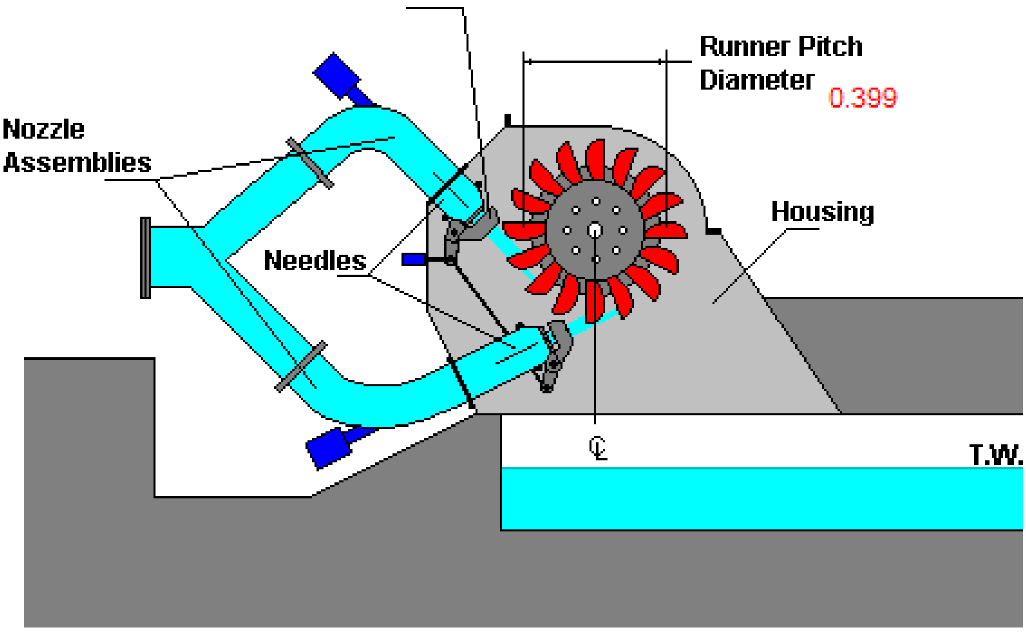


Figure 36: Letseng-la-Letsie Section view of Pelton Turbine

Figure 35 and Figure 36 show some typical parts of the turbine and their positions within the integrated unit for Quthing River and Letseng-la-Letsie respectively. The diameter of the housing for Quthing River turbine is shown with the diameter of 1.63m and runner pitch diameter of 0.511m. The runner pitch for Letseng-la-Letsie is small at 0.399 m. The positions of nozzle assemblies, deflectors and needles are also shown. Turbine shaft together with shaft seal and turbine bearing positions are also highlighted. This technical drawing information is very important for installation, assembling and maintenance.

One of the important factors concerning the turbine is about how water turns the turbine shaft using jets, per the configuration of the study area. Figure 37 and Figure 38 show water passage through the turbine for Quthing River and Letseng-la-Letsie respectively.

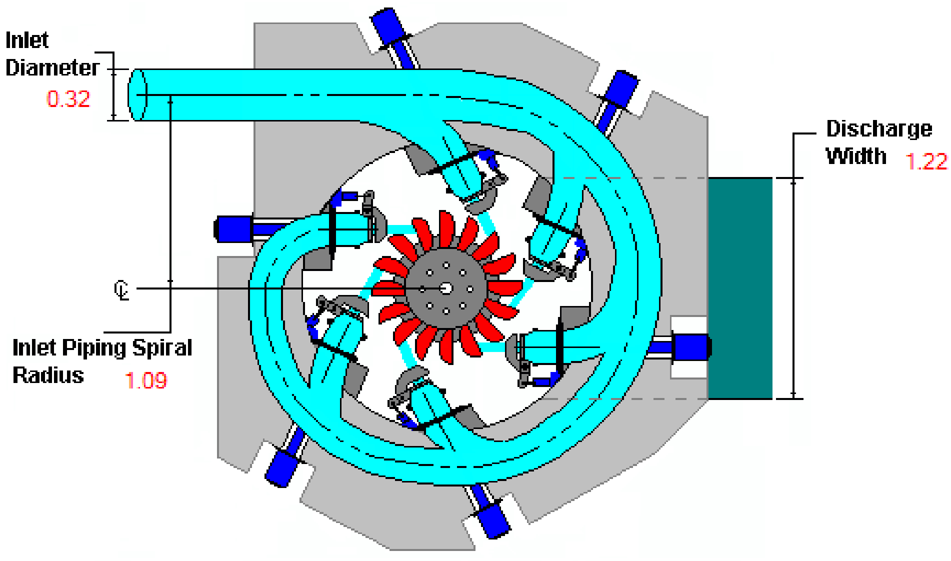


Figure 37: Quthing River Pelton turbine water passage

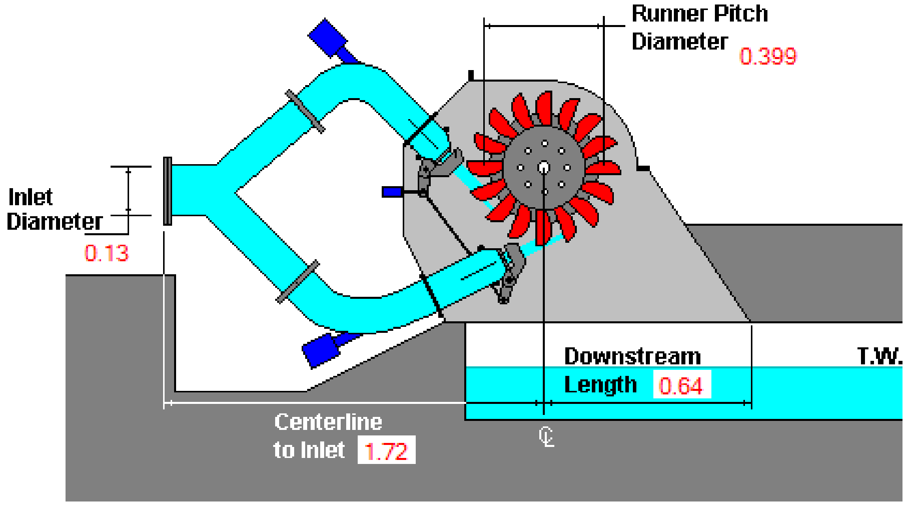


Figure 38: Letseng-la-Letsie Pelton turbine water passage

Figure 37 and Figure 38 show that water from penstock is coupled into the turbine through the inlet pipe which has got diameter of 0.32m for Quthing River and diameter of 0.13 m for Letseng-la-Letsie. The water in the inlet pipe is then distributed to all jets which are appropriately adjusted to face splitters of the buckets on the turbine runner. Pelton turbine being an impulse turbine, each blade is impacted momentarily by water from each jet and relayed to another jet. As this happens the blades rotate and eventually spin the hub since they are connected together. The exhausted water is then released from the turbine through its main outlet to the draft tube which will lead to the tail race.

The spinning of the hub due to water pressure from the jets creates a torque which develops mechanical power. This mechanical power which is Pelton turbine output (815 kW for Quthing

River and 221 kW for Letseng-la-Letsie) is the power which will be the input to the generator for generation of hydropower electricity. Figure 39 and Figure 40 show how Pelton turbine hub is connected to the generator and the associated orientation arrangement.

