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STUDY OF THE FEASIBILITY OF A PROPOSED MICRO HYDROPOWER SYSTEM FOR RURAL ELECTRIFICATION:

THE CASE OF BURUNDI

Defended on 05/08/2018 Before the Following Committee:

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DECLARATION

I **Jean Michel MUSAMBI**, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material, and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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ABSTRACT

Recently, decentralized energy systems are recognized as one of the major solutions to increase electricity access in remote areas. Micro hydropower (MHP) has attracted considerable attention in recent studies due to its numerous advantages including the cost-effectiveness, reliability, and viability. Previous research has indicated the practicability of MHP schemes in hilly and remote regions; especially in developing countries. Most studies in the field of MHP system have mostly focused on site conditions characterized by low head and high flow rate. This corresponds to the range of cross-flow and reaction turbines.

The aim of this study was to design a simple, viable and reliable MHP system to provide electricity in rural areas in Burundi. This thesis also assesses the feasibility of the proposed MHP system. The sustainability assessment was also considered in this study.

A field surveying provided all the characteristic of the selected site required for the design of the MHP system. RETscreen Analysis software was used for the feasibility study. Results showed that there is a gross head of 84 m and 0.0736 m^3/s of available flow rate. The expected power output is 36.5 kW. These characteristics suggest a Pelton turbine of 34 cm of wheel diameter and 72 mm of jet diameter. The feasibility study suggested a total initial cost of \$95,339 and an equity payback of 9.8 years. The sustainability assessment of the proposed system has shown a score of 3.487. The results of this study support the view that the MHP system can be technically and economically achieved.

Keywords: Decentralized energy systems, Micro hydropower, Pelton turbine, rural and remote areas.

RÉSUMÉ

Les systèmes énergétiques décentralisés représentent actuellement une solution pour accroître l'accès à l'électricité dans les zones reculées. Un bon nombre d'études récentes se rapportent aux microcentrales hydroélectriques grâce à leurs multiples avantages tels que la rentabilité, la viabilité et la fiabilité. Les recherches précédentes ont démontrés la faisabilité des microcentrales hydroélectriques dans les régions montagneuses et reculées spécialement dans les pays en voie de développement. Beaucoup de recherches se sont focalisées principalement sur les sites de haut débit d'écoulement et de faible hauteur de chute. Ces caractéristiques correspondent au champ d'application de la turbine Cross-flow et des turbines à réaction.

L'objectif de cette étude est de concevoir un système simple, viable et fiable dans le but d'augmenter le taux d'accès à l'électricité en milieu rural au Burundi. Une étude de la faisabilité du système s'inclue aussi comme objectif de cette étude. Une évaluation de la durabilité du système proposé.

Les caractéristiques du site choisi nécessaire pour la conception de la microcentrale hydroélectrique ont été prélevées lors de la visite de terrain. Le logiciel Retscreen a été utilisé pour effectuer l'étude de faisabilité. Les résultats trouvés indiquent une hauteur de chute de 84 m and un débit d'écoulement de 0.0736 m^3/s. La capacité pouvant être générée est de 36.5 kW. Ces résultats suggèrent une turbine Pelton de 34 cm de diamètre avec un injecteur de diamètre 72 mm of jet diamètre. L'étude de faisabilité suggère un investissement initial de 95,339 (USD) et un délai de remboursement de 9.8 années. L'étude de durabilité du système propose ont données un score de 3.487. De cette étude, les résultats montrent que la microcentrale proposée peut être techniquement et économiquement réalisable.

Mots clés: systèmes énergétiques décentralisés, microcentrales hydroélectriques, turbine Pelton, région rurales et reculées.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols	Unit	Meaning
A_c	m^2	Cross section area
a, b, h_i	m	top and bottom width and height of the river
V_s	m/s	surface average velocity
Q	m^3/s	Discharge or flow rate
L	m	Length
T	s	Time
P	kW	Power
g	m^2/s	Constant of gravity
H	m	Head
ρ	kg/m^3	Density
η	$-$	Efficiency
f	$-$	Friction coefficient
D	m	Diameter
e	m	roughness height
k_i	$-$	Bend coefficient
n	$r.p.m$	rotational speed
f	Hz	frequency
p	$-$	Number of pair poles
N_s	$-$	Specific speed
c_v	$-$	Nozzle coefficient
u	m/s	Wheel velocity
k_u	$-$	Speed ratio
d_0	m	Jet diameter
z	$-$	Number of bucket
m	$-$	Jet ratio
α_o	deg	Bucket position angle
B_l, B_d, B_t, B_w	m	Bucket length, depth, axial and cavity width

L_{ab} ,V_b	m	Length of the moment arm, volume of the bucket
β_2, R_{br}	deg, m	Exit angle, Radius of bucket centre of mass to centre of runner
S	m	Submergence
C	$-$	Gordon coefficient
C_d	$-$	Coefficient of discharge
n'	m/s	Manning roughness coefficient
R_h	m	Hydraulic radius
s	$-$	slope
RF	mm	rainfall
ET	mm	Evapotranspiration
Se	mm	Seepage
R_a	kW/m^2	Solar radiation
T_a	$°C$	Average daily temperature
t	m	Thickness
E	N/mm^2	Young’s Modulus
γ	kN/m^3	Unit Weight
α_1	$-$	Coefficient of linear expansion

LIST OF ACCRONYMS

MHP:	Micro hydropower
IEA:	International Energy Association
EAC:	East Africa Community
REN21:	Renewable Energy Policy Network for the 21st Century
UNIDO:	United Nations Industrial Development Organization
ISTEEBU	Institut de statistiques et d'études économiques du Burundi
MEM:	Ministère de l’Energie et Mine
REGIDESO:	Régie de Production et Distribution d’Eau et d’Electricité
SDG:	Sustainable Development Goal
UNDP:	United Nations Development Programme
DC-AC:	Direct Current- Alternative Current
CFD:	Computational Fluid Dynamics
IG:	Induction generator
LMS:	Least mean squares
IGC:	Induction Generator Controller
IMG:	Induction Motor as generator
AVR:	Automatic Voltage Regulator
IGEBU:	Institut Géographique du Burundi
NASA:	National Aeronautics and Space Administration
GHG:	Green House Gases
NPV:	Net present Value
BPC:	Butwal Power Company
ASCE:	American Society of civil Engineers
IGC:	Induction Generator Controller
O&M:	Operating and Maintenance cost
IRR:	Internal Rate of Return

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Chapter 1. INTRODUCTION

1.1. General Context

Access to sustainable and modern energy is a crucial element for human development and economic growth. However, 1.8 billion of the world population is still relying on solid biomass as the principal source of energy. Moreover, one-in-six people in the world are lacking access to electricity. Actually, 1.2 billion people, 16% of the world's population, with the majority 633 million being in sub-Saharan Africa, were estimated to live without access to electricity in 2014 (IEA, 2016).

In 2015, the East African Community (EAC) region displays an electricity access of less than 22% below the average electrification rate of 33.5% for sub-Saharan Africa. The alarming record was observed in one of the EAC partner states, South Sudan, with only 1% of the population being grid-connected, putting this country at the lowest electrification level on the African continent (REN21, 2012).

Nevertheless, some developing countries are putting much effort in order to increase electricity access. As a matter of fact, in Asia, India has made significant progress by enhancing electrification rate from 67% in 2000 up to 89% in 2016. Moreover, 100 million people in Indonesia and 90 million in Bangladesh has also gained access since 2000 (IEA, 2017).

Despite the highlighted outlook above, the overall electrification rate in sub-Saharan Africa is currently 43%. Only 20% of the population with access lives in the urban area. Access to electricity in the rural area is less than 25%, compared with 71% in the urban area. There is still a long way to go in order to achieve full electrification as it has been done in China in 2015 (IEA, 2017).

The improvement of electricity access has mostly come from fossil fuels source such as coal, natural gas and oil, since 2000. Recently, new technologies have allowed the shift from fossil fuel to renewables as a source of electricity generation. Decentralized energy systems such as mini-grid and off-grid systems have contributed successfully to the growth electricity access in many contexts around the world.

The development of new technologies has consequently produced a significant reduction of the cost of renewable technology. These technologies have appeared to be the most cost-effective and environmentally friendly electricity generation facilities.

Furthermore, renewable energy technologies are becoming one of the major global energy industry. Indeed, hydropower and bioenergy are the largest source of supply and have overtaken the largest source, coal becoming the second-largest source of electricity supply. In 2014, among 23% of global electricity supply, 70% was from Hydropower with 17% from variable renewables (IEA, 2016).

However, despite this improvement in new technologies, the available and huge potential of the renewable energy has not been tapped in most of developing countries especially in sub-Saharan Africa. For example, in Africa, the total small hydropower potential is estimated at 12,197 MW and the installed capacity for Africa is 580 MW, which represents 5%. The Eastern Africa region has the highest overall potential small hydropower in the African continent. Still, among the total of 6,759 MW only 3%, that is 216 MW, has already been tapped into (UNIDO, 2016).

The rural and remote areas have the lowest rate of electricity access. More often, these areas are characterized by a dispersed population and not close the grid infrastructure. In addition, grid-based solutions prove to be exorbitantly expensive, hence more possibly unfordable for developing countries. Moreover, decentralized energy systems have been recognized as the investments that should be taken to have the fastest path to energy access (Power for All, 2016). Therefore, mini and off-grid technologies have to play a crucial part in enhancing electricity access in developing countries. More especially in their remote areas where the rugged terrain and hilly location make the grid-connected solutions almost unfeasible. In addition, the decentralized system presents considerable advantages such as the cost-effectiveness, reliability and sustainability of the small-scale technologies. The next section discusses some achievement of decentralized hydropower solutions in developing countries.

1.2. Decentralized hydropower systems in developing countries

In the southern part of Asia, India, the centralized model has not been able to provide electricity and achieve the rural electrification where the population was located in remote, hilly and forested regions whereas the decentralized has worked successfully (Deshmukh, 2009). In Nepal, some studies have highlighted the challenges and issues of the small and mini-hydro projects that have succeeded in providing electricity in remote rural areas where the grid-connected solutions were un-economical. It has also been shown that the implementation of this kind of solution requires relatively short time for implementation and provides a breakthrough to the several constraints of the large-scale hydropower (Gippner, Dhakal, & Sovacool, 2013).

In Sri Lanka, micro hydropower has become more attractive than the main alternative, diesel-fuelled generators, which is unreliable due to the fluctuation of the prices of the fuel. On the socioeconomic level, micro hydropower technologies have contributed to the development of several communities, by improving income levels, matching the gender gap, enhancing access to education and information, and reducing migration patterns. Moreover, some key parameters including the participation of rural communities in the achievement of a hydropower project and the comprehensiveness among the population in villages have permitted the success of the implementation of small hydropower projects (Jalayath & Ekanayake, 1997).

Despite the fact that the micro hydropower has been proven to be a cost-effective, indigenous, and reliable source of electrical power in southern Asia, as mentioned above, the micro hydropower also presents some barriers and challenges (Singh, 2014)(Singh, 2014). In addition, the system components of the most common type of micro hydropower, the "run-of-the-river", due to its relatively low cost of installation, are still expensive for most of the rural areas. To meet the needed efficiency and the sustainability of the system, the technologies used have to be applied in some specific cases and context with accurate technics. In rural areas, energy loads have to be studied. In many cases, the choice of micro hydro has to be motivated by the size of the localities in rural areas, the size of the population and its distributions. Some survey of innovative technologies, to increase the viability of micro hydropower, have been made in South Africa to highlight the possible option to increase the cost-effectiveness. These technologies include induction motors as generators, pumps as turbines or propeller turbines and high-density polyethylene as penstock (Kusakana, 2014).

Regardless of the several advantages of the hydropower decentralized systems, for small scale, the potential of small hydropower schemes are not always reliable. Most of those systems are constructed on streams which flow rate is not constant throughout the whole year. In order to cover up this intermittency, some hybrid systems of micro hydropower with other renewables have been proposed with the aims solving issues of rural electrification (Kenfack et al., 2009). Depending on weather and seasonal conditions, these combinations are designed to increase the reliability of the micro hydropower systems, by covering for the irregularity in the availability of water during the dry season.

Many micro hydropower systems have been successfully implemented with low cost in many developing countries. Hence, they provide a novel solution for the challenging issue of electricity access in the remote areas. This decentralized scheme also solves issues related to long transmission lines of large hydropower systems which are not economically feasible considering the energy demand of the small communities in remotes areas.

1.3. Electricity Situation in Burundi

1.3.1. Geographical and Demographical situation

With its area of 27,834 square km², Burundi is sited between the 29° and 30°25 eastern meridians and between the 2°20 and 4°25 southern parallels. It is bordered by the Democratic Republic of the Congo and Tanganyika Lac in the West, Rwanda in the North and Tanzania in the East. Burundi is characterized by an equatorial climate. The climate is swapping between rainy and dry seasons. The relief is characterized by a plain in near the Tanganyika Lake and Ruzizi river with high temperature (between 24°C and 31°C), a high mountainous area in the northern and western part of the country with chiller temperature (between 12°C and 16°C), and plateaus at the central and eastern region with warm temperature (between 18°C and 22°C) (UNIDO, 2016). Burundi belongs to two hydrographical basins, namely the Nile Basin with an area of 13,800 km² and the Congo basin with an area of 14,034 km². According to the provisional general census results of 2015, Burundi population is estimated at 10,816,860 inhabitants (ISTEEBU, 2017).

Burundi has important potential for hydropower energy generation from the existing rivers (see APPENDIX A). Several large rivers along its borders and throughout the country can provide enough power for domestic and regional consumption. The potential of small hydropower was evaluated to reach up to a number of 156 potential sites (MEM, 2012).

1.3.2. Electricity Access in Burundi

In 2016, the electrification access rate to electricity is 5%, with 2 % in the rural areas and 28 % in the urban areas. This access rate is relatively low compared to 10% in 2012. The total generation capacity is 55 MW with about 34 MW from hydropower and 20.5 from thermal power. The other source of electricity generation comes from energy imports (48.2% of the total consumption) (UNIDO, 2016). The production and distribution of electrical power are state-owned and the company which controls all the activities is the Régie de Production et Distribution d’Eau et d’Electricité (REGIDESO). It manages the thermal power stations and 96.5 % of installed hydropower. There are few micro hydropower owned by the private sector for self-use (UNIDO, 2016).

1.4. Problem statement

The Medium and Small hydropower station has failed to cover electricity access in the rural area in Burundi due to the scattered population which high transmission and distribution lines cost. The economic constraints of Burundi do not allow initiation of huge projects in order to provide enough power because of the colossal initial investment cost of hydropower schemes. Moreover, big hydropower systems need high maintenance cost in case of failure and have many environmental impacts compared to micro hydropower. The construction and operation of big hydropower schemes require enough human resources including engineers and technicians which are not available in Burundi. Grid-connected solutions seem to not be convenient for the case of Burundi.

In addition, the current electricity demand of rural population is not so high. This includes lighting, food processing (grinding) and charging of some telecommunication tools (televisions, radios, phones, etc.). This study is suggesting a system which will contribute to the enhancing the electricity access by tapping into the potential of small (mini and micro) hydropower in Burundi.

1.5. Objectives and Purpose of study

The purpose of this study is to propose a simple, reliable, viable and cost-effective system to provide electricity to remote areas with access to hydropower resources. The proposed system should be scalable and adjustable; and can be implemented in other communities with the same hydropower potential and having similar characteristic including the topography of the relief, demographic characteristic, and the socio-economical needs.

The economic and technical feasibility of the system will be taken into accounts such as a low initial investment cost of the system component or the type of turbine suitable depending on the existing head and water flow. The component will have to include local material and adaptable tools mixing indigenous and genuine method with the aim of enhancing the end-user involvement for a sustainability purpose.

The specific objectives are the following: to use hydrological data to confirm the technical feasibility of a micro hydropower, to approximate available water flow and head for the remote areas, to select the type of turbine for the available head and water flow, to design the MHP system, to run the feasibility study of the proposed system, and to assess the sustainability of the project.

The aim of this study is to provide the feasibility an adaptable micro hydro to contribute to the enhancement of electricity access in Burundi. This proposed system will be able to be used by any project that intends to supply electricity using micro hydropower potential.

1.6. Thesis outlines

This study aims to give a brief description of a micro hydropower system for rural electrification in the case of Burundi and its feasibility study with the real condition of the proposed system.

The first chapter has given a general overview of the global and regional context of the study. This chapter has also highlighted some cases of micro hydropower system existing in developing countries.

The electricity access in Burundi was also briefly discussed so as to give the specific context of the study.

The second chapter starts with a short introduction of hydropower systems as a renewable energy system in the framework of achieving the 7th Sustainable Development Goal. Then, the hydropower system theory and a general description of micro hydropower will be presented. This chapter ends by emphasizing the recent trends in micro hydropower and the knowledge gap.

The third chapter gives the methodology used in this study, starting with a brief description of the selected site, followed by a thorough design of the mechanical and civil structure of the micro hydropower system. The feasibility study of the hydropower is then given in the second part of this chapter. The pros and cons of the proposed micro hydropower are also highlighted.

Conclusions and Recommendations are revealed in the fourth and last chapter.

Chapter 2. LITERATURE REVIEW

2.1. Introduction

In the Agenda 2030 for sustainable development, the 7th Sustainable Development Goal (SDG) promotes an access to affordable, reliable, sustainable and modern energy for all. However, the SDG 7 still has many challenges such as the improvement of energy efficiency and the enhancement of access to clean energy especially in developing countries (UNDP, 2015).

In sub-Saharan Africa, 57% of the population remains without access to electricity. Despite this huge concentration, efforts are being made to reduce this percentage. Indeed, in east Africa the number of people without access has decreased by 14% since 2012 making it the subregion accounting the fastest growth of electricity access. Moreover, in sub-Saharan Africa, the total capacity of Hydropower is expected to double by 2030 accounting by the largest share followed by coil and natural gaz. In addition, issues related to climate change, environmental concerns and the need for access to clean energy are putting the renewable energy as the promising sources to overcome those challenges (IEA, 2017).

Nevertheless, the initial cost of investment in renewable energy project is substantially very high compared to conventional energy generation. In fact, conventional hydropower systems require very huge generation cost and are not appropriate in some conditions. A country like Ethiopia has succeeded to tap into its huge potential by investing in large-scale hydropower system. However, its hilly topography was suitable for a development of small hydropower system. The growth of these decentralized energy systems is still slow (UNIDO, 2016).

Furthermore, conventional hydropower presents many environmental and social challenges which have already discouraged the development of new project in some places such as northern America countries.

In remote areas, due to the long transmission line, big hydropower is more often not convenient; instead, it is wise to multiply several micro hydropower which is economically feasible and present several advantages, such as low initial investment cost, operational and maintenance cost. They are also cost-effective and environmental friendly compared to large systems.

This decentralized energy solution for electricity supply has been applied in many countries in southern Asia such as Nepal and India. It has proved to be successful in that region. The other advantages of micro hydropower are the reliability, affordability, and replicability of small schemes.

Nonetheless, there are still many challenges linked to the implementation of the small hydroelectric system such as the lack of technical knowledge and operational skills, environmental regulations and limited available data.

Hydropower is the power that is converted from the energy of moving water, which is harnessed for any kind of purposes including the most common electric power generation called hydroelectricity. The conventional hydroelectric power uses the potential energy of dammed water. The potential energy is then converted into kinetic power via a water turbine and lastly transformed in electric power by means of a generator. The theory of hydropower generation is explicitly discussed in the following section.

2.2. Hydropower system Theory

The amount of power that can be generated in a hydroelectric scheme depends on two major parameters: the available flow rate of water (discharge) and the head of water.

The Hydroelectric power that can be generated in a hydropower plant is determined from the following expression (Nag, 2008):

$$P = \gamma\, H_n\, Q, \tag{2.1}$$

where γ is the specific weight $(\rho * g)$, H_n the net head, Q the discharge and η_o the overall efficiency.

Gross head of a hydropower plant is the difference between headwater elevation and tailwater elevation. The Net head can be defined as the effective head on the turbine and is equal to the gross head minus the hydraulic losses before the entrance to the turbine and outlet losses. The overall efficiency is the product of the penstock efficiency, the turbine efficiency, and the generator efficiency.

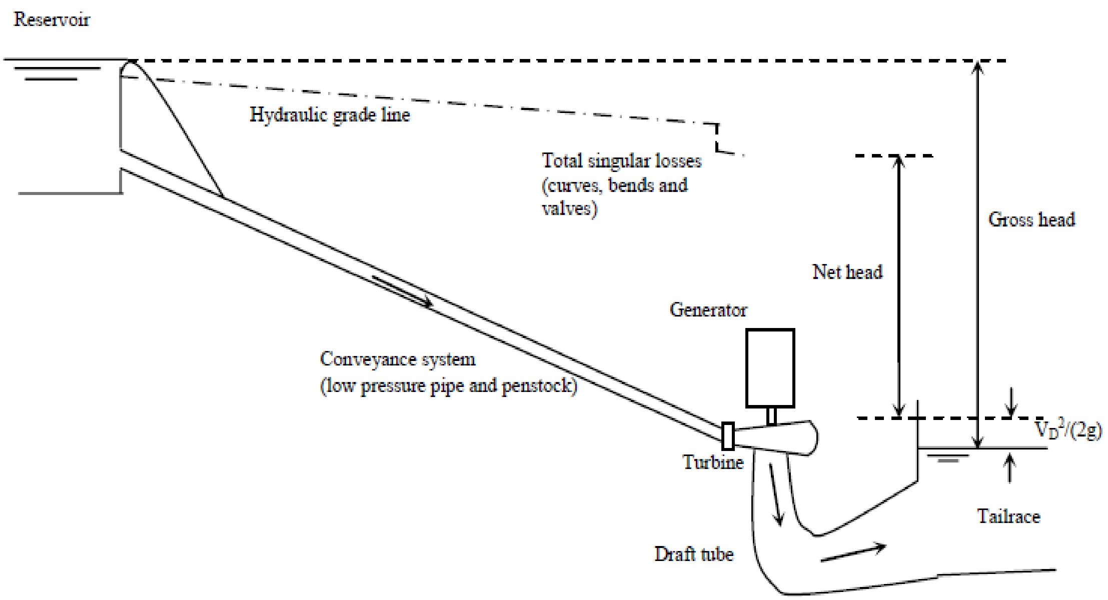


Figure 2.1 Hydraulic grade line of a hydro scheme showing the Net and Gross Head (Ramos, Almeida, Portela, & Almeida, 2000).

There are three categories of hydroelectric facility including (Nag, 2008):

- Impoundment plant
- Run-of-river plant
- Pumped-storage plant

The hydroelectric power can also be classified depending on the capacity generated as it is shown in Table 2.1. As we will see in the coming section, the case of our study fall into the categories of run-of-river and micro hydropower plant.

Table 2.1 Classification of hydropower system with the capacity generated (Celso Penche et al., 2009).

Terminology	Capacity limits
Large	>300 MW
Medium	10-300 MW
Small	1-10 MW
Mini	100-1,000 kW
Micro	11-100 kW
Pico	≤10 kW

Figure 2.2 gives the general scheme of a typical run-of-river plant.

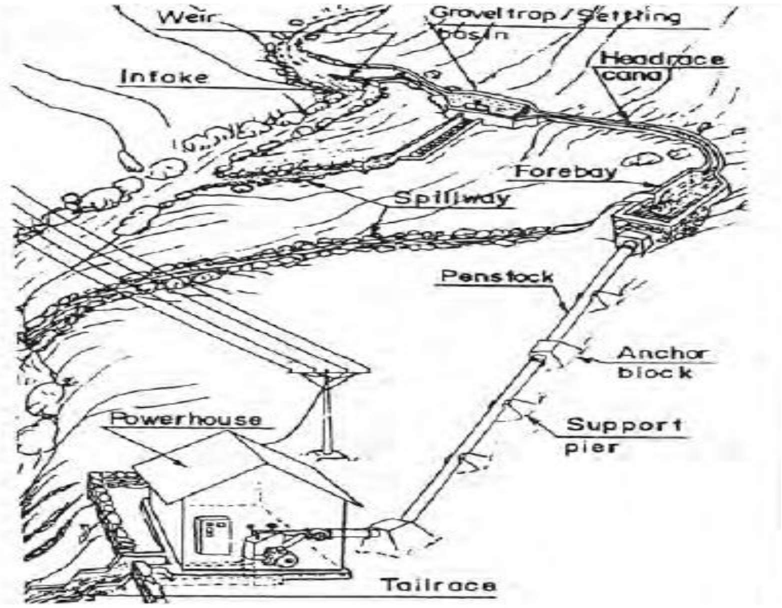


Figure 2.2 Scheme of a run-of-river hydropower system (BPC, 2002).

For a selection of a good site of a run-of-river plant, there are several factors that can be considered including mainly:

- Availability of the water

- Head of water
- Distance from the load
- Accessibility of the site

2.3. Description of the components of a micro hydropower system

In this section, the components of a typical micro hydropower are discussed. They are grouped into two main parts namely the civil work and the electromechanical component. A detailed description of the important distinct components will be given later during the selection and the design of the different component of the micro hydro system.

2.3.1. Civil work

The component of the civil work can also be divided into three main groups including the structure, water conveyance, and water control devices (ASCE, 2007). This subsection will shortly discuss each part by giving on the function.

2.3.1.1. Structure

The structure regroups mainly the intake, diversion weir, spillways, powerhouses and trash racks.

a. Intake

Generally, the intake is the component that has a function of diverting water from the source such as river or reservoir into an open canal (or power channel) or directly into a conduit leading to the powerhouse (ASCE, 2007). This transition is more often composed of a trash rack and gates as a flow control structure. Intakes can be regrouped into two different categories depending on the purpose of the conduits. Intakes that supplies directly the turbine using a pressure conduit are the power intake. Those that do not directly supply turbines but canals or tunnels are called the conveyance intake. Those two types are both designed to drawn specific flow rate in order to allow a maximum hydraulic efficiency.

The intake is preferably designed to be perpendicular to the trash rack in order to avoid vortices that can causes problems during the operation of the turbines (ASCE, 2007).

b. Diversion weir

A diversion weir is small structures constructed across the river or stream to retain water and divert a part of the river flow into the hydropower system. This weir can be either permanent or temporary depending on each specific cases. Depending on the characteristic of each specific case, this component can also be avoided for instance when water enters directly into an intake device submerged into the falling water.

c. Spillway

Spillways are also part of the retaining structures but its specific function is to regulate the release of water into the water conveyance system. Hence the main purpose of spillways is to control the water that enters the canal, tunnel or forebay by means of a specific design of an exit of water that returns back to the stream. They are also designed to carry flood during rainy seasons to avoid any damaged of the retaining structures. They can be either gated or ungated structure depending on the specific function. There are also several categories of spillways depending on their different purposes. This can include the service spillways designed for frequent use in normal flows and floodwaters, auxiliary spillways for infrequent use and emergency spillways for extra protection to prevent damage under extreme conditions (ASCE, 2007).

d. Powerhouse

The powerhouse is a building that accommodates the electrical and mechanical components such as the turbine and generator in order to protect them from any weather and environmental concerns (BPC, 2002). Moreover, the powerhouse can also accommodate the energy storage system, ventilation equipment, control equipment, protecting devices, and damping load such as ballast. It can also give enough space to personnel in charge of maintenance and also to repairing the equipment can occur (ASCE, 2007).

In some case, the powerhouse is built with a draft tube typically when the chosen turbine is a reaction turbine. The draft tube is set just under the turbine at a level above the tailrace to allow a further extraction of the kinetic energy of the falling water at the runner outlet which would be wasted otherwise. It also allows any maintenance or inspection of the turbine (Nag, 2008).

e. Trash Rack

Trash racks are designed in form of grill located at the intake and have a function of protecting the turbine or any other equipment by preventing debris to enter in the water conveyance system (ASCE, 2007).

2.3.1.2. Water conveyances

Water conveyance system includes components such as gravel traps, settling basin, forebays, headrace canals (or power canal), penstocks, and tailraces.

a. Gravel trap and settling basin

These two components are designed as a basin that removes heavy particles like gravel in the gravel trap as well as fine suspended particles in the settling basin. The function of both structures is to avoid any damage in the last component of the waterway system that is the penstock (BPC, 2002).

b. Headrace canal

This structure is more often designed as an open canal made to convey water from the upstream to a lower component that can be a settling basin or straight to the forebay. In some case, the slope of this canal is gentle to avoid any heavy sediment to enter into the forebay. In some other, the slope is steeper to allow weighty sediment to flow along with the discharge and to be trapped in the settling basin located before the forebay (BPC, 2002). Canals are constructed with a spillway so as to allow the overflowing water to be drawn back to the river. This is located downstream of the intake. Those canals can be designed in many shapes and sizes such as v-shaped, u-shaped or hemispherical shape. In general, this structure does not work under hydraulic pressure (BPC, 2002).

c. Forebay

As part of the conveyance system, the forebay represents the temporal storage to allow any abrupt changes during the operation of the power station. The forebay is constructed as a tank before the intake of the penstock. This tank allows a smooth transition from the low pressure point of the power channel to the pressure of the penstock. Indeed, forebays are set to provide enough water so as to increase the power output or to work as a surge tank when there is a sudden decrease in the load or an abrupt stop of the power generating system (ASCE, 2007).

This component is also designed with an overflow spillway in order to spill the excess of water during flood season or the entire flow in case of emergency of the plant. In some case, the settling basin and the forebay are combined with the aim of reducing the civil component structure (BPC, 2002).

d. Penstock

Penstocks are constructed as a pressurized pipe to carry water from the surface water or forebay straight to the turbine. Usually at low head, the penstock is set directly from water intake to the turbine in the powerhouse if the topography of the area is suitable for this arrangement (ASCE, 2007). This structure works under high hydraulic pressure and supported usually by the anchor block and support pier to ensure its stability.

e. Tailrace

This structure is located under the turbine at the exit of water after the draft tube. Tailraces are designed as a channel or a pipe to carry the leaving water from the turbine down back to the river. If the powerhouse is near the river, the falling water is directly drawn to the river otherwise the tailrace is constructed by means of a canal that connects the flow from powerhouse to the river (ASCE, 2007).

2.3.1.3. Water control devices

a. Gates

The main function of gates is to regulate or to block the discharge in the water conveyance system. They can be located at between the intake canal and the diversion weir, at the level of the spillway to divert and bypass the discharge before the plant, or at the entrance of the powerhouse. In addition to this, gates also control the water levels between the upstream and downstream of the hydroelectric power plant (ASCE, 2007).

b. Valves

The function of valves and gates are similar. However, valves are mechanical devices that regulate the flow and the pressure in the penstock. Moreover, they are also used in case of emergency to protect the penstock or any other equipment. Then again, valves are very useful in case of maintenance of the turbine (or generator) or to control the energy output by regulating the pressure in the penstock (ASCE, 2007).

2.3.2. Electromechanical component

The electromechanical component can be categorized into two main part namely electric devices and mechanical components. These two categories include mainly turbines, generators, electronic load controller, regulator and power transmission lines.

2.3.2.1. Turbines

This is a mechanical device that uses the mechanical energy of the flowing water and converts it into a kinetic rotational energy that is transmitted via a shaft to an electric generator to produce electric power (Nag, 2008). According to their working system, turbines can be classified into two categories:

- In an impulse turbine, all the potential energy is converted into kinetic energy via a nozzle. The water comes out from the nozzle in forms of a jet that strikes the bucket of the runner. The rotational motion produced is then transmitted to the shaft. The water falls directly into the tailrace. Impulse turbines work under atmospheric pressure and are usually used in high head and low flow. Pelton and Turgo are the most common impulse turbine (Nag, 2008).
- In a reaction turbine, both potential and kinetic energy of the falling water is converted into mechanical energy. The system is conceived such that the water enters into a closed circuit from the entrance of the turbine through the blade of the runner and the draft tube downstream to the tailrace. This type of turbines is more often used in low head and high flow. The Francis, Propeller, and Kaplan are the most common reaction turbine (Nag, 2008).