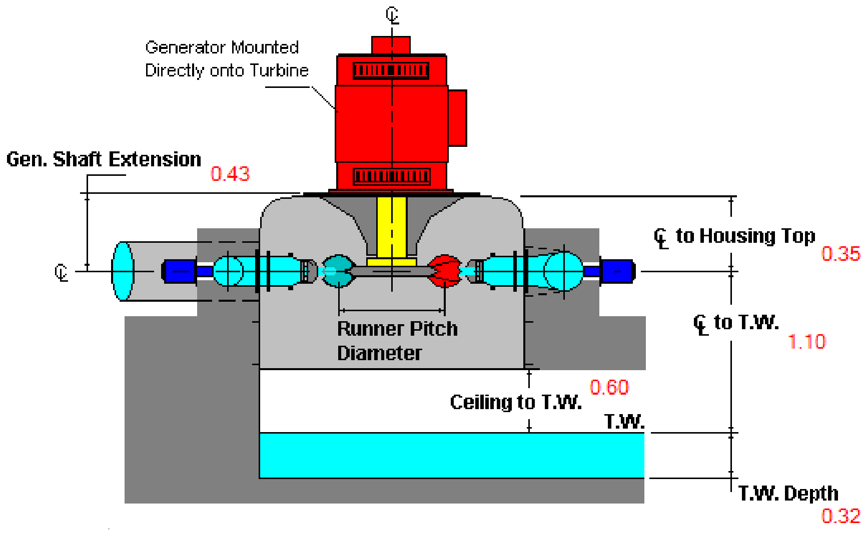


Figure 39: Quthing River Turbine Arrangement

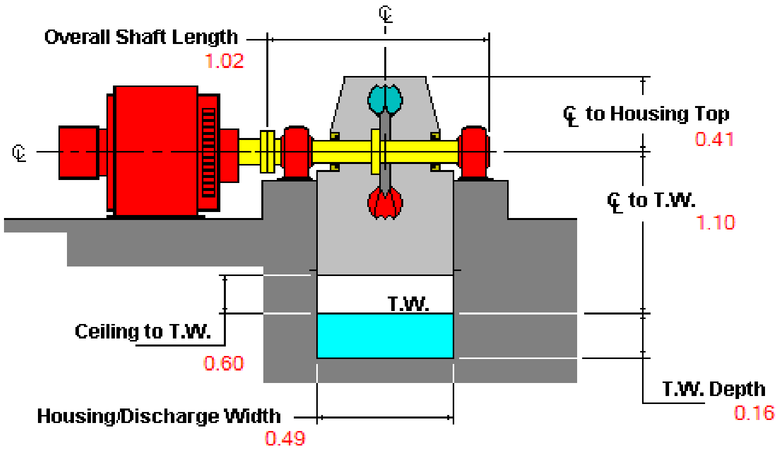


Figure 40: Letseng-la-Letsie Turbine Arrangement

Turbine arrangement can be configured in two ways which are horizontal configuration and vertical configuration. The two configurations can be further subdivided, with respect to shaft arrangement, into runner overhang on generator shaft or runner on turbine shaft with bearings. From Figure 39 it can be seen that due to the size of the turbine, vertical configuration had to be used. This orientation requires tall power house profile and may require greater power house crane capacity. However the advantages of this orientation are: the lesser floor space, or foot print than horizontal orientation and greater flow range and higher speed with smaller runner diameters.

From Figure 40 it can be seen that due to the small size of the turbine, horizontal configuration can be used. Unlike vertical orientation which required tall power house profile, horizontal orientation equipment occupies large horizontal space hence requires wide power house profile. The advantage of this orientation is less power house crane capacity. However, the disadvantages of this orientation are: the wide floor space, more foot print than vertical orientation and smaller flow range.

The turbine performance, hence its efficiency, is mainly dependent on the head of the site and flow rate. Figure 41 and Figure 42 show hill curves for Quthing River and Letseng-la-Letsie respectively.

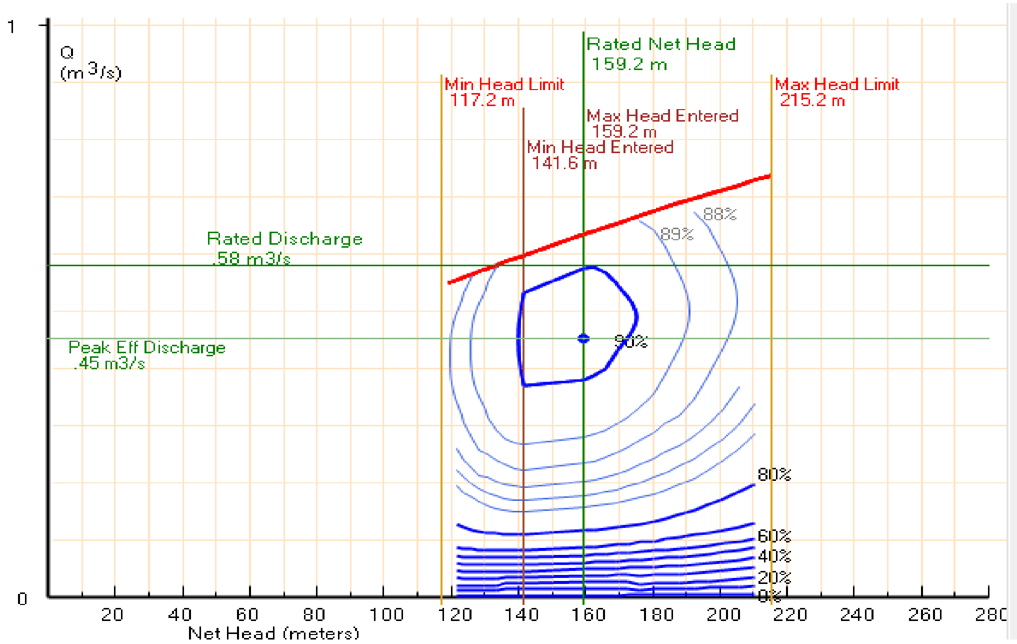


Figure 41: Quthing River Pelton Turbine Performance Hill curve

From Figure 41 it can be seen graphically that peak efficiency of the turbine, as a function of flow rate and head, is reached at the flow rate of 0.45 m^3/s for the rated head of 159.2 m. The peak efficiency at this discharge rate of 0.45 m^3/s and rated head of 159.2 m is shown as 90.2%. The figure also shows that as the flow rate is increased, i.e. to rated discharge of 0.58 m^3/s, the efficiency decreases to around 89%. Similarly, if the flow rate is decreased to around 0.27 m^3/s keeping head constant at 159.2 m, the efficiency decreases to approximately 89%. Thus, for optimum results, the turbine has to be operated at flow rate of 0.45 m^3/s. However, the optimization objective is power. Therefore, the turbine will be operated at 0.58 m^3/s.