Another kind of turbine more used in low-head and high flow is the Crossflow turbines or Banki turbine. Even though classified as an impulse turbine, the Crossflow turbine is not a pure impulse turbine because it also uses the pressure energy of the falling water that is converted into mechanical energy. A brief summary of the classification of turbines is given in Table 2.2.

2.3.2.2. Generators

Generators are electromechanical devices that convert mechanical energy into electric energy. They are coupled with the turbine via the shaft. In some cases such low head turbines, the shaft is fixed to speed increaser in order to use all the available torque.

Table 2.2 Classification of turbines using the available net head (Harvey & Brown, 1993).

	High Head	Medium Head	Low Head
Impulse turbines	• Pelton • Turgo	• Cross-flow • Multi-jet Pelton • Turgo	• Cross-flow
Reaction turbines		• Francis	• Propeller • Kaplan

The generators fall into two categories according to the type of output current. The DC generators that are more often used in very small systems. They are coupled with batteries and inverters, and the power then is converted into AC power. The AC generators are also classified into two types: synchronous and asynchronous (or induction) generators. Depending on the operational requirements of the generator and the types of the grid the generator will be connected to, an induction or synchronous generator is selected to be used for each specific case. In an isolated system, the synchronous generator is more often used. For strong grid schemes, the induction generator is more preferred to the synchronous generators.

2.3.2.3. Governor control system

Generally used in isolated schemes, the governor control system is a feedback control system that regulates the speed and power output of the turbine. It senses the water level of the hydraulic system (or available pressure head) or the power and the speed of the generator and takes action to regulate the discharge (via blades or needles) or the load controller according to the reference point. The types of governor control system can be mechanical controller devices or electro-hydraulic governor.

2.3.2.4. Electronic load controller

The speed of the turbine and the voltage are affected when there are variations of the load applied to the system. The governor control systems are expensive and or not cost effective for micro hydroelectric system. For synchronous generators, electronic load control systems are another way of regulating the speed of the turbine by diverting all excess electric power of a plant to a ballast load (immersion of a heater with cooled water).

2.3.2.5. Transformer and Transmission lines

A transformer is a static unit with the aim of increasing or reducing the voltage in order to facilitate the transport of the generated power. This is realised by stepping up the voltage to the grid voltage level or stepping down the grid voltage to a lower voltage for distribution. This is accomplished by taking an appropriate number of loops in the primary and secondary windings.

From the powerhouse through the voltage transformation system to the distribution system, the transmission lines have the purpose of carrying electricity out to reach the consumers.

2.4. Recent development in micro hydropower plant

The development of Hydropower technology has been very significant in this last decades. Even though hydroenergy is considered to be an environmentally friendly renewable energy, large and medium hydropower plants have several ecological impacts related to huge dams. Recently, researchers are having interest in decentralized energy systems such as micro hydropower plant (MHP). The main benefits are mostly the cost-effectiveness, sustainability, and reliability of this system. In addition to this, the capability of this kind of system to supply remote areas justifies the interest in such small scale schemes.

Several research have been made so as to improve the performance of MHP system by increasing the efficiency and to promote low-cost technologies especially for developing countries which need to supply electricity in rural areas.

Hoghooghi H. *et al.* (Hoghooghi, Durali, & Kashef, 2018) developed a new design process of a low-cost swirler employed in axial micro-turbines. They developed a swirler of 12 fixed blades made of thin steel sheet, cut to shape and formed as constant thickness blades. Using Computational Fluid Dynamics (CFD) analysis, they made calculations and proposed corrections on the flow to blade angles. The design of the swirler was made to cover a wider range of applications by a family of turbines having a fixed propeller with different rotational speed.

Ion C. P. and Marinescu C. (Ion & Marinescu, 2011) proposed a single control structure for an autonomous micro hydro power plant to ensure both the voltage and frequency regulation of an isolated induction generator (IG). They performed simulations and experiments on the proposed configuration so as to validate the reliability under a static and dynamic load.

Dadua V. *et al.* (Dadu, Dadu, Frunza, Catarig, & Popa, 2017) highlighted innovative concepts and technical solutions applied to small hydropower plants. They proposed new concepts on the hydraulic structures of the intakes, diversion pipes and features of power equipment. These concepts are suggested to ensure a maximum efficiency of the hydropower development.

Alexander K.V. *et al.* (Alexander & Giddens, 2008) designed four different specific speed micro hydro propeller turbines operating at heads between 4 m and 9 m. The hydraulic turbines efficiency was 68% in all the turbine models. From the test of the built turbines, the propeller proved to cover microhydro with wilder range from 2 m to about 40 m of head.

Pasalli Y. R. and Reheira A. B. (Pasalli & Rehiara, 2014) investigated a design planning of a MHP in Hink River in Indonesia. Under flow conditions of 0.3 m^3/s and head height of 8.6 m, they proposed a cross flow turbine coupled with a 3 phase synchronous generator. The project proved to be economically feasible with a payback period of about 17.32 years and benefit factor 1.94.

Gallagher J. *et al.* (Gallagher, Styles, Mcnabola, & Williams, 2015) analysed the life cycle environmental balance and greenhouse gas mitigation potential of micro hydropower energy recovery in the water industry. The authors quantified the environmental impacts of electricity generation from three MHP case studies, using a life cycle assessment approach. They demonstrated that MHP installations in the water industry have a strongly positive environmental balance.

Derakhshan S. and Kasaeian N. (Derakhshan & Kasaeian, 2012) developed an optimal design of axial hydro turbine for MHP for some low heads micro potential flow. They optimized the runner geometry by evolutionary optimization algorithms but kept the design of the initial runner with the classical methods. They obtained an improvement of 3.5% in the turbine efficiency by optimization of the turbine blade.

Hanmandlu M. and Goyal H. (Hanmandlu & Goyal, 2008) proposed an advanced control technique for MHP using an electric servomotor as a governor applied especially for isolated systems. The advanced controller was developed with four control schemes: The linear part combining the fast transversal filter algorithm and normalized LMS algorithm, and the non-linear part using the Fuzzy PI and a neural network. This new controller proved to have better performance than other control schemes.

Nouni M.R. *et al.* (Nouni, Mullick, & Kandpal, 2006) investigated the techno-economic feasibility analysis of MHP projects for decentralized power supply for remote locations in India. The financial viability of the MHP projects was found to be critically dependent on the plant load factor which ranges in remote rural areas from 25 to 45%.

Chae K. J. (Chae, Kim, Ren, & Cheon, 2015) suggested an introduction of a flow-variable MHP system in wastewater treatment plant as a way of energy recovery. This system was designed to have a semi-Kaplan, with only adjustable turbine blades without guide vanes. Therefore, it is a simple and inexpensive structure but still with high-level of performance.

Williams A.A. (Williams, 1996) proposed a very low-cost system for MHP with centrifugal pumps used as a hydraulic turbine (pump as turbines) coupled with an integral induction motor used as a generator. These two components being massively produced in many countries make this system very cost effective. In addition, due to a variable power output, a standard Induction Generator Controller (IGC) was design to enable the system to be used for isolated micro hydropower schemes.

2.5. Research gap

Based on the literature review discussed in the previous section, it has been highlighted that the most recent research carried in the field of MHP was characterized by high flow rate and low head. Therefore, most of the studied turbine was the type of reactive turbines such as Propeller, Kaplan and the impulsive cross-flow. In addition to this, in developing countries, the Pelton turbine is more often used for pico hydropower generation (<5kW) whereas the reactive turbine and the cross-flow turbine are reserved for MHP systems.

Despite the fact that, sites with low head and high discharge are suitable for reactive turbine, high discharge needs a very huge turbine corresponding with relatively high cost. And this raises an economical constraint for developing countries. Consequently, there is need of more research of MHP project especially under conditions of high head and low flow rate. In this study, the topological schemes of the chosen site shows that there is very low flow rate and sufficient head height (relatively high). These two conditions are enough for a significant power extraction.

Moreover, the potential of MHP is very significant in the region where the selected site was identified. This area correspond to the Congo-Nile Divide characterized by very mountainous relief irrigated with many medium and small rivers.

Chapter 3. METHODS

3.1. Description of the specific case study

The case study is located in the province of Rumonge, in the commune of Muhuta, exactly in Buyezi at 10 km from the Nation Road 3. Rumonge is a new province that includes four communes namely Muhuta, Bugarama, Buyengero, and Burambi. The site is situated at 3°38'0.24" South and 29°23'22.56" East, and at an elevation of 1510 m. The site is close to a very small village accessible by road where the reconnaissance survey was conducted. The targeted villages to be supplied by electric power are not close to the main national grid.

From the reconnaissance study, based on the topographic profile, a small diversion weir will be constructed. It will be connected to an above-ground canal together with a settling basin and a forebay tank. By reason of enough available discharge throughout the year at the specific location, there is no pond that needs to be built. The water conveyance system will allow enough supply of water even during dry season. The powerhouse location was identified downstream of the mountain (3°37'48.11" South and 29°23'10.28" East) at an elevation of 1426m. An estimate of the canal will be constructed of about 60 m and a welded steel penstock of about 380m between the forebay tank and the powerhouse.

3.2. Design process

3.2.1. Site surveying

In order to estimate the power generation, two main factors are involved as discussed above: the water flow-rate and the gross head. When these parameters are measured, then the net head of the hydropower plant can be approximated.

The design of the turbine will be made so as to be able to extract all the maximum mechanical energy from the moving water in the turbine. Hence, it is crucial to determine the exact flow-rate and net head available on the site.

However, the investigation of a suitable site for an implementation of micro hydropower was the first step during site surveying. Then, it was followed by the collection of data on the identified site.

3.2.1.1. Identification of the best site

As described in the first chapter, Burundi has high mountainous relief in West region. Therefore, the South West region was considered due to the suitable condition (hilly region with presence of Small

River) of an easy implementation of micro hydropower with low initial cost. The main characteristics targeted was the following:

- Higher head sites with low (or medium) discharge due to the economic constraint,
- Streams that flow during the whole year and not the seasonal ones,
- Good site (reliable potential) rather than the closest site,
- Environmentally friendly intake site fitting the topographic condition,
- Easy access to prevent very high cost of civil work and long transmission line.

3.2.1.2. Measuring the Gross head

To measure the vertical drop of the pressure head many methods can be used such as:

- Topological surveying (using theodolite)
- Water-filled method
- Abney level method
- Digital altimeter
- GPS unit

For our case, a GPS unit with enough accuracy has been used and the difference between the altitude of the intake of the penstock and the level of the powerhouse has been calculated to find the available gross head.

The intake location is at an altitude of 1510m above the sea level and the location of the powerhouse at 1426m. Hence the available gross head is the difference of the altitude making that is 84 m.

3.2.1.3. Measuring the available flow rate

Several methods can be used to approximate the flow rate of a river flow. The main methods usually used are the following:

- Bucket method (only suitable for flows less than about 10 l/s)
- Float method (suitable for large river)
- Weir method
- Salt Gulp Analysis method
- Current meters

The float method or velocity-area method has been used because of the characteristics of Nyamusenyi River. This choice has been made due to an available flow seemingly greater than 50 l/s and the simplicity of the method which is suitable for a uniform width and area of the river.

Two steps are considered in order to determine the approximated flow rate:

- Measuring the cross section area (A_c),
- Measuring the surface average velocity (V_s).

The first step is to compute the cross section using a trapezoidal approach by the following formula:

$$A_c = \frac{a+b}{2} * \frac{1}{k}\sum_{i=1}^{k} h_i \,, \tag{3.1}$$

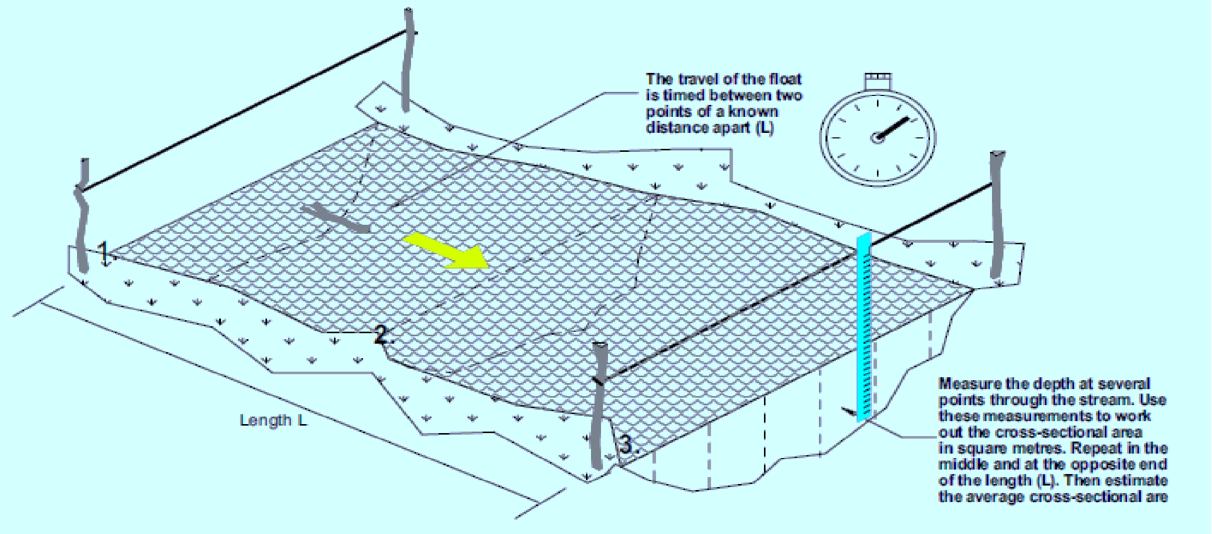
where a and b are respectively the top and bottom with of the river and the second term of the product is the average height of water in the river.

Table 3.1 Value measured in meter in situ of the cross section parameter.

a	b	k	h_1	h_2	h_3	h_4	h_5	h_6	h_7
3.2	3.4	7	0.03	0.05	0.11	0.15	0.18	0.06	0.04

Using the equation (3.1) and Table 3.1, the cross section area found is 0.2922m^2.

The second step is to calculate the mean velocity surface of a floating object which can be a dry piece of wood or a half filled plastic bottle. Between two specific points distant from one to another by a length of around 10 m, the time is measured from when the float passes the first point to when it passes the second. A repeated measurement is needed in order to get consistent results.


The travel of the float is timed between two points of a known distance apart (L)

Measure the depth at several points through the stream. Use these measurements to work out the cross-sectional area in square metres. Repeat in the middle and at the opposite end of the length (L). Then estimate the average cross-sectional are

Figure 3.1 Schematic of a Float method using average depth of the stream and the mean time of the float (Phillip & Nigel, 2001).

The average flow velocity value measured has to be multiplied by a correction factor (It varies between 0.6 and 0.8 depending on the roughness of the bottom of the river and the water depth). A value of 0.7 can be chosen as the mean of 0.6 and 0.8 (Nasir, 2013), therefore the corrected surface average velocity V_{sc} is given by:

$$V_{sc} = 0.7 * V_s\,. \qquad (3.2)$$

The approximated available discharge is determined by doing the product of the two calculated parameters:

$$Q = A_c * V_{sc}\,. \qquad (3.3)$$

Table 3.2 Values measured in situ of the flow rate.

L (m)	T (s)	V_s ($m.s^{-1}$)	V_{sc} ($m.s^{-1}$)	A_c (m^2)	Q (m^3s^{-1})
5.4	15	0.36	0.252	0.2922	0.0736

Hence, using the equation (3.3) and Table 3.1, the flow rate is approximated to 0.0736 m^3s^{-1}.

3.2.2. Approximation of the power output

The output power generated from the chosen hydro turbine is approximated using the following expression:

$$P = \rho g H_n \, Q \eta_g \eta_p \eta_t, \tag{3.4}$$

where η_g, η_p, η_t are respectively the efficiency of the generator, penstock, and the turbine. Knowing the available gross, the next step is determined all the losses and subtracted them from the gross head in order to deduce the net head:

$$H_n = H_g - H_l. \tag{3.5}$$

The losses can be grouped into three categories:

- Head loss at the entry and the exit,
- Head loss due to friction and
- Head loss due to bending of the penstock

The friction head loss can be determined by the Darcy-Weisbach formula:

$$h_f = f * \frac{L}{D} * \frac{V^2}{2g}, \tag{3.6}$$

where f is the coefficient of friction loss, L and D respectively the length and diameter of the penstock.

In a laminar flow, the friction loss coefficient can be calculated using the expression:

$$f = \frac{64\nu}{VD} = \frac{64}{Re}, \tag{3.7}$$

With the Reynold Number $Re = \rho VD/\mu$, V the velocity in the penstock, D the diameter of the penstock, μ the dynamic viscosity and ν the kinematic viscosity.

As it will be calculated in the subsection of the design of the penstock the diameter of the penstock is 200 mm. Estimated using the GPS coordinate, the length of the penstock is 380 m. The average water velocity is $V = \frac{4Q}{\pi D^2} = 2.3\ m/s$.

If we choose the penstock is in galvanized iron, the roughness $\varepsilon = 0.015$. The relative roughness $e = \varepsilon/D$ will be equal to $7.5 \cdot 10^{-4}$. The Reynold number $Re = 2 \cdot 10^5$ (turbulent flow).

Thus, the friction loss is found using the Moody diagram (See APPENDIX B.) by means of ε and Re. Hence, we find the head loss with $f = 0.016$:

$$h_f = 0.016 \times \frac{380}{0.2} \times \frac{2.3^2}{2 * 9.81} = 2.1\, m.$$

The minor losses at the bend, entry or exit of the penstock can be summarized as follow (Singhal, 2015):

$$h_m = (\sum_i k_i) \times \frac{V^2}{2g}, \tag{3.8}$$

where k_i are constant related to the angle of the bend of the penstock or the type junction.

Table 3.3 Summary of the loss coefficients depending on the type of junction.

Types of junction	Entry	2 Bends of 30°	2 Bends of 45°	Unions	Total
k_i	0.2	2×0.2	2×0.4	10×0.008	2.2

Hence, the minor losses are given by:

$$h_m = 2.2 \times \frac{2.3^2}{2 * 9.81} = 0.6\, m.$$

The total head loss is the sum of head loss due to bend, friction and the loss at the entry and the exit.

$$H_l = 2.1 + 0.6 = 2.7\, m.$$

The net head is deduced from equation (3.5):

$$H_n = 84 - 2.7 = 81.3\, m.$$

Figure 3.2 gives an overview of the penstock profile. The efficiency of the penstock is equal to:

$$\eta_p = \frac{81.3}{84} \times 100 = 96.7\%.$$

If we assume the efficiency of the generator to be 75% and the efficiency of the turbine 85%, the approximated power putout is, therefore:

$$P = 9.81 \times 81.3 \times 0.0736 \times 0.97 \times 0.75 \times 0.85\ (in\ KW),$$

$$P = 36.5\ kW.$$

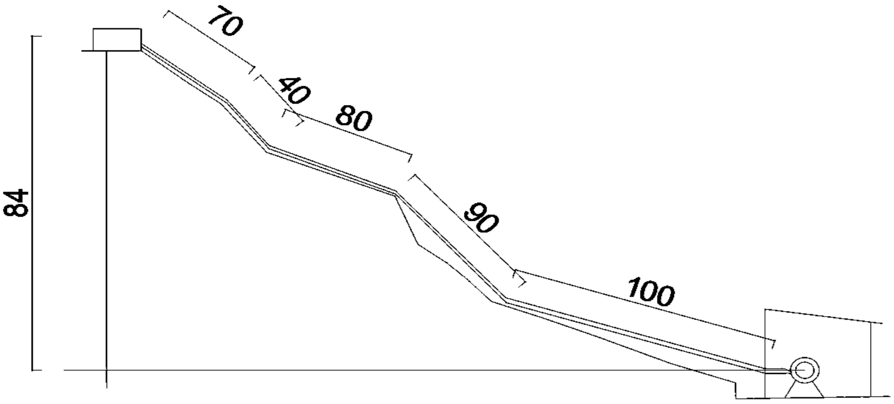


Figure 3.2 Summary of the penstock profile.

3.2.3. Estimated Energy consumption

The selected small centre Gitaza to be supplied with electricity was estimated to have a number of 500 households, 15 business centres (shops, grinding mill, fisheries conservation stock), 1 Central Market; 1 administrative office and 1 hospital and 3 schools.

Figure 3.3 Gitaza view by Google earth.

The estimated annual energy consumption summarized in the Table 3.4:

Table 3.4 Estimated energy consumption

Electrical Appliance (Households and Institutions)	**Quantity**	**Power rating (W)**	**hours**	**Annual Energy consumption (MWh)**
ELECTRIC LIGHTS LAMPS (CFL) ($per building)	2000	20	5	72
RADIO/MUSIC SYSTEM	500	60	2	21.6
TV	500	200	2	72
MOBILE	500	5	2	1.8
REFRIGATOR	8	250	8	5.76
Electric Motors	4	1000	4	5.76
Computer laptop	4	80	5	0.576
Total Energy Consumption				179.496

If we consider an estimated annual energy consumption of 179.5 MWh, the estimated power output will be enough to cover the energy demand of Gitaza centre. Moreover, in section 3.3, considering the site condition, the annual generated electricity is 196 MWh.

3.2.4. Selection of the turbine

The selection of the turbine is a major step in designing a hydropower system. This selection can be done using many different criteria. The net head and the available discharge can give a rough approximation of the type of turbine to be used as shown in the Figure 3.4.

From the found values, the previous graph shows that the Pelton turbine is the most suitable turbine to be used in those conditions.

The selection of a turbine can be also made based on the value of the specific speed. The specific speed can be defined as the speed of a similar turbine with unit head and unit output power during similar operating conditions. The specific speed gives an estimation of the size and the type of the turbine. It is calculated using the following expression:

$$N_s = n\frac{\sqrt{P}}{H_n^{5/4}}, \tag{3.9}$$

where n is the nominal rotational speed (in round per minute), P the power output (in kW) and H_n the net head (in m).

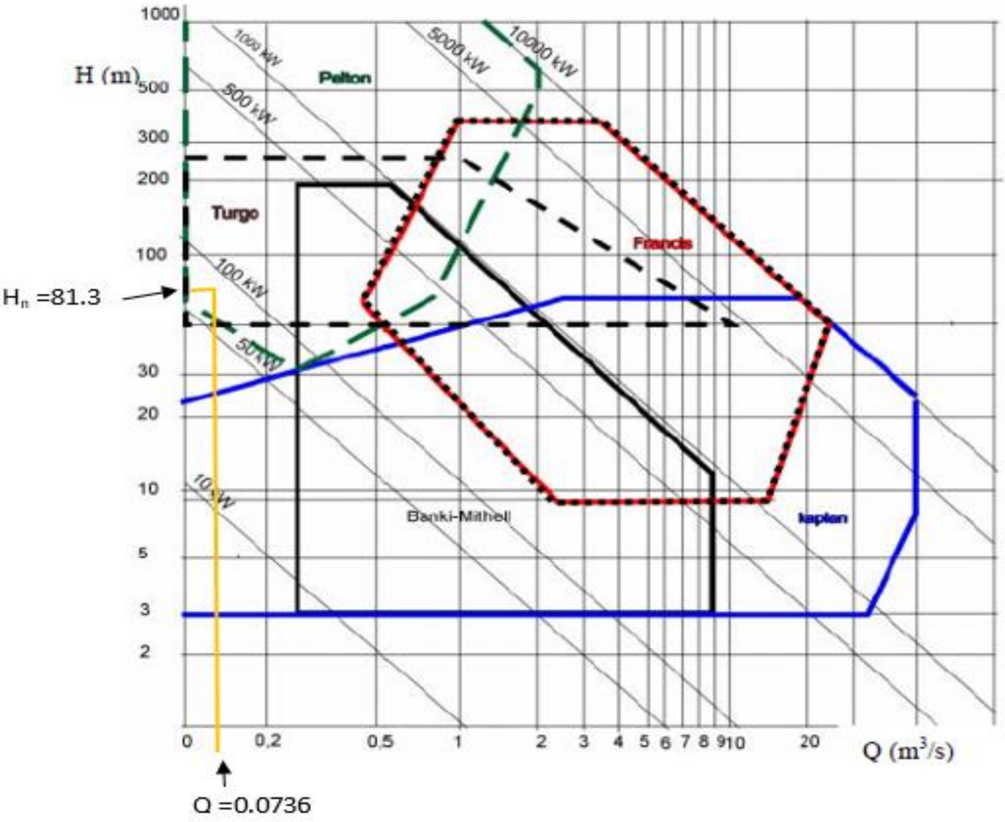


Figure 3.4 Turbine selection using net head and available discharge adapted from (Sangal, Garg, & Kumar, 2013).

The rotational speed is determined using the frequency and the number of pair poles p using the expression below:

$$n = \frac{60 \times f}{p}, \tag{3.10}$$

with the rotational speed being in round per min. The frequency is more often standardized in some country at 50 Hz and in others by 60 Hz, in our case the frequency the 50 Hz is considered. The number of pair pole is chosen to be six pair poles. Hence, n is equal to 500 r.p.m.

If we consider a net head of 81.3m and the power output to be 36.5 kW, the specific speed is calculated using equation 3.9.

$$N_s = 500 \frac{\sqrt{36.5}}{(81.3)^{5/4}} = 12.30.$$

From Table 3.5, this result approves also the choice of a Pelton turbine.

Table 3.5 Range of application of turbine depending on the head, discharge, power output, and specific speed (Ramos et al., 2000).

Hydraulic Turbines		H (m)	Q (m^3/s)	P (kW)	N_s (r.p.m) (kW, m)
Reaction	Bulb	2-10	3-40	100-2500	200-450
	Kaplan and Propeller (Axial Flow)	2-20	3-50	50-5000	250-700
	Francis with high specific speed (Diagonal flow)	10-40	0.7-10	100-5000	100-250
	Francis with high specific speed (Radial flow)	40-200	1-20	500-15000	30-100
Impulse	Pelton	60-1000	0.2-5	200-15000	<30
	Turgo	30-200		100-600	
	Cross Flow	2-50	0.01-0.12	2-15	

3.2.5. Design of a Pelton turbine and Injector

In designing a Pelton turbine, two fundamental parameters are required that is the net head and the designed flow rate. As seen before, after measuring those parameters, the hydraulic power output was determined. Hence, the size of the turbine can be well defined. In sizing the Pelton, some parameter has to be chosen with some justifiable assumption and others under some constraints.

The first step is to find the real velocity of the jet that is given by the following expression:

$$V_j = c_v\sqrt{2gH_n}, \tag{3.11}$$

where c_v is the nozzle coefficient which varies from 0.96 to 0.98. Here we choose $c_v = 0.96$. Therefore, the absolute velocity of the water jet is:

$$V_j = 0.96 * \sqrt{2 \cdot 9.81 \cdot 81.3} = 38.34\, m/s.$$

Then, the peripheral velocity of the wheel is found using the expression:

$$u = k_u \sqrt{2gH_n}, \tag{3.12}$$

where k_u is the speed ratio and ranges from 0.44 to 0.46. We choose $k_u = 0.45$.

$$u = 0.45\sqrt{2 \cdot 9.81 \cdot 81.3} = 17.97 m/s.$$

Afterward, if we choose the Pelton turbine with a single jet, the diameter of the jet d_0 can be determined using the expression:

$$Q = \frac{1}{4}\pi d_0^2 c_v \sqrt{2gH_n}\,, \tag{3.13}$$

Hence, we get:

$$d_0 = \sqrt{\frac{Q}{\pi c_v \sqrt{gH_n}}}, \tag{3.14}$$

$$d_0 = \left(\frac{0.0736}{3.14 * 0.45\sqrt{9.81 * 81.3}}\right)^{0.5} = 0.072\, m.$$

Next, the wheel diameter can be deduced from this expression of the wheel velocity:

$$u = \frac{\pi D n}{60}, \tag{3.15}$$

hence,

$$D = \frac{60u}{\pi n} = \frac{60 * 17.28}{3.14 * 1000} = 0.34\, m.$$

The number of bucket z is determined using the empirical expression:

$$z = 0.5m + 15, \tag{3.16}$$

where m is jet ratio that is the ratio of the diameter of the wheel to the diameter of the jet ($m = \frac{D}{d_o}$).

Therefore,

$$z = 0.5 * \frac{0.34}{0.072} + 15 = 17.3 \approx 17.$$

We can consider a Pelton of 17 buckets.

Finally, the size of the buckets including length, width, and depth in terms of jet d_0 is given by the condition below (Nasir, 2013).

- Radial length of the bucket:

$$B_l = 3d_0, \tag{3.17}$$

- Axial width of the bucket:

$$B_w = 3.4d_0, \tag{3.18}$$

- Depth of the bucket:

$$B_d = 1.2d_0, \tag{3.19}$$

- Length of the moment arm of the bucket:

$$L_{ab} = 0.195D, \tag{3.20}$$

- Bucket cavity width:

$$B_t = 1.2d_0, \tag{3.21}$$

- Radius of bucket centre of mass to centre of runner:

$$R_{br} = 0.47D, \tag{3.22}$$

- Bucket volume:

$$V_b = 0.0063D^3, \tag{3.23}$$

The bucket exit angle β_2 can be determined from Figure 3.5. If the inclination of the bucket trailing edge $\alpha = 10°$ and the flow angle $\beta_2' = 115°$ then $\beta_2 = 165°$.

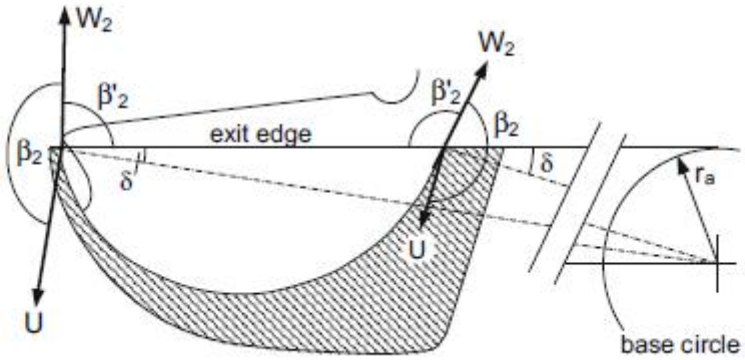


Figure 3.5 Determination of the bucket exit angle (Zhang, 2016).

Table 3.6 Results of the specific parameters of the bucket.

B_l (cm)	$B_w(cm)$	$B_d(cm)$	$B_t(cm)$	$L_{ab}(m)$	$R_{br}(m)$	$V_b(m^3)$	β_2
21.67	24.56	8.66	8.66	0.0669	0.1614	$2.5 * 10^{-4}$	165°

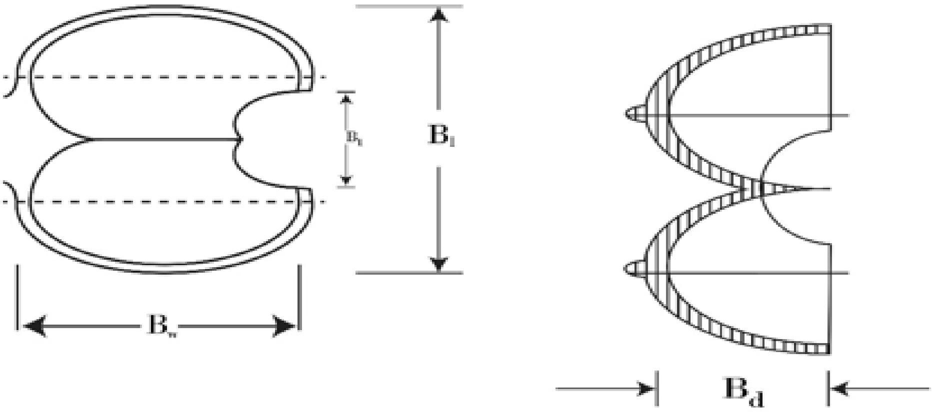


Figure 3.6 Top view and transversal cross section of a bucket of a Pelton turbine

From the Figure 3.7, it follows,

$$Cos\ \alpha_0 = \frac{R_c}{R}, \tag{3.24}$$

where R_c is the circle diameter of the bucket cutout edge.