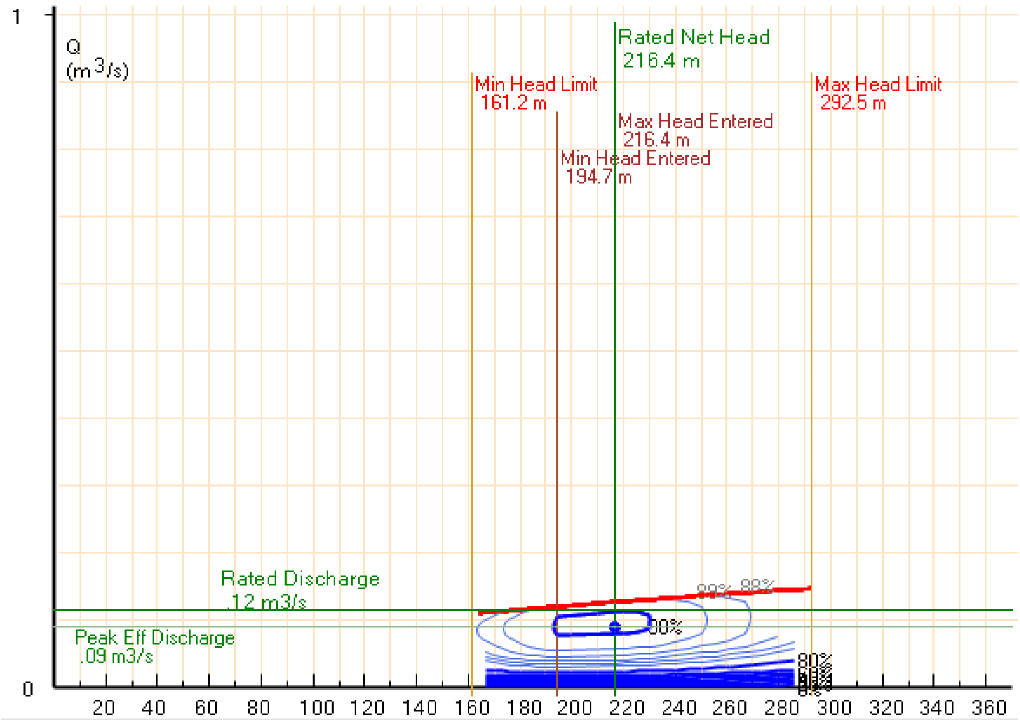


Figure 42: Letseng-la-Letsie Pelton Turbine Hill curve

Figure 42 shows that, the peak efficiency of the turbine is reached at the flow rate of 0.09 m^3/s for the rated net head of 216.4m. The peak efficiency at this discharge rate of 0.09m^3/s for the rated net head of 216.4m is shown as 90.2%. The figure also shows that as the flow rate is increased i.e. to rated discharge of 0.12m^3/s, while keeping head constant at 216.4 m, the efficiency decreased to 90%. Similarly, if the flow rate is kept constant at peak efficiency discharge of 0.09 m^3/s and the head is increased beyond rated head (216.4 m), efficiency drops below 90.2%. Thus, deviation of head or flow rate from peak efficiency coordinates decreases the efficiency of the turbine. This implies that for efficiency optimization the turbine is supposed to be run with flow rate of 0.09m^3/s for rated head of 216.4m. However, the optimal objective of the study is more power. Therefore, the recommendation will be to run the turbine at its rated discharge of 0.12m^3/s with rated net head of 216.4m.

4.6 Electrical Power

Since the speed of the runner of the turbine for Quthing River and Letseng-la-Letsie is 1000 rpm and 1500 rpm respectively, a less expensive salient pole synchronous generator can feature for the conversion from mechanical power into electrical power. The frequency of electrical power in Lesotho is 50 Hz. Thus, according to equation 14, the number of poles for the rotor regarding Quthing River generator will be 3 pole pairs. With the same criteria, the pole pairs for the rotor of the generator regarding Letseng-la-Letsie will be 2 pole pairs.

The efficiency of synchronous generators in power plants is usually 99% because generators are normally regarded as lossless power equipment. The output of the generator (plant capacity) for Quthing River will therefore be the output of the turbine minus losses of the generator which results to 807 kW. The plant capacity for Letseng-la-Letsie after subtracting the losses of the generator results to 219 kW. The typical capacity factor of hydropower generation in Africa, according to Energy Information Administration (EIA) table in Appendix 6, is 49%. Thus, the annual energy for Quthing River will be 3.46 MWh while the annual energy that can be harnessed from Letseng-la-Letsie will be 0.95 MWh.

Chapter 5: Conclusion

The exploration and evaluation of hydropower potential of Letseng-la-Letsie and Quthing River were conducted. The analysis of key parameters for Quthing River provided net head of 159.23 m and design flow rate of 0.58 m^3/s. The analysis of Letseng-la-Letsie provided net head of 216.37 m and design flow rate of 0.116 m^3/s.

The analysis for mechanical power per given sites from TURBNPRO gave the output power of 815 kW for Quthing River turbine while the power output for Letseng-la-Letsie turbine was 221 kW. Using typical hydro-electric generators efficiency and typical capacity factor for Africa, the capacity from Quthing River was found to be 807 kW with annual energy of 3.46 MWh. The capacity for Letseng-la-Letsie was found to be 219 kW with annual energy of 0.95 MWh.

The potential capacity of Quthing River with 807 kW and annual energy of 3.46 MWh is viable and addresses national strategic development plan (increase clean energy production capacity and develop small-scale electricity generation models that are viable for communities, where connection to the national power grid is not cost-effective). If this potential can reach the stage of project implementation, challenges of power deficit would need to be addressed to some degree. Along with addressing of power deficit, the amount of electricity imported from both South Africa and Mozambique could be decreased. The public funds investment to this project is therefore encouraged.

The potential capacity of Letseng-la-Letsie with 221 kW and annual energy capacity of 0.95 MWh is very low. The investments to this project would be encouraged if there is funding available for the project. It is discouraged for the low economy country to invest into hydropower project of this small magnitude.

Recommendations

The method (catchment area method) applied for the assessment of flow rates is theoretical and still need to be reinforced with practical measured data. It is therefore recommended that practical measurements of flows at the identified abstraction points of study sites be taken. It is also recommended that surveyors are deployed to the study area to produce practical site map with contours which can be correlated with the DEM produced using GIS and Aster-DEM.

Since Lesotho energy policy aspires that energy shall universally be accessible and affordable in a sustainable manner, with minimal impact on the climate; it is therefore recommended that these studies are taken further from reconnaissance level since hydropower is clean energy forming part of global agenda.