The ratio of the bucket length to the bucket width is between 0.88. Therefore,

$$D_c - D = 0.88B_w. \tag{3.25}$$

Hence,

$$Cos\ \alpha_0 = \frac{1}{1 + 0.88/D}. \tag{3.26}$$

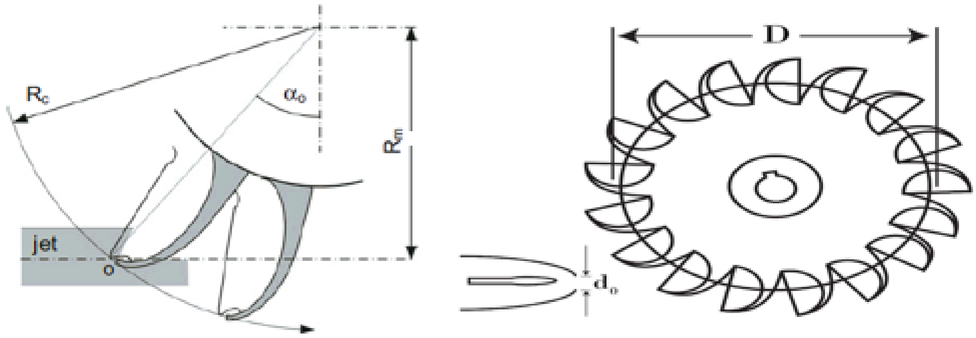


Figure 3.7 Bucket position angle α_o, adapted from (Zhang, 2016).

The injector nozzle is frequently constructed with a contraction angle α_D of about 42° to 45° and the needle typically has a half vertex angle α_N of about 25°. The needle diameter $d_N$can be approximated to 1.4 d_o and the injector diameter $d_D = 2.1d_0$ (see Figure 3.10). The needle stroke s can be optimum from the expression of the nozzle outlet section that depends on the stroke the injector (see Figure 3.11) (Zhang, 2016).

$$A_0 = \pi \sin\alpha \left(d_0 \cdot s - \frac{\sin 2\alpha_N}{2} \cdot s^2\right), \tag{3.27}$$

$$Q = A_0 \cdot V_j. \tag{3.28}$$

If we take $\alpha_N = 22.5,$ needle stroke is 0.178 m.

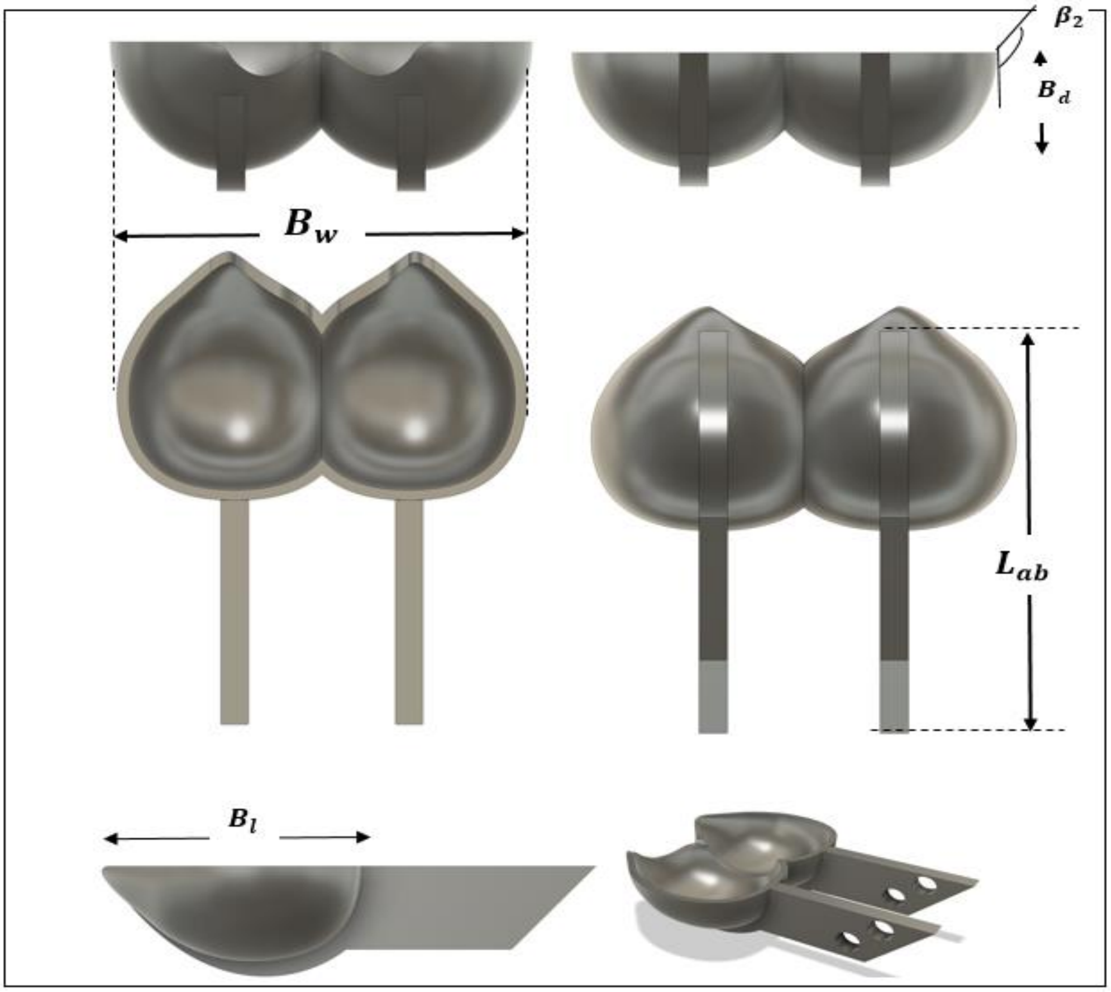


Figure 3.8 3-dimensional view of the Pelton Bucket.

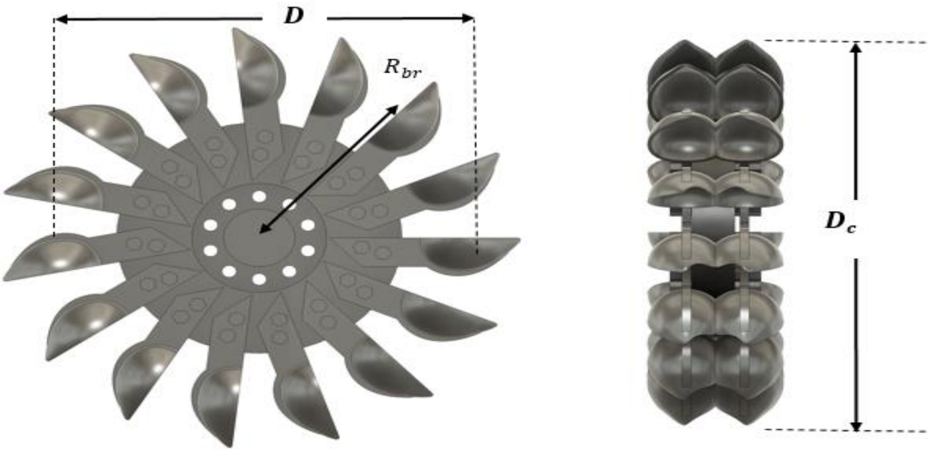


Figure 3.9 3-dimension view of the bucket of a Pelton wheel.

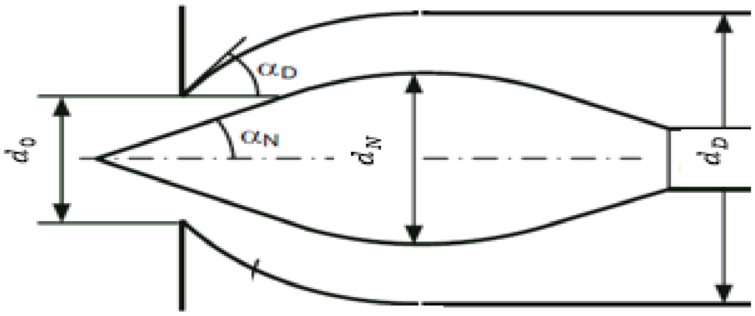


Figure 3.10 Dimension of the injector, adapted from (Zhang, 2016).

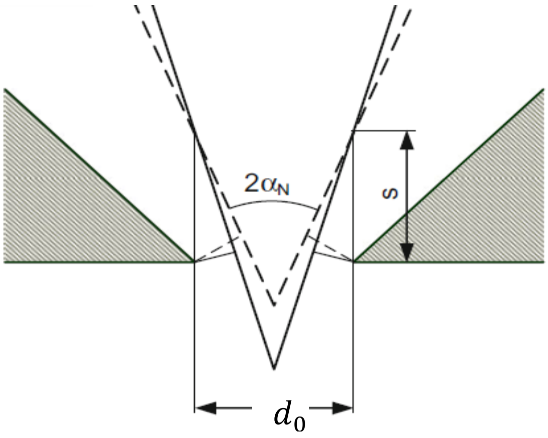


Figure 3.11 Scheme of the needle stroke and jet diameter adapted from (Zhang, 2016).

3.2.6. Flow Simulation of the turbine design

The flow simulation has been developed using SolidWorks 2015. Using CFD computation, this software gives the expected behaviour of the flow through the designed Pelton turbine under design condition. The flow trajectories are simulated on the bucket of the Pelton turbine. The result obtained from the flow simulation are displayed here after. The parameters considered are the velocity, pressure, and vorticity.

It has revealed in the flow simulation that there is a significant reduction of velocity in the Z axis compared to the X and Y axis (see Figure 12 and 13). An implication of this is the transmission of the kinetic energy of the jet on the blade principally in the Z axis. There is no significant contribution of the kinetic energy on the X and Y axis.

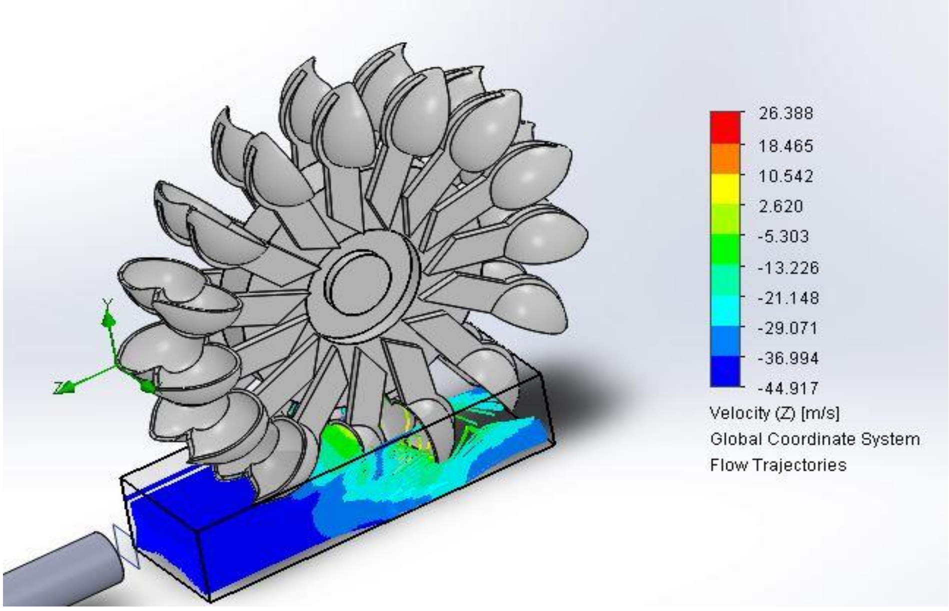


Figure 3.12 Velocity in the Z axis of the flow.

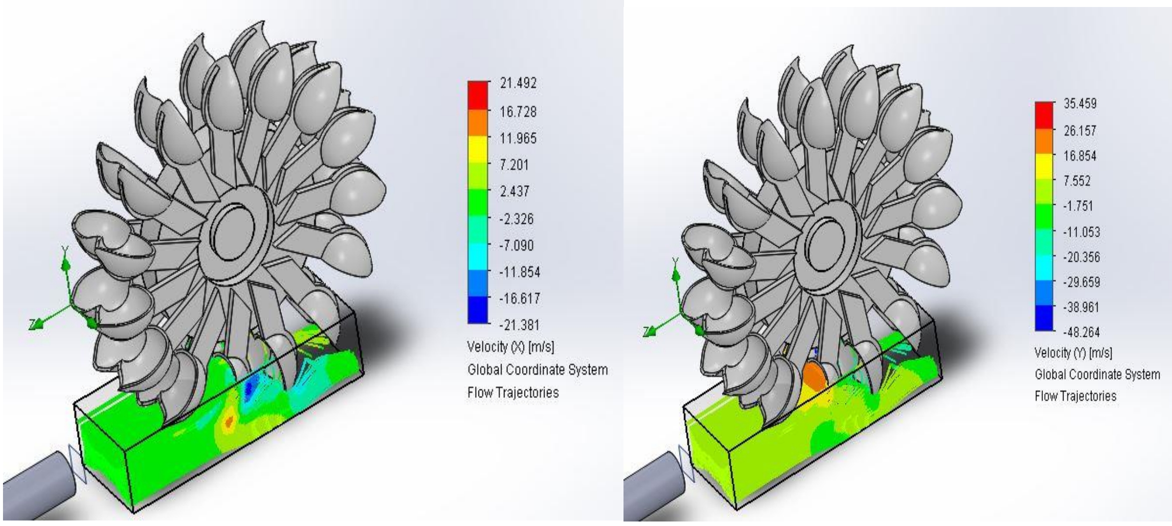


Figure 3.13 Velocity in the X and Y axis in the flow trajectories.

The pressure energy of the jet plays no major role in the transmission of the energy from the jet to the turbine (see Figure 3.14). This is comes from the fact that the interaction between the water jet and the bucket of the turbine is made under atmospheric pressure conditions.

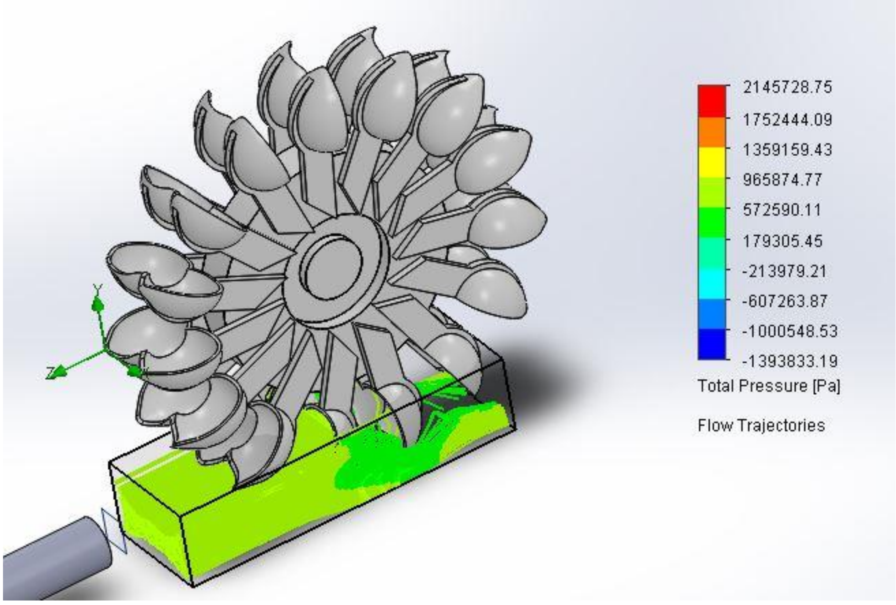


Figure 3.14 Total pressure in the flow trajectories.

From the simulation, it has been shown that there is also formation of vorticity under the two buckets where the water jet strikes the turbine (see Figure 3.15). This justifies the drop of pressure in the same region where there is formation of turbulence.

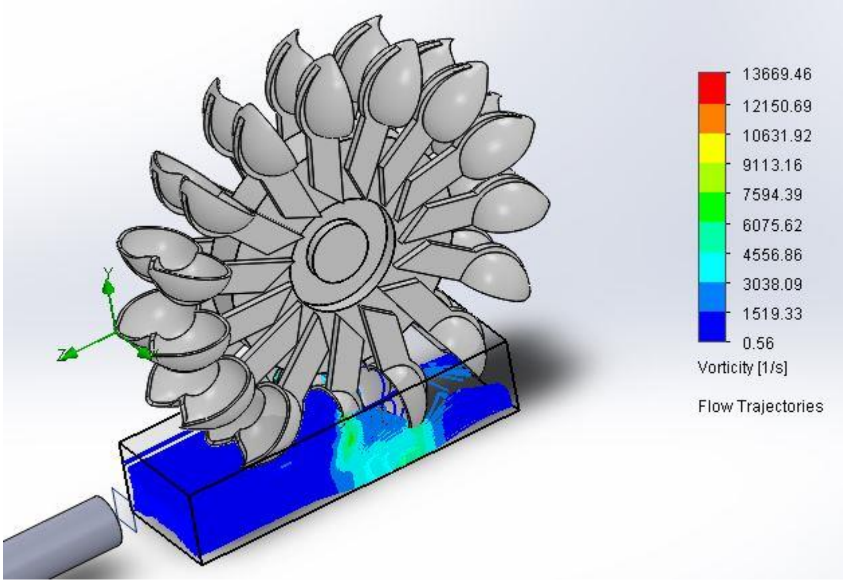


Figure 3.15 Vorticity in the flow trajectories.

Figure 3.16, 3.17 and 3.18 display the force acting on the bucket in the three dimensions. It is found that there is far more contributions on the Z axis compared to X and Y axis.

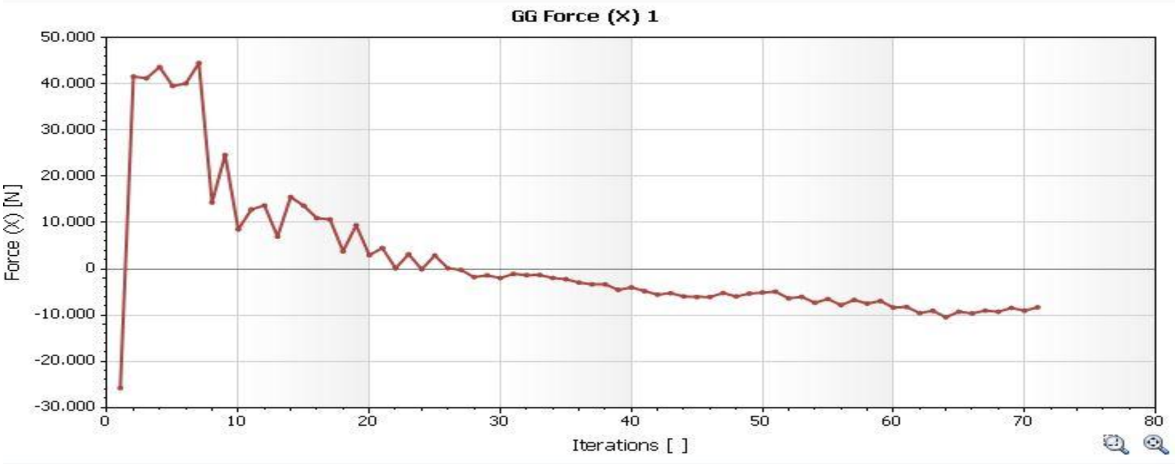


Figure 3.16 Force acting on bucket in X axis in the flow trajectories.

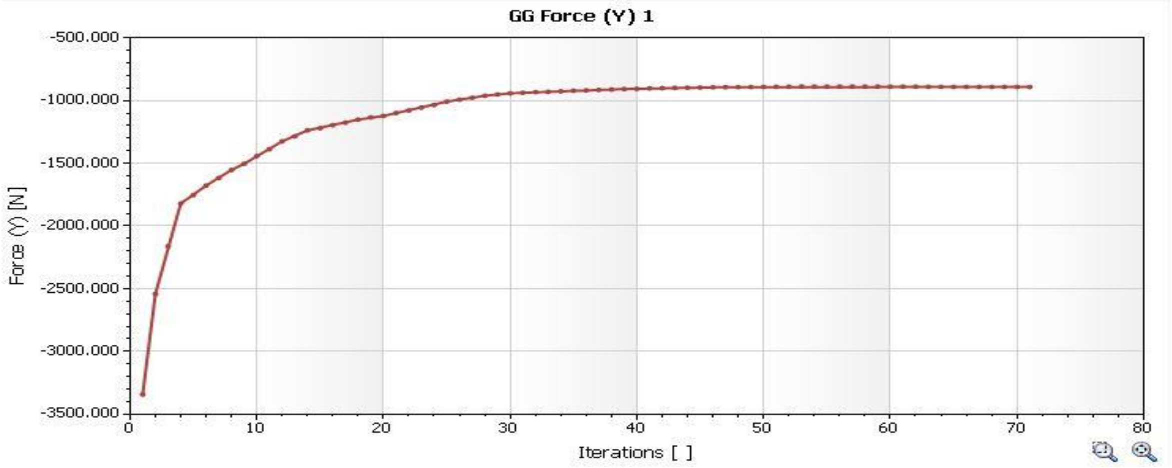


Figure 3.17 Force acting on bucket in Y axis in the flow trajectories.

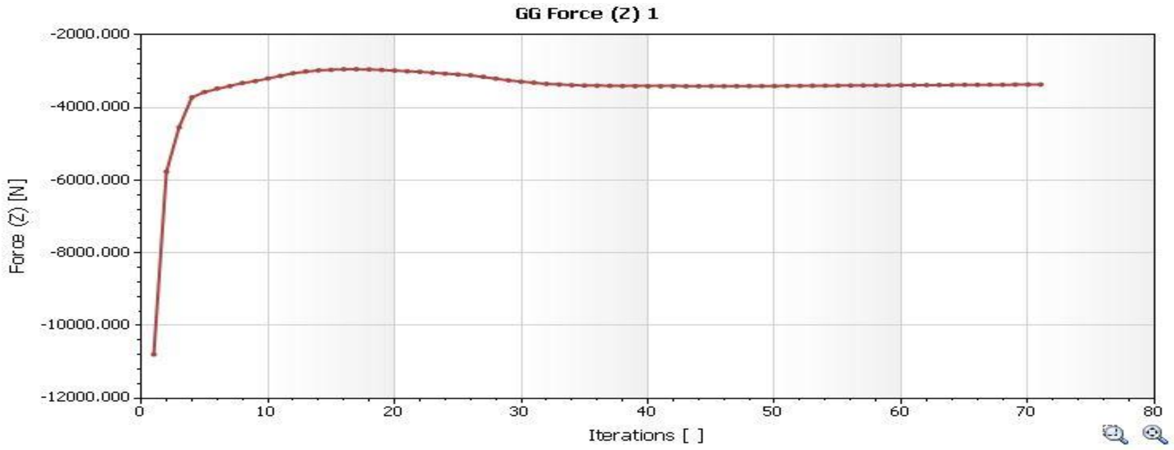


Figure 3.18 Force acting on bucket in Z axis in the flow trajectories.

Figure 3.16, 3.17 and 3.18 display the force acting on the bucket in the three dimensions. It is found that there is far more contributions on the Z axis compared to X and Y axis.

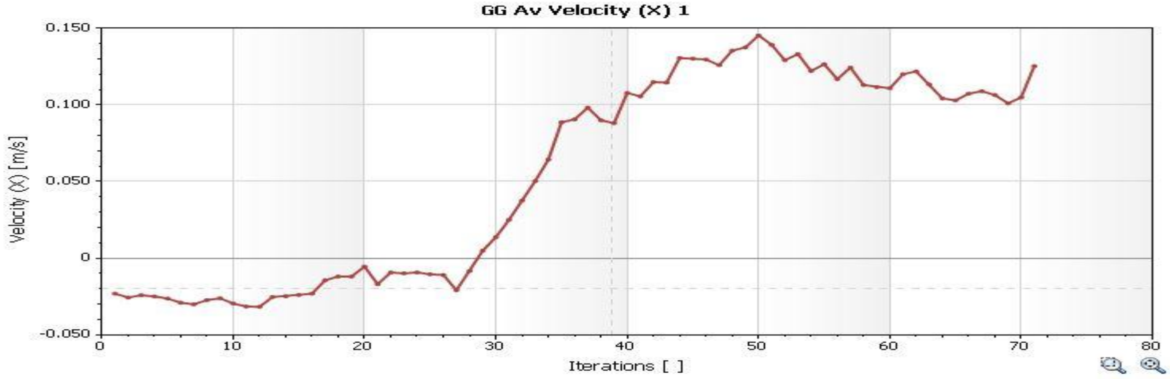


Figure 3.19 Velocity of the jet in X axis in the flow trajectories.

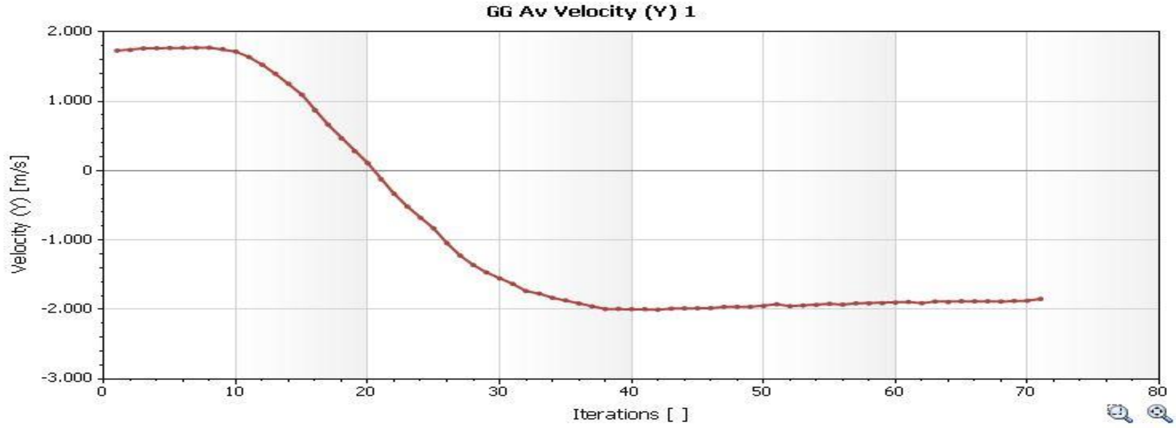


Figure 3.20 Velocity of the jet in Y axis in the flow trajectories.

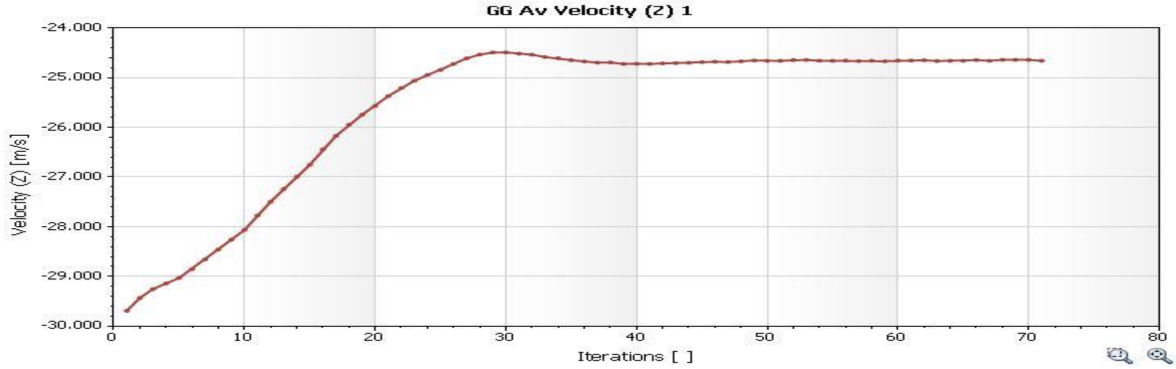


Figure 3.21 Velocity of the jet in X axis in the flow trajectories.

Figure 3.19, 3.20 and 3.21 display the behaviour of the water jet according to the velocity in the three dimensions. It is revealed that there is significant drop of the velocity in Z axis which implies a high transmission of the kinetic energy to the bucket of the turbine.

3.2.7. Design of the civil structure

The overall design of the civil structure can be pictured in the Figure 3.22:

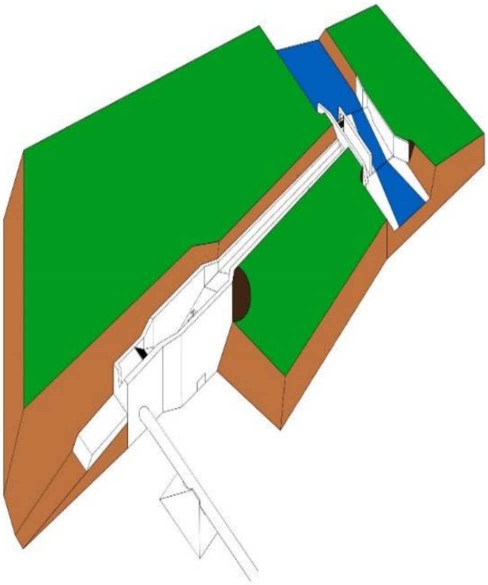


Figure 3.22 Civil Structure of the micro hydropower system.

3.2.7.1. Intake

The design of the intake is made in such a way of having a minimum submergence for the purpose of non-vortex formation (air entering in the conveyance system). An empirical model has been developed by Gordon in order to avoid the formation of vortices. Gordon has developed the following dimensionless expression (Ramos et al., 2000):

$$S = CV\sqrt{d}\,, \tag{3.29}$$

where S is the submergence (m); d is the intake opening (m); V is the mean velocity flow at the inlet (m/s); g is the gravity acceleration (9.8 m/s^2) and $C = 0.7245$(asymmetric) or $C = 0.5434$ (symmetric).

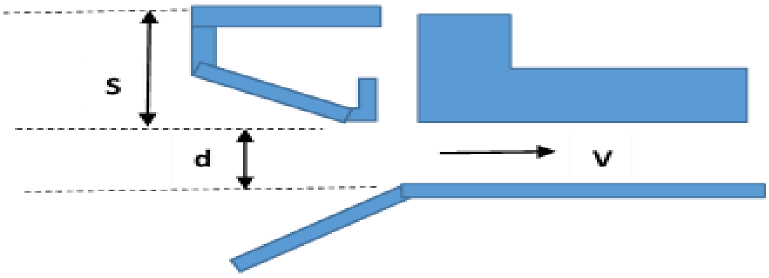


Figure 3.23 Intake scheme with minimum submergence with Gordon symbols, adapted from (Ramos et al., 2000).

For a flow rate of 0.0736 m^3/s and trash rack of a flow area of 0. 4 m^2, the approaching flow velocity is calculated to be 0.184 m/s. A trash rack at the entrance of the intake is set with space between bars of 30 mm and diameter bar of 15 mm. The angle of the trash rack to the horizontal is 60°. If we consider an asymmetric configuration, the submergence depth is calculated to be at 0.231 m below the water level to avoid the formation of vortices.

3.2.7.2. Design of the weir

The discharge of the weir is given by the following equation:

$$Q_r = C_d \cdot L_w \cdot H_{top}^{3/2}, \qquad (3.30)$$

where Q_r is the discharge of the river, C_d the coefficient of discharge of the weir, L_w the length of the weir and H_{top} the head over the top of weir.

If the length of the weir is taken as the width of the river 3.2 m, the mean discharge of the river 0.0736 m^3/s and the discharge coefficient of the weir 0.6 (concrete weir), the head over the top of the weir is:

$$H_{top} = \left(\frac{Q_r}{C_d \cdot L_w}\right)^{2/3}. \qquad (3.31)$$

Hence,

$$H_{top} = \left(\frac{0.0736}{0.6 \cdot 3.2}\right)^{2/3} = 0.114\,m.$$

If we approximate the height of the weir to be 0.7 m, the total height is 0.814 m.