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Appendices

Appendix 1: Computed power, Percentage exceedance and efficiency

Letseng- la-Letsie						Quthing River					
% exceedance	Flow (m^3/s)	Hydraulic power (kW)	Rated Hydraulic power (kW)	Turbine Efficiency %	Mechanical Power (KW)	% exceedance	Flow (m^3/s)	Hydraulic Power (kW)	Rated Hydraulic Power (kW)	Turbine Efficiency (%)	Mechanical Power (kW)
0.01	6.0860	12918.1	246.2	90.00	222	0.01	30.430	47533	906	90.00	815
0.02	5.8313	12377.5	246.2	90.00	222	0.02	29.157	45544	906	90.00	815
0.03	5.7667	12240.3	246.2	90.00	222	0.03	28.833	45039	906	90.00	815
0.04	5.6987	12095.9	246.2	90.00	222	0.04	28.493	44508	906	90.00	815
0.05	5.6560	12005.4	246.2	90.00	222	0.05	28.280	44175	906	90.00	815
0.06	5.5727	11828.5	246.2	90.00	222	0.06	27.863	43524	906	90.00	815
0.07	5.4553	11579.4	246.2	90.00	222	0.07	27.277	42607	906	90.00	815
0.08	5.3820	11423.8	246.2	90.00	222	0.08	26.910	42035	906	90.00	815
0.09	5.3593	11375.7	246.2	90.00	222	0.09	26.797	41858	906	90.00	815
0.10	5.3400	11334.6	246.2	90.00	222	0.10	26.700	41707	906	90.00	815
0.11	5.2660	11177.6	246.2	90.00	222	0.11	26.330	41129	906	90.00	815
0.12	5.1747	10983.7	246.2	90.00	222	0.12	25.873	40415	906	90.00	815
0.13	5.1280	10884.6	246.2	90.00	222	0.13	25.640	40051	906	90.00	815
0.14	4.9220	10447.4	246.2	90.00	222	0.14	24.610	38442	906	90.00	815
0.15	4.8887	10376.6	246.2	90.00	222	0.15	24.443	38182	906	90.00	815
0.16	4.8880	10375.2	246.2	90.00	222	0.16	24.440	38176	906	90.00	815
0.17	4.8233	10238.0	246.2	90.00	222	0.17	24.117	37671	906	90.00	815
0.18	4.8033	10195.5	246.2	90.00	222	0.18	24.017	37515	906	90.00	815
0.19	4.7800	10146.0	246.2	90.00	222	0.19	23.900	37333	906	90.00	815
0.20	4.7533	10089.4	246.2	90.00	222	0.20	23.767	37125	906	90.00	815
0.21	4.7413	10063.9	246.2	90.00	222	0.21	23.707	37031	906	90.00	815
0.21	4.7413	10063.9	246.2	90.00	222	0.21	23.707	37031	906	90.00	815
0.23	4.7407	10062.5	246.2	90.00	222	0.23	23.703	37026	906	90.00	815
0.24	4.7340	10048.3	246.2	90.00	222	0.24	23.670	36974	906	90.00	815
0.25	4.7093	9996.0	246.2	90.00	222	0.25	23.547	36781	906	90.00	815
0.26	4.6913	9957.8	246.2	90.00	222	0.26	23.457	36640	906	90.00	815
0.27	4.6660	9904.0	246.2	90.00	222	0.27	23.330	36443	906	90.00	815
0.28	4.6573	9885.6	246.2	90.00	222	0.28	23.287	36375	906	90.00	815

0.29	4.6167	9799.3	246.2	90.00	222	0.29	23.083	36057	906	90.00	815
0.30	4.6107	9786.6	246.2	90.00	222	0.30	23.053	36010	906	90.00	815
0.31	4.5987	9761.1	246.2	90.00	222	0.31	22.993	35917	906	90.00	815
0.32	4.4933	9537.5	246.2	90.00	222	0.32	22.467	35094	906	90.00	815
0.33	4.4867	9523.4	246.2	90.00	222	0.33	22.433	35042	906	90.00	815
0.34	4.4553	9456.8	246.2	90.00	222	0.34	22.277	34797	906	90.00	815
0.35	4.4380	9420.1	246.2	90.00	222	0.35	22.190	34662	906	90.00	815
0.36	4.3707	9277.1	246.2	90.00	222	0.36	21.853	34136	906	90.00	815
0.37	4.3460	9224.8	246.2	90.00	222	0.37	21.730	33943	906	90.00	815
0.38	4.3167	9162.5	246.2	90.00	222	0.38	21.583	33714	906	90.00	815
0.38	4.3167	9162.5	246.2	90.00	222	0.38	21.583	33714	906	90.00	815
0.40	4.2927	9111.6	246.2	90.00	222	0.40	21.463	33527	906	90.00	815
0.41	4.2693	9062.0	246.2	90.00	222	0.41	21.347	33344	906	90.00	815
0.42	4.2520	9025.3	246.2	90.00	222	0.42	21.260	33209	906	90.00	815
0.43	4.2413	9002.6	246.2	90.00	222	0.43	21.207	33126	906	90.00	815
0.44	4.2387	8997.0	246.2	90.00	222	0.44	21.193	33105	906	90.00	815
0.45	4.2340	8987.0	246.2	90.00	222	0.45	21.170	33069	906	90.00	815
0.46	4.2193	8955.9	246.2	90.00	222	0.46	21.097	32954	906	90.00	815
0.47	4.1860	8885.2	246.2	90.00	222	0.47	20.930	32694	906	90.00	815
0.48	4.1820	8876.7	246.2	90.00	222	0.48	20.910	32662	906	90.00	815
0.49	4.1807	8873.8	246.2	90.00	222	0.49	20.903	32652	906	90.00	815
0.50	4.1727	8856.9	246.2	90.00	222	0.50	20.863	32589	906	90.00	815
0.51	4.1480	8804.5	246.2	90.00	222	0.51	20.740	32397	906	90.00	815
0.52	4.1420	8791.8	246.2	90.00	222	0.52	20.710	32350	906	90.00	815
0.53	4.1347	8776.2	246.2	90.00	222	0.53	20.673	32293	906	90.00	815
0.54	4.1140	8732.3	246.2	90.00	222	0.54	20.570	32131	906	90.00	815
0.55	4.1073	8718.2	246.2	90.00	222	0.55	20.537	32079	906	90.00	815
0.56	4.0880	8677.1	246.2	90.00	222	0.56	20.440	31928	906	90.00	815
0.57	4.0847	8670.1	246.2	90.00	222	0.57	20.423	31902	906	90.00	815
0.58	4.0687	8636.1	246.2	90.00	222	0.58	20.343	31777	906	90.00	815
0.59	4.0567	8610.6	246.2	90.00	222	0.59	20.283	31684	906	90.00	815
0.60	4.0540	8605.0	246.2	90.00	222	0.60	20.270	31663	906	90.00	815
0.61	4.0473	8590.8	246.2	90.00	222	0.61	20.237	31611	906	90.00	815
0.62	4.0367	8568.2	246.2	90.00	222	0.62	20.183	31527	906	90.00	815
0.63	4.0320	8558.3	246.2	90.00	222	0.63	20.160	31491	906	90.00	815
0.64	4.0220	8537.1	246.2	90.00	222	0.64	20.110	31413	906	90.00	815
0.65	4.0033	8497.4	246.2	90.00	222	0.65	20.017	31267	906	90.00	815
0.66	4.0007	8491.8	246.2	90.00	222	0.66	20.003	31246	906	90.00	815
0.67	3.9693	8425.3	246.2	90.00	222	0.67	19.847	31001	906	90.00	815
0.68	3.9540	8392.7	246.2	90.00	222	0.68	19.770	30882	906	90.00	815
0.69	3.9320	8346.0	246.2	90.00	222	0.69	19.660	30710	906	90.00	815
0.70	3.9273	8336.1	246.2	90.00	222	0.70	19.637	30673	906	90.00	815
0.71	3.9267	8334.7	246.2	90.00	222	0.71	19.633	30668	906	90.00	815
0.72	3.9060	8290.8	246.2	90.00	222	0.72	19.530	30507	906	90.00	815

0.73	3.8880	8252.6	246.2	90.00	222	0.73	19.440	30366	906	90.00	815
0.74	3.8813	8238.5	246.2	90.00	222	0.74	19.407	30314	906	90.00	815
0.75	3.8560	8184.7	246.2	90.00	222	0.75	19.280	30116	906	90.00	815
0.76	3.8527	8177.6	246.2	90.00	222	0.76	19.263	30090	906	90.00	815
0.77	3.8460	8163.5	246.2	90.00	222	0.77	19.230	30038	906	90.00	815
0.78	3.8287	8126.7	246.2	90.00	222	0.78	19.143	29903	906	90.00	815
0.79	3.8253	8119.6	246.2	90.00	222	0.79	19.127	29877	906	90.00	815
0.80	3.8100	8087.1	246.2	90.00	222	0.80	19.050	29757	906	90.00	815
0.81	3.8060	8078.6	246.2	90.00	222	0.81	19.030	29726	906	90.00	815
0.82	3.7887	8041.8	246.2	90.00	222	0.82	18.943	29590	906	90.00	815
0.83	3.7873	8039.0	246.2	90.00	222	0.83	18.937	29580	906	90.00	815
0.84	3.7867	8037.5	246.2	90.00	222	0.84	18.933	29575	906	90.00	815
0.85	3.7780	8019.1	246.2	90.00	222	0.85	18.890	29507	906	90.00	815
0.86	3.7767	8016.3	246.2	90.00	222	0.86	18.883	29497	906	90.00	815
0.87	3.7700	8002.2	246.2	90.00	222	0.87	18.850	29445	906	90.00	815
0.89	3.7567	7973.9	246.2	90.00	222	0.89	18.783	29340	906	90.00	815
0.90	3.7467	7952.6	246.2	90.00	222	0.90	18.733	29262	906	90.00	815
0.91	3.7407	7939.9	246.2	90.00	222	0.91	18.703	29215	906	90.00	815
0.92	3.7240	7904.5	246.2	90.00	222	0.92	18.620	29085	906	90.00	815
0.93	3.7227	7901.7	246.2	90.00	222	0.93	18.613	29075	906	90.00	815
0.94	3.7207	7897.4	246.2	90.00	222	0.94	18.603	29059	906	90.00	815
0.95	3.7180	7891.8	246.2	90.00	222	0.95	18.590	29038	906	90.00	815
0.96	3.7153	7886.1	246.2	90.00	222	0.96	18.577	29018	906	90.00	815
0.97	3.7067	7867.7	246.2	90.00	222	0.97	18.533	28950	906	90.00	815
0.98	3.7060	7866.3	246.2	90.00	222	0.98	18.530	28945	906	90.00	815
0.99	3.6920	7836.6	246.2	90.00	222	0.99	18.460	28835	906	90.00	815
1.00	3.6893	7830.9	246.2	90.00	222	1.00	18.447	28815	906	90.00	815
59.77	0.1165	247.2	246.2	90.00	222	59.77	0.582	910	906	90.00	815
59.77	0.1165	247.2	246.2	90.00	222	59.77	0.582	910	906	90.00	815
59.94	0.1164	247.1	246.2	90.00	222	59.94	0.582	909	906	90.00	815
59.95	0.1163	246.8	246.2	90.00	222	59.95	0.581	908	906	90.00	815
59.95	0.1163	246.8	246.2	90.00	222	59.95	0.581	908	906	90.00	815
59.95	0.1163	246.8	246.2	90.00	222	59.95	0.581	908	906	90.00	815
59.98	0.1162	246.6	246.2	90.00	222	59.98	0.581	908	906	90.00	815
59.98	0.1162	246.6	246.2	90.00	222	59.98	0.581	908	906	90.00	815
59.98	0.1162	246.6	246.2	90.00	222	59.98	0.581	908	906	90.00	815
60.01	0.1160	246.2	246.2	90.00	222	60.01	0.580	906	906	90.00	815
60.01	0.1160	246.2	246.2	90.00	222	60.01	0.580	906	906	90.00	815
60.01	0.1160	246.2	246.2	90.00	222	60.01	0.580	906	906	90.00	815
60.01	0.1160	246.2	246.2	90.00	222	60.01	0.580	906	906	90.00	815
60.01	0.1160	246.2	246.2	90.00	222	60.01	0.580	906	906	90.00	815
60.01	0.1160	246.2	246.2	90.00	222	60.01	0.580	906	906	90.00	815
60.07	0.1159	246.1	246.1	89.97	221	60.07	0.580	905	905	89.97	815

60.08	0.1159	245.9	245.9	89.95	221	60.08	0.579	905	905	89.95	814
60.09	0.1158	245.8	245.8	89.92	221	60.09	0.579	904	904	89.92	813
60.10	0.1157	245.7	245.7	89.90	221	60.10	0.579	904	904	89.90	813
60.11	0.1155	245.2	245.2	89.82	220	60.11	0.578	902	902	89.82	810
60.11	0.1155	245.2	245.2	89.82	220	60.11	0.578	902	902	89.82	810
60.11	0.1155	245.2	245.2	89.82	220	60.11	0.578	902	902	89.82	810
60.11	0.1155	245.2	245.2	89.82	220	60.11	0.578	902	902	89.82	810
60.11	0.1155	245.2	245.2	89.82	220	60.11	0.578	902	902	89.82	810
60.16	0.1155	245.1	245.1	89.79	220	60.16	0.577	902	902	89.79	810
60.17	0.1154	244.9	244.9	89.77	220	60.17	0.577	901	901	89.77	809
60.17	0.1154	244.9	244.9	89.77	220	60.17	0.577	901	901	89.77	809
60.19	0.1153	244.7	244.7	89.72	220	60.19	0.576	900	900	89.72	808
60.20	0.1152	244.5	244.5	89.69	219	60.20	0.576	900	900	89.69	807
60.20	0.1152	244.5	244.5	89.69	219	60.20	0.576	900	900	89.69	807
60.22	0.1151	244.4	244.4	89.66	219	60.22	0.576	899	899	89.66	806
60.23	0.1151	244.2	244.2	89.64	219	60.23	0.575	899	899	89.64	806
60.23	0.1151	244.2	244.2	89.64	219	60.23	0.575	899	899	89.64	806
60.25	0.1150	244.1	244.1	89.61	219	60.25	0.575	898	898	89.61	805
60.26	0.1149	244.0	244.0	89.59	219	60.26	0.575	898	898	89.59	804
60.26	0.1149	244.0	244.0	89.59	219	60.26	0.575	898	898	89.59	804
60.28	0.1149	243.8	243.8	89.56	218	60.28	0.574	897	897	89.56	803
60.29	0.1147	243.4	243.4	89.48	218	60.29	0.573	896	896	89.48	801
60.29	0.1147	243.4	243.4	89.48	218	60.29	0.573	896	896	89.48	801
60.31	0.1146	243.2	243.2	89.46	218	60.31	0.573	895	895	89.46	801
60.31	0.1146	243.2	243.2	89.46	218	60.31	0.573	895	895	89.46	801
60.31	0.1146	243.2	243.2	89.46	218	60.31	0.573	895	895	89.46	801
60.31	0.1146	243.2	243.2	89.46	218	60.31	0.573	895	895	89.46	801
60.35	0.1145	243.0	243.0	89.40	217	60.35	0.572	894	894	89.40	799
60.36	0.1143	242.5	242.5	89.33	217	60.36	0.571	892	892	89.33	797
60.37	0.1142	242.4	242.4	89.30	216	60.37	0.571	892	892	89.30	796
60.37	0.1142	242.4	242.4	89.30	216	60.37	0.571	892	892	89.30	796
60.39	0.1141	242.3	242.3	89.27	216	60.39	0.571	891	891	89.27	796
60.40	0.1141	242.1	242.1	89.25	216	60.40	0.570	891	891	89.25	795
60.41	0.1140	242.0	242.0	89.22	216	60.41	0.570	890	890	89.22	794
60.42	0.1139	241.8	241.8	89.19	216	60.42	0.570	890	890	89.19	794
60.42	0.1139	241.8	241.8	89.19	216	60.42	0.570	890	890	89.19	794
60.44	0.1139	241.7	241.7	89.17	216	60.44	0.569	889	889	89.17	793
60.45	0.1138	241.6	241.6	89.14	215	60.45	0.569	889	889	89.14	792
60.45	0.1138	241.6	241.6	89.14	215	60.45	0.569	889	889	89.14	792
60.45	0.1138	241.6	241.6	89.14	215	60.45	0.569	889	889	89.14	792
60.45	0.1138	241.6	241.6	89.14	215	60.45	0.569	889	889	89.14	792
60.49	0.1137	241.4	241.4	89.12	215	60.49	0.569	888	888	89.12	792
60.50	0.1137	241.3	241.3	89.09	215	60.50	0.568	888	888	89.09	791
60.50	0.1137	241.3	241.3	89.09	215	60.50	0.568	888	888	89.09	791