3.2.7.3. Power canal

The flow rate through an open channel is given by the Manning equation for uniform flows (Ceslo Penche, 1998)

$$Q = \frac{1}{n'} A R_h^{2/3} s^{1/2}, \tag{3.32}$$

where n is the Manning roughness coefficient, A the cross-sectional area of the canal, R_h the hydraulic radius and s the slope of the open channel.

For a rectangular channel of dimension d and W, the previous equation becomes (Ceslo Penche, 1998):

$$\frac{Qn}{s^{1/2}} = d\,W\left(\frac{dW}{W+2d}\right)^{2/3}. \tag{3.33}$$

Assuming a slope of $1/1500$ and the roughness $n' = 0.012$, the ratio

$$\frac{Qn}{s^{1/2}} = 0.0342,$$

If we assume the ratio $d = W/2$, then we find $d = 0.258\,m$ and $W = 0.51\,m$.

3.2.7.4. Design of the Desilting basin

The working principle of a desilting basin (or settling basin) is due to the gravity of the fine particle in the flowing water. It is designed in such a way of reducing the velocity of the water in order to allow the sedimentation process within the length of the settling basin. This basin has four zones namely the inlet, outlet, settling and sludge storage zones.

For an ideal settling basin, Figure 3.23 gives the main dimensions for sizing a desilting zone.

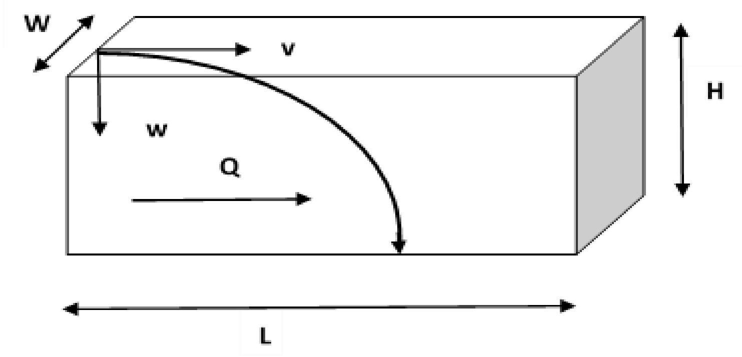


Figure 3.24 Schematic of an ideal desilting basin (Bishwakarma, 1997)

The dimensions of settling basin are the settling width, height, and length. The maximum critical velocity can be estimated using the Vischer and Huber (1982) formula:

$$v_{crit} = 0.44 \cdot \sqrt{d}, \tag{3.34}$$

where d is the diameter of the particles.

Using the formula of the discharge, the settling height can be deduced:

$$Q = A \cdot v = W_s \cdot H_s \cdot v_{crit}, \tag{3.35}$$

Therefore,

$$H_s = \frac{Q}{W_s \cdot v_{crit}}. \tag{3.36}$$

The flow velocity in the settling basin is given by the expression:

$$v = \frac{Q}{W_s \cdot H_s}. \tag{3.37}$$

The fall velocity over the entire range of the Reynolds number, in terms of drag coefficient, is given by (Bishwakarma, 1997):

$$w^2 = \frac{4gd}{3C_D} \cdot \frac{\gamma_s - 1}{\gamma}. \tag{3.38}$$

Then, we deduced the length of the settling basin:

$$L_s = H_s \frac{v}{w}. \tag{3.39}$$

Thus, the volume of settling basin is:

$$V_s = L_s \cdot H_s \cdot W_s. \tag{3.40}$$

Next, the volume of collection basin can be approximated as follow:

$$V_c = \frac{V_s}{4}. \tag{3.41}$$

Hence,

$$H_c = \frac{V_c}{W_s \cdot L_s}. \tag{3.42}$$

Table 3.7 Dimension of the settling basin:

d (mm)	L_s (m)	H_s (m)	W_s(m)	H_c (m)
0.2	0.577	0.366	1.02	0.1

3.2.7.5. Design of the Forebay tank

We consider the forebay tank to have a live storage of half a minute, the depth of water above penstock have to satisfy the condition (Ramos et al., 2000):

$$h_{st} > 1.5 * \frac{V^2}{2g}. \tag{3.43}$$

We assume $h_{st} = 0.5\ m$ which fulfills that condition.

The volume of the forebay is, therefore:

$$V_{st} = Q \cdot T, \tag{3.44}$$

$$V_{st} = 0.0736 \times 30 = 2.2\ m^3,$$

Then the area is:

$$A = \frac{V_{st}}{h_{st}}, \tag{3.45}$$

$$A = \frac{2.2}{0.5} = 4.4\ m^2.$$

Assuming a width of $W_{st} = 2\ m$, the length of the forebay will be $L_{st} = 2.2\ m$.

3.2.7.6. Design of the Penstock

The inner penstock diameter can be approximated from the flow rate, the gross head and the pipe length using the expression (Nasir, 2014):

$$D_p = 2.69 \cdot \left({n_p}^2 Q^2 \frac{L_p}{H_g} \right)^{0.1875}, \tag{3.46}$$

where n_p is the Manning's coefficient water flow rate (m^3/s) and L_p penstock length.

The thickness of the penstock can be estimated as (Nasir, 2014):

$$t_p = \frac{D_p + 508}{400} + 1.2. \tag{3.47}$$

The penstock will have 20.8 cm of inner diameter and a thickness of 2.4 mm.

3.2.7.7. Design of Anchor Blocks

The design of Anchor block has been made by the help of the Anchor Block Design Aids developed by Gurung P. (Gurung, 2014). We consider a soil type of soft clay and slits (Unit Weight, $\gamma = 16\ kN/m^3$, friction angle 22° and allowable bearing pressure of $50\ N/m^2$). The physics characteristics of the penstock in steel are the following:

- Young’s Modulus E (N/mm^2): 2×10^5

- Coefficient of linear expansion α_1 : 1.25×10^{-5}
- Ultimate Tensile S (N/mm^2): 320
- Unit Weight γ (kN/m^3): 77

If we also consider the penstock to slide on an anchor block in concrete, the friction factor is 0.6. The final design for an angle of 30° and 45° are given in Figure 3.25.

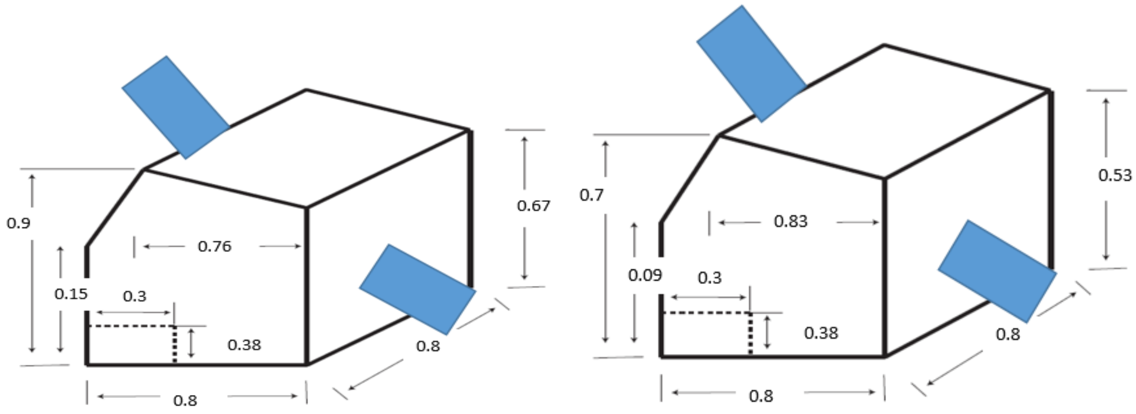


Figure 3.25 Design of the anchor block 45° (right) and 30° (left).

3.2.8. Generator description

The Induction Motor as Generators (IMG) and the Synchronous Generators are the suitable generator choices of a micro hydropower system. In this case, we choose to use a synchronous generator with the following rating:

- Generator voltage: 415 V (± 10%)
- Generator rotational speed: 1000 rpm
- Frequency: 50 Hz
- Number of phases: 3
- Power factor: 0.8
- Apparent power: 45 kVA
- brushless type for the exciter (250V DC)
- Automatic Voltage Regulator (AVR) as the regulator

3.3. Feasibility study of the micro hydropower system

3.3.1. Hydropower energy potential

The first step in estimating the energy potential of hydropower power plant is to generate the flow duration curve. This curve displays for a given period (on daily, monthly or yearly basis), the percentage of time of various flows (equalled or exceeded). It can be generated by the Rank ordered technique or the Class-interval technique. For this case, the flow duration curve is generated in a monthly basis using the Rank ordered technique. The discharge in situ data for the selected site Nyamusenyi River is not available. The discharge is approximated using the rainfall data. A water balance equation is used using the evapotranspiration and the seepage of the selected site.

$$Q = RF - ET - Se, \tag{3.48}$$

where Q is the discharge, ET the evapotranspiration and Se the seepage.

The rainfall data are available for the area where Nyamusenyi River is situated. IGEBU is the Institute in charge of geographical and meteorological data. The rainfall data of the Muhuta (site near Nyamusenyi River) is given in APPENDIX C.

The evapotranspiration is approximated using the solar radiation and the daily temperatures (Minimum and Maximum Temperatures) by means of an empirical formula proposed by Hargreaves and Samani (Subedi & Chávez, 2015):

$$ET = 0.0023 \cdot R_a \cdot (T_a + 17.8)(\Delta T)^{0.5}, \tag{3.49}$$

where R_a is the solar radiation in $\frac{MJ}{m^2}/day$, T_a the average daily temperature and ΔT the difference between the maximum and minimum temperature.

The data used for solar radiation and temperature are found on the NASA geographical website and given in APPENDIX D.

The seepage is approximated for clay type of soil to be 5 % of total amount of rainfall.

The discharge of the Nyamusenyi River is computed in mm then converted in m^3/s using the catchment area (see Figure 3.26) and the period of time with the formula.

$$Q(m^3/s) = Q(mm)\frac{CA}{24 \cdot 30 \cdot 3600 \cdot 1000}, \tag{3.50}$$

where CA is the catchment area is m^2.

Figure 3.26 Location of the catchment area of Nyamusenyi River.

The catchment area was approximated to 5.1 km^2 using Google earth. The approximation of the discharge is given in Table 3.8 for the year 2016.

Table 3.8 Monthly Precipitation in Muhuta in 2016.

Month	RAINFALL (mm)
January	197.9
February	149.9
March	117.2
April	150.9
May	88.9
June	17
July	12
August	9,6
September	59,3
October	174.9
November	195.5
December	297.7

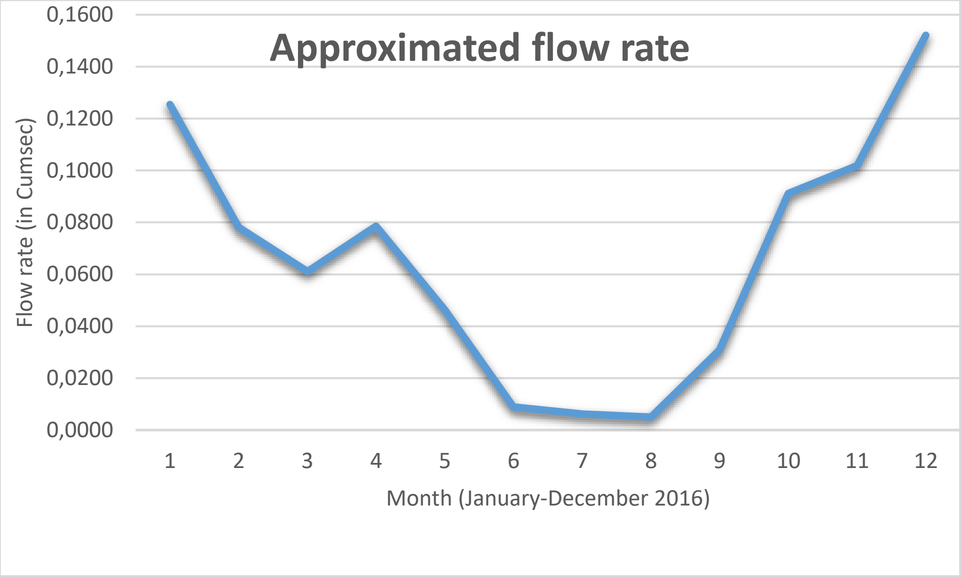


Figure 3.27 Approximate flow rate of Nyamusenyi River at the location of the intake.

Finally the flow duration curve can be deduced using the Rank ordered technic (see Figure 3.28).

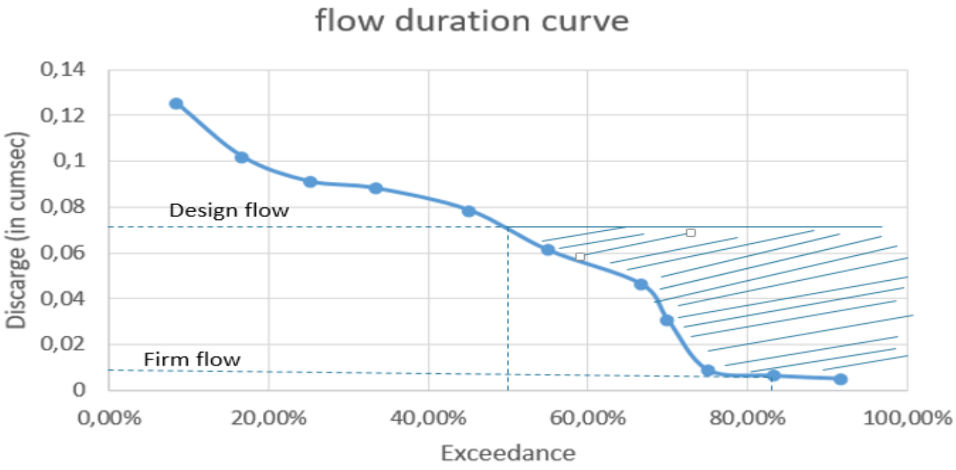


Figure 3.28 Generated flow duration curve.

For the micro hydropower to be operational through the whole year, a small reservoir with a capacity of 0.04 TMC has to be considered.