60.50	0.1137	241.3	241.3	89.09	215	60.50	0.568	888	888	89.09	791
60.50	0.1137	241.3	241.3	89.09	215	60.50	0.568	888	888	89.09	791
60.50	0.1137	241.3	241.3	89.09	215	60.50	0.568	888	888	89.09	791
60.56	0.1136	241.1	241.1	89.06	215	60.56	0.568	887	887	89.06	790
60.56	0.1136	241.1	241.1	89.06	215	60.56	0.568	887	887	89.06	790
60.58	0.1135	241.0	241.0	89.04	215	60.58	0.568	887	887	89.04	790
60.59	0.1135	240.8	240.8	89.01	214	60.59	0.567	886	886	89.01	789
60.60	0.1134	240.7	240.7	88.99	214	60.60	0.567	886	886	88.99	788
60.60	0.1134	240.7	240.7	88.99	214	60.60	0.567	886	886	88.99	788
60.60	0.1134	240.7	240.7	88.99	214	60.60	0.567	886	886	88.99	788
60.63	0.1133	240.6	240.6	88.96	214	60.63	0.567	885	885	88.96	787
60.64	0.1133	240.4	240.4	88.93	214	60.64	0.566	885	885	88.93	787
60.64	0.1133	240.4	240.4	88.93	214	60.64	0.566	885	885	88.93	787
60.64	0.1133	240.4	240.4	88.93	214	60.64	0.566	885	885	88.93	787
60.67	0.1132	240.3	240.3	88.91	214	60.67	0.566	884	884	88.91	786
60.68	0.1131	240.1	240.1	88.88	213	60.68	0.566	884	884	88.88	785
60.69	0.1130	239.9	239.9	88.83	213	60.69	0.565	883	883	88.83	784
60.69	0.1130	239.9	239.9	88.83	213	60.69	0.565	883	883	88.83	784
60.69	0.1130	239.9	239.9	88.83	213	60.69	0.565	883	883	88.83	784
60.69	0.1130	239.9	239.9	88.83	213	60.69	0.565	883	883	88.83	784
60.69	0.1130	239.9	239.9	88.83	213	60.69	0.565	883	883	88.83	784
60.69	0.1130	239.9	239.9	88.83	213	60.69	0.565	883	883	88.83	784
60.75	0.1129	239.7	239.7	88.80	213	60.75	0.565	882	882	88.80	783
60.75	0.1129	239.7	239.7	88.80	213	60.75	0.565	882	882	88.80	783
60.77	0.1129	239.6	239.6	88.78	213	60.77	0.564	882	882	88.78	783
60.78	0.1128	239.4	239.4	88.75	212	60.78	0.564	881	881	88.75	782
60.79	0.1127	239.3	239.3	88.72	212	60.79	0.564	880	880	88.72	781
60.80	0.1127	239.1	239.1	88.70	212	60.80	0.563	880	880	88.70	780
60.81	0.1125	238.9	238.9	88.64	212	60.81	0.563	879	879	88.64	779
60.82	0.1123	238.3	238.3	88.54	211	60.82	0.561	877	877	88.54	776
60.83	0.1122	238.2	238.2	88.51	211	60.83	0.561	876	876	88.51	776
60.84	0.1121	238.0	238.0	88.49	211	60.84	0.561	876	876	88.49	775
60.85	0.1121	237.9	237.9	88.46	210	60.85	0.560	875	875	88.46	774
60.86	0.1119	237.6	237.6	88.41	210	60.86	0.560	874	874	88.41	773
60.87	0.1119	237.4	237.4	88.38	210	60.87	0.559	874	874	88.38	772
60.88	0.1118	237.3	237.3	88.36	210	60.88	0.559	873	873	88.36	772
60.88	0.1118	237.3	237.3	88.36	210	60.88	0.559	873	873	88.36	772
60.90	0.1117	237.0	237.0	88.30	209	60.90	0.558	872	872	88.30	770
60.91	0.1115	236.7	236.7	88.25	209	60.91	0.558	871	871	88.25	769
60.92	0.1115	236.6	236.6	88.22	209	60.92	0.557	871	871	88.22	768
60.92	0.1115	236.6	236.6	88.22	209	60.92	0.557	871	871	88.22	768
60.94	0.1113	236.3	236.3	88.17	208	60.94	0.557	870	870	88.17	767
60.94	0.1113	236.3	236.3	88.17	208	60.94	0.557	870	870	88.17	767
60.94	0.1113	236.3	236.3	88.17	208	60.94	0.557	870	870	88.17	767

60.94	0.1113	236.3	236.3	88.17	208	60.94	0.557	870	870	88.17	767
60.94	0.1113	236.3	236.3	88.17	208	60.94	0.557	870	870	88.17	767
98.89	0.0082	17.5	17.5	23.97	4	98.89	0.041	64	64	23.97	15
98.89	0.0082	17.5	17.5	23.97	4	98.89	0.041	64	64	23.97	15
98.89	0.0082	17.5	17.5	23.97	4	98.89	0.041	64	64	23.97	15
98.89	0.0082	17.5	17.5	23.97	4	98.89	0.041	64	64	23.97	15
98.89	0.0082	17.5	17.5	23.97	4	98.89	0.041	64	64	23.97	15
98.89	0.0082	17.5	17.5	23.97	4	98.89	0.041	64	64	23.97	15
98.89	0.0082	17.5	17.5	23.97	4	98.89	0.041	64	64	23.97	15
98.89	0.0082	17.5	17.5	23.97	4	98.89	0.041	64	64	23.97	15
99.06	0.0082	17.3	17.3	23.87	4	99.06	0.041	64	64	23.87	15
99.07	0.0082	17.3	17.3	23.86	4	99.07	0.041	64	64	23.86	15
99.08	0.0081	17.3	17.3	23.84	4	99.08	0.041	64	64	23.84	15
99.09	0.0081	17.2	17.2	23.81	4	99.09	0.041	63	63	23.81	15
99.10	0.0078	16.6	16.6	23.35	4	99.10	0.039	61	61	23.35	14
99.11	0.0078	16.5	16.5	23.27	4	99.11	0.039	61	61	23.27	14
99.13	0.0077	16.3	16.3	23.17	4	99.13	0.038	60	60	23.17	14
99.14	0.0074	15.6	15.6	22.66	4	99.14	0.037	57	57	22.66	13
99.15	0.0073	15.6	15.6	22.65	4	99.15	0.037	57	57	22.65	13
99.16	0.0073	15.6	15.6	22.63	4	99.16	0.037	57	57	22.63	13
99.17	0.0073	15.6	15.6	22.62	4	99.17	0.037	57	57	22.62	13
99.18	0.0073	15.4	15.4	22.53	3	99.18	0.036	57	57	22.53	13
99.19	0.0072	15.3	15.3	22.46	3	99.19	0.036	56	56	22.46	13
99.19	0.0072	15.3	15.3	22.46	3	99.19	0.036	56	56	22.46	13
99.19	0.0072	15.3	15.3	22.46	3	99.19	0.036	56	56	22.46	13
99.19	0.0072	15.3	15.3	22.46	3	99.19	0.036	56	56	22.46	13
99.19	0.0072	15.3	15.3	22.46	3	99.19	0.036	56	56	22.46	13
99.19	0.0072	15.3	15.3	22.46	3	99.19	0.036	56	56	22.46	13
99.19	0.0072	15.3	15.3	22.46	3	99.19	0.036	56	56	22.46	13
99.19	0.0072	15.3	15.3	22.46	3	99.19	0.036	56	56	22.46	13
99.19	0.0072	15.3	15.3	22.46	3	99.19	0.036	56	56	22.46	13
99.19	0.0072	15.3	15.3	22.46	3	99.19	0.036	56	56	22.46	13
99.29	0.0071	15.2	15.2	22.33	3	99.29	0.036	56	56	22.33	12
99.30	0.0068	14.4	14.4	21.75	3	99.30	0.034	53	53	21.75	12
99.31	0.0067	14.3	14.3	21.69	3	99.31	0.034	53	53	21.69	11
99.32	0.0065	13.7	13.7	21.26	3	99.32	0.032	51	51	21.26	11
99.33	0.0064	13.6	13.6	21.11	3	99.33	0.032	50	50	21.11	11
99.34	0.0064	13.5	13.5	21.11	3	99.34	0.032	50	50	21.11	11
99.35	0.0063	13.4	13.4	21.00	3	99.35	0.032	49	49	21.00	10
99.35	0.0063	13.4	13.4	21.00	3	99.35	0.032	49	49	21.00	10
99.35	0.0063	13.4	13.4	21.00	3	99.35	0.032	49	49	21.00	10
99.35	0.0063	13.4	13.4	21.00	3	99.35	0.032	49	49	21.00	10
99.35	0.0063	13.4	13.4	21.00	3	99.35	0.032	49	49	21.00	10

99.35	0.0063	13.4	13.4	21.00	3	99.35	0.032	49	49	21.00	10
99.35	0.0063	13.4	13.4	21.00	3	99.35	0.032	49	49	21.00	10
99.35	0.0063	13.4	13.4	21.00	3	99.35	0.032	49	49	21.00	10
99.35	0.0063	13.4	13.4	21.00	3	99.35	0.032	49	49	21.00	10
99.44	0.0062	13.1	13.1	20.79	3	99.44	0.031	48	48	20.79	10
99.45	0.0059	12.5	12.5	20.24	3	99.45	0.029	46	46	20.24	9
99.46	0.0058	12.4	12.4	20.19	3	99.46	0.029	46	46	20.19	9
99.47	0.0058	12.3	12.3	20.13	2	99.47	0.029	45	45	20.13	9
99.48	0.0058	12.3	12.3	20.10	2	99.48	0.029	45	45	20.10	9
99.49	0.0056	11.8	11.8	19.69	2	99.49	0.028	43	43	19.69	9
99.50	0.0055	11.6	11.6	19.56	2	99.50	0.027	43	43	19.56	8
99.50	0.0055	11.6	11.6	19.56	2	99.50	0.027	43	43	19.56	8
99.50	0.0055	11.6	11.6	19.56	2	99.50	0.027	43	43	19.56	8
99.53	0.0051	10.7	10.7	18.79	2	99.53	0.025	39	39	18.79	7
99.54	0.0051	10.7	10.7	18.78	2	99.54	0.025	39	39	18.78	7
99.55	0.0049	10.4	10.4	18.51	2	99.55	0.025	38	38	18.51	7
99.56	0.0047	10.0	10.0	18.14	2	99.56	0.024	37	37	18.14	7
99.57	0.0047	9.9	9.9	18.05	2	99.57	0.023	36	36	18.05	7
99.58	0.0046	9.8	9.8	17.92	2	99.58	0.023	36	36	17.92	6
99.59	0.0044	9.3	9.3	17.46	2	99.59	0.022	34	34	17.46	6
99.60	0.0041	8.7	8.7	16.89	1	99.60	0.020	32	32	16.89	5
99.61	0.0041	8.7	8.7	16.89	1	99.61	0.020	32	32	16.89	5
99.62	0.0040	8.5	8.5	16.77	1	99.62	0.020	31	31	16.77	5
99.62	0.0040	8.5	8.5	16.77	1	99.62	0.020	31	31	16.77	5
99.62	0.0040	8.5	8.5	16.77	1	99.62	0.020	31	31	16.77	5
99.62	0.0040	8.5	8.5	16.77	1	99.62	0.020	31	31	16.77	5
99.62	0.0040	8.5	8.5	16.77	1	99.62	0.020	31	31	16.77	5
99.67	0.0037	7.8	7.8	15.99	1	99.67	0.018	29	29	15.99	5
99.68	0.0035	7.5	7.5	15.72	1	99.68	0.018	28	28	15.72	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.69	0.0034	7.2	7.2	15.42	1	99.69	0.017	27	27	15.42	4
99.81	0.0033	7.1	7.1	15.26	1	99.81	0.017	26	26	15.26	4
99.82	0.0031	6.7	6.7	14.82	1	99.82	0.016	25	25	14.82	4
99.83	0.0029	6.1	6.1	14.17	1	99.83	0.014	22	22	14.17	3

99.84	0.0026	5.5	5.5	13.50	1	99.84	0.013	20	20	13.50	3
99.85	0.0024	5.0	5.0	12.82	1	99.85	0.012	18	18	12.82	2
99.85	0.0024	5.0	5.0	12.82	1	99.85	0.012	18	18	12.82	2
99.85	0.0024	5.0	5.0	12.82	1	99.85	0.012	18	18	12.82	2
99.85	0.0024	5.0	5.0	12.82	1	99.85	0.012	18	18	12.82	2
99.85	0.0024	5.0	5.0	12.82	1	99.85	0.012	18	18	12.82	2
99.85	0.0024	5.0	5.0	12.82	1	99.85	0.012	18	18	12.82	2
99.91	0.0023	4.9	4.9	12.67	1	99.91	0.011	18	18	12.67	2
99.92	0.0021	4.5	4.5	12.21	1	99.92	0.011	17	17	12.21	2
99.93	0.0019	4.0	4.0	11.54	0	99.93	0.010	15	15	11.54	2
99.94	0.0017	3.6	3.6	10.92	0	99.94	0.009	13	13	10.92	1
99.95	0.0017	3.6	3.6	10.90	0	99.95	0.009	13	13	10.90	1
99.96	0.0016	3.5	3.5	10.68	0	99.96	0.008	13	13	10.68	1
99.97	0.0015	3.3	3.3	10.38	0	99.97	0.008	12	12	10.38	1
99.98	0.0004	0.9	0.9	5.33	0	99.98	0.002	3	3	5.33	0
99.99	0.0000	0.1	0.1	1.40	0	99.99	0.000	0	0	1.40	0
100.00	0.0000	0.0	0.0	0.00	0	100.00	0.000	0	0	0.00	0

Appendix 2: Kinematic viscosity of water

Temperature	Pressure	Dynamic viscosity			Kinematic viscosity
[°C]	[MPa]	[Pa s], [N s/m2]	[cP], [mPa s]	[lbf s/ft^2 *10^{-5}]	[m^2/s*10^{-6}], [cSt])
0.01	0.000612	0.0017914	1.79140	3.7414	1.7918
10	0.0012	0.0013060	1.30600	2.7276	1.3065
20	0.0023	0.0010016	1.00160	2.0919	1.0035
25	0.0032	0.0008900	0.89004	1.8589	0.8927
30	0.0042	0.0007972	0.79722	1.6650	0.8007
40	0.0074	0.0006527	0.65272	1.3632	0.6579
50	0.0124	0.0005465	0.54650	1.1414	0.5531
60	0.0199	0.0004660	0.46602	0.9733	0.4740
70	0.0312	0.0004035	0.40353	0.8428	0.4127
80	0.0474	0.0003540	0.35404	0.7394	0.3643
90	0.0702	0.0003142	0.31417	0.6562	0.3255
100	0.101	0.0002816	0.28158	0.5881	0.2938
110	0.143	0.0002546	0.25461	0.5318	0.2677
120	0.199	0.0002320	0.23203	0.4846	0.2460
140	0.362	0.0001966	0.19664	0.4107	0.2123
160	0.618	0.0001704	0.17043	0.3559	0.1878
180	1.00	0.0001504	0.15038	0.3141	0.1695
200	1.55	0.0001346	0.13458	0.2811	0.1556
220	2.32	0.0001218	0.12177	0.2543	0.1449
240	3.35	0.0001111	0.11106	0.2320	0.1365
260	4.69	0.0001018	0.10181	0.2126	0.1299
280	6.42	0.0000936	0.09355	0.1954	0.1247
300	8.59	0.0000859	0.08586	0.1793	0.1206
320	11.3	0.0000783	0.07831	0.1636	0.1174
340	14.6	0.0000703	0.07033	0.1469	0.1152
360	18.7	0.0000603	0.06031	0.1260	0.1143

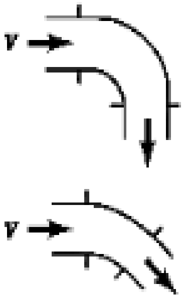
Appendix 3: Pipe roughness factor

PIPE MATERIAL	ABSOLUTE ROUGHNESS, ε (mm)
Cast iron	0.26
Commercial Steel and wrought iron	0.045
Concrete	0.3 - 3.0
Drawn tubing	0.0015
Galvanized iron	0.15
Plastic,(and glass)	0.0 (smooth)
Riveted steel	0.9 – 9.0

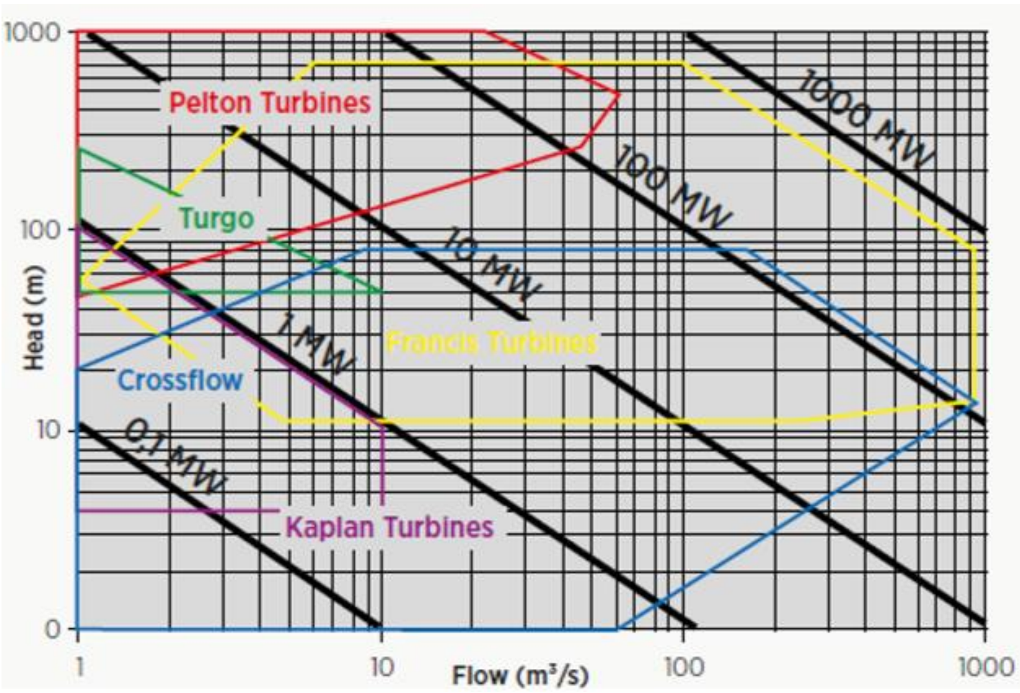
Appendix 4: loss coefficients (k)

Loss Coefficients for Pipe Components $\left(h_L = K_L \frac{V^2}{2g}\right)$

Component	K_L
a. Elbows	
Regular 90°, flanged	0.3
Regular 90°, threaded	1.5
Long radius 90°, flanged	0.2
Long radius 90°, threaded	0.7
Long radius 45°, flanged	0.2
Regular 45°, threaded	0.4



Appendix 5: Turbine Selection Table



Appendix 6: Typical average capacity factor

Electric generator capacity factors in various countries and regions, 2008-12 average
capacity factor