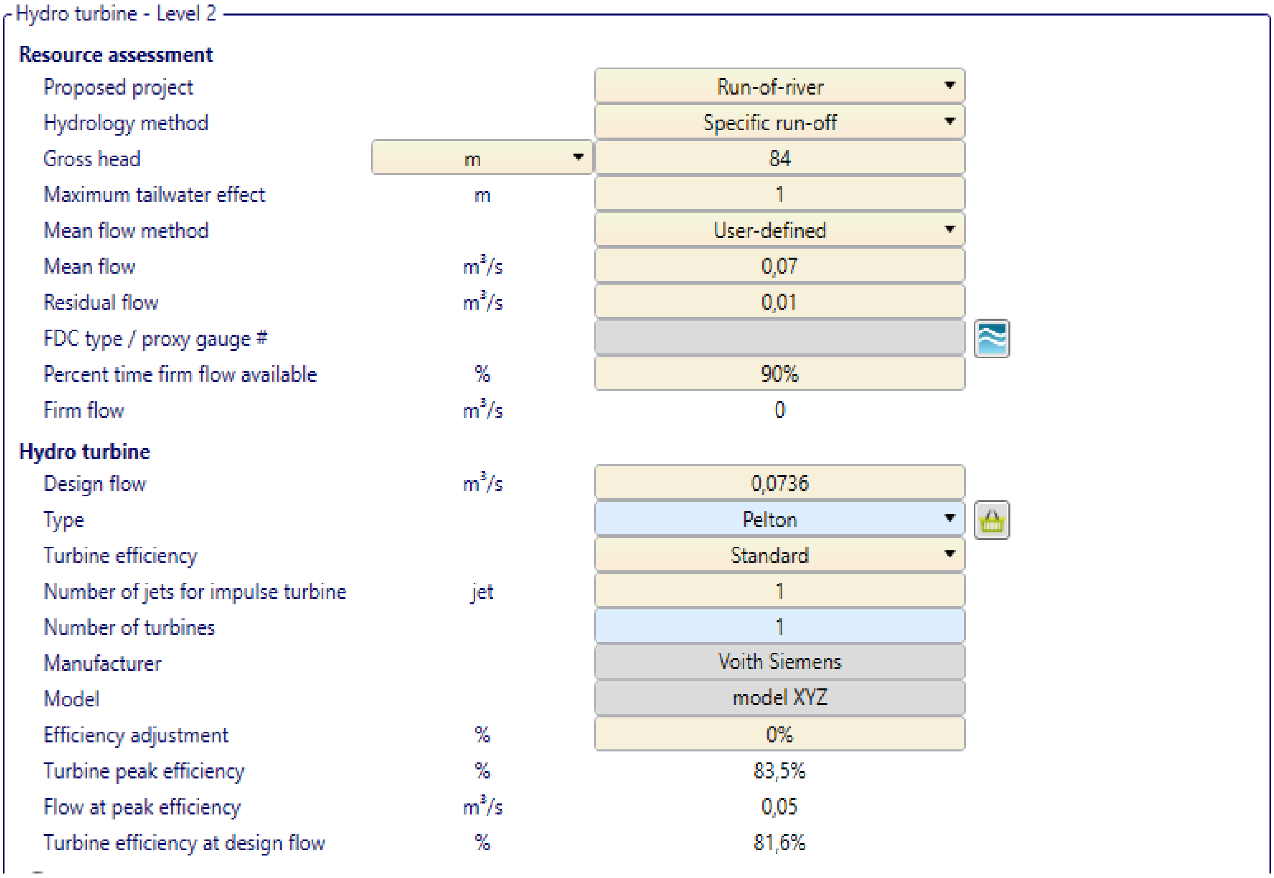
3.3.2. Feasibility Analysis

The feasibility analysis is developed using the RETscreen Software. This project analysis is made in five steps (RETScreen, 2005):

- Energy Model: This takes as input mainly the location of the energy project, the type of system used and the technology. And then, it calculates the annual energy production or energy savings.
- Cost Analysis: The inputs are the initial, annual, and periodic costs for the specific case including the credits for any base case costs that are avoided in the proposed case.
- Greenhouse Gas (GHG) Analysis: in this analysis, the software calculates the annual reduction in the emission of greenhouse gases stemming from using the proposed system compared to the given conventional technology.
- Financial Summary: The inputs are different financial parameter including the avoided cost of energy, production credits, GHG emission reduction credits, incentives, inflation, discount rate, debt, and taxes. Then, RETScreen calculates several financial indicators such as the Net Present Value (NPV), annual life cycle savings, and the Benefit-Cost ratio evaluate the viability of the project. It also includes the cumulative cash flow graph
- Sensitivity and/or Risk Analysis: It determines how uncertainty in the estimates of various key parameters may affect the financial viability of the project.

3.3.2.1. Energy Model

After the specification of climate data location and the facility location of the proposed project, the hydrological data are specified via the flow-duration curve, which represents the flow conditions of Nyamusenyi River. The data are entered manually. The flow-duration curve gives the maximum and minimum flow. It is used to assess the availability of flow over time. The power and energy are therefore deduced. The software calculates the firm flow using the residual flow and the percent time firm flow available. As it is displayed in Figure 3.29, the proposed project is taken as a run-of-river plant with a gross head of 84m. The maximum tailwater is assumed to be 1m. The mean flow and the residual flow are respectively 0.07 and 0.01 m^3/s. The hydro turbine is a Pelton type with a single jet. Considering a standard turbine efficiency as it displayed in Figure 3.30, the power and flow duration curves are generated.



Hydro turbine - Level 2

Resource assessment		
Proposed project		Run-of-river
Hydrology method		Specific run-off
Gross head	m	84
Maximum tailwater effect	m	1
Mean flow method		User-defined
Mean flow	m^3/s	0,07
Residual flow	m^3/s	0,01
FDC type / proxy gauge #		
Percent time firm flow available	%	90%
Firm flow	m^3/s	0
Hydro turbine		
Design flow	m^3/s	0,0736
Type		Pelton
Turbine efficiency		Standard
Number of jets for impulse turbine	jet	1
Number of turbines		1
Manufacturer		Voith Siemens
Model		model XYZ
Efficiency adjustment	%	0%
Turbine peak efficiency	%	83,5%
Flow at peak efficiency	m^3/s	0,05
Turbine efficiency at design flow	%	81,6%

Figure 3.29 Input data of the Energy Model.

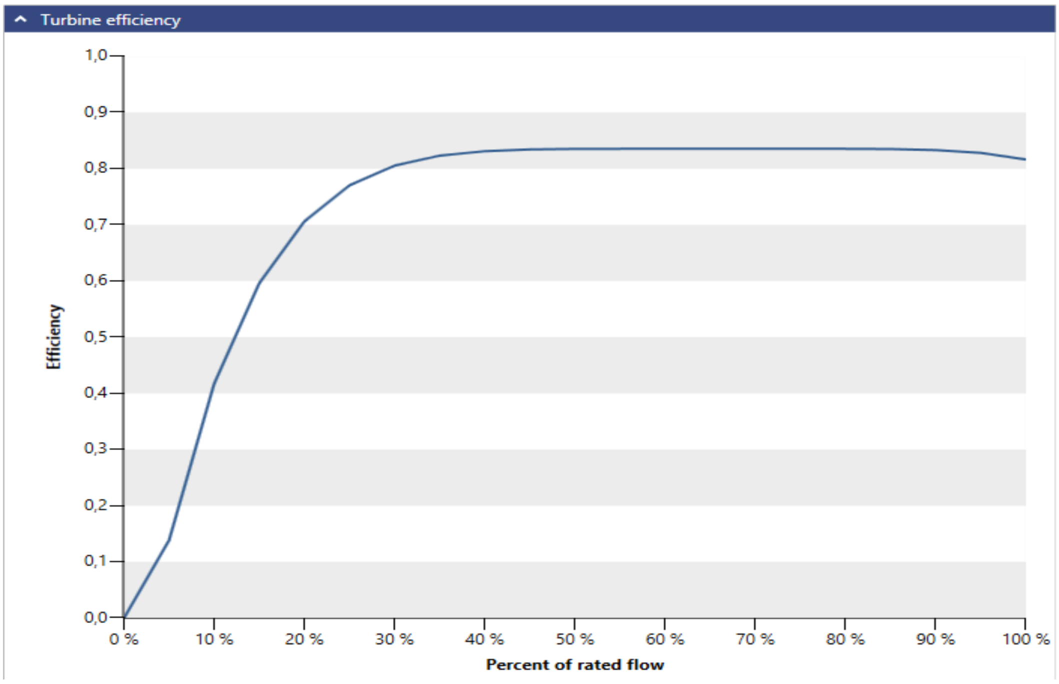


Figure 3.30 Turbine Efficiency Curve.

Figure 3.31 and Figure 3.32 give the respectively the flow duration curve and the power duration curve with the specific given conditions.

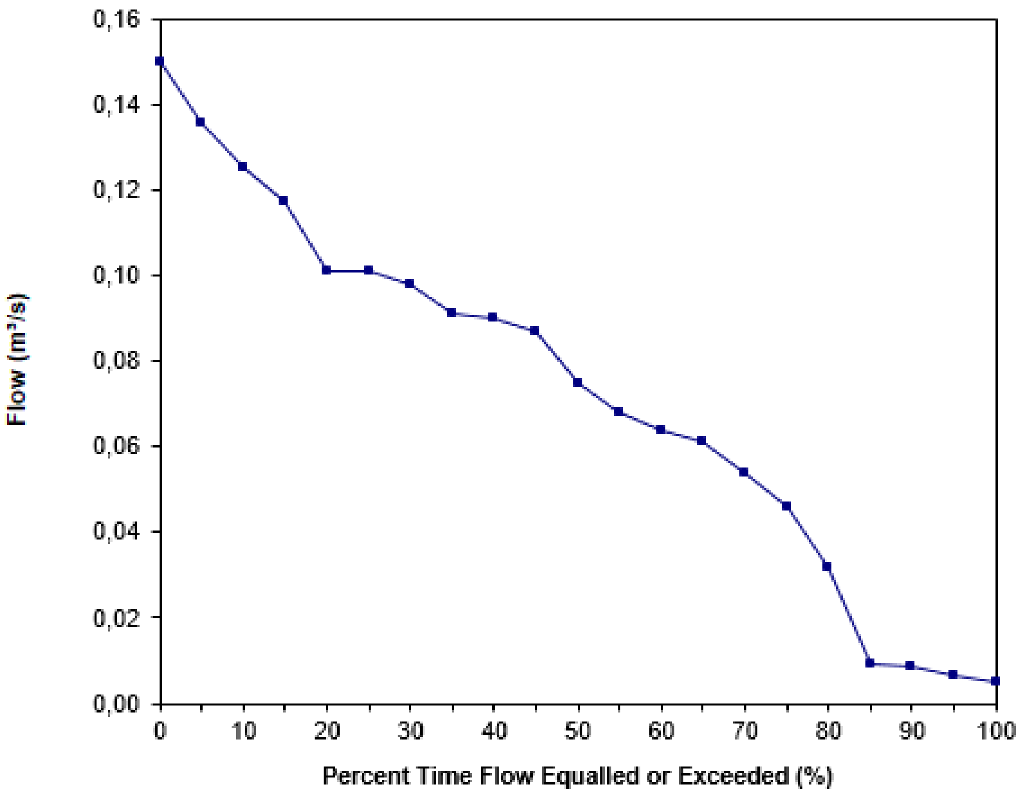


Figure 3.31 Output Flow duration curve.

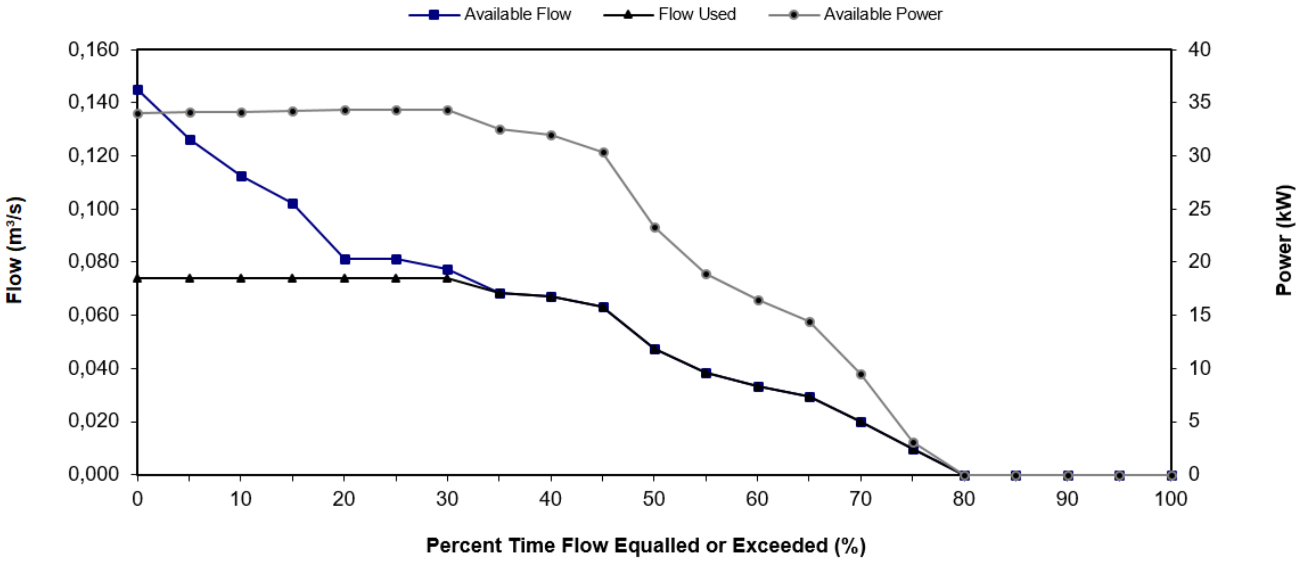
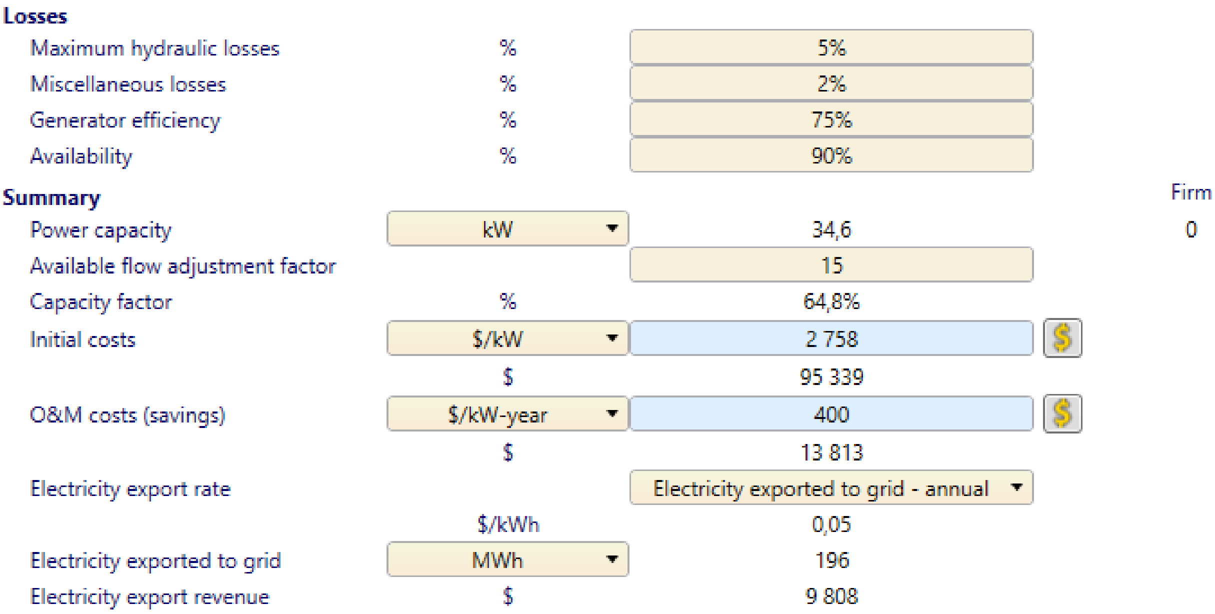


Figure 3.32 Combined Flow duration and Power duration curves.

Figure 3.32 shows the relationship between the available flow (FDC) at the site and the corresponding generated power out. The line representing the available power is determined using the site conditions including the gross head, tailwater effect and residual flow; and the system characteristics such as turbine type, efficiencies and losses. The average flow used is about 0.073 m^3/s and the average power output 34kW. The turbine peak efficiency and the turbine efficiency at design flow are respectively 83.5% and 81.6%. The flow at peak efficiency is 0.05 m^3/s.



Losses			
Maximum hydraulic losses	%	5%	
Miscellaneous losses	%	2%	
Generator efficiency	%	75%	
Availability	%	90%	
Summary			Firm
Power capacity	kW	34,6	0
Available flow adjustment factor		15	
Capacity factor	%	64,8%	
Initial costs	$/kW	2 758	
	$	95 339	
O&M costs (savings)	$/kW-year	400	
	$	13 813	
Electricity export rate		Electricity exported to grid - annual	
	$/kWh	0,05	
Electricity exported to grid	MWh	196	
Electricity export revenue	$	9 808	

Figure 3.33 Output of the Energy model.

The hydro system power capacity (maximum power output of the site) is 34.6kW. The capacity factor is 64.8%. Taking into consideration the electricity export rate and electricity exported to the grid, the annual electricity export revenue is $ 9808.

3.3.2.2. Cost Analysis

The initial cost of the project includes the following tasks:

- organising a feasibility study,
- performing the project development functions,
- finalizing the necessary engineering,
- purchasing and installing the energy equipment,
- implementing energy efficiency measures, construction of the balance of system and costs for any other miscellaneous items

The summary of the cost analysis is given in Table 3.9.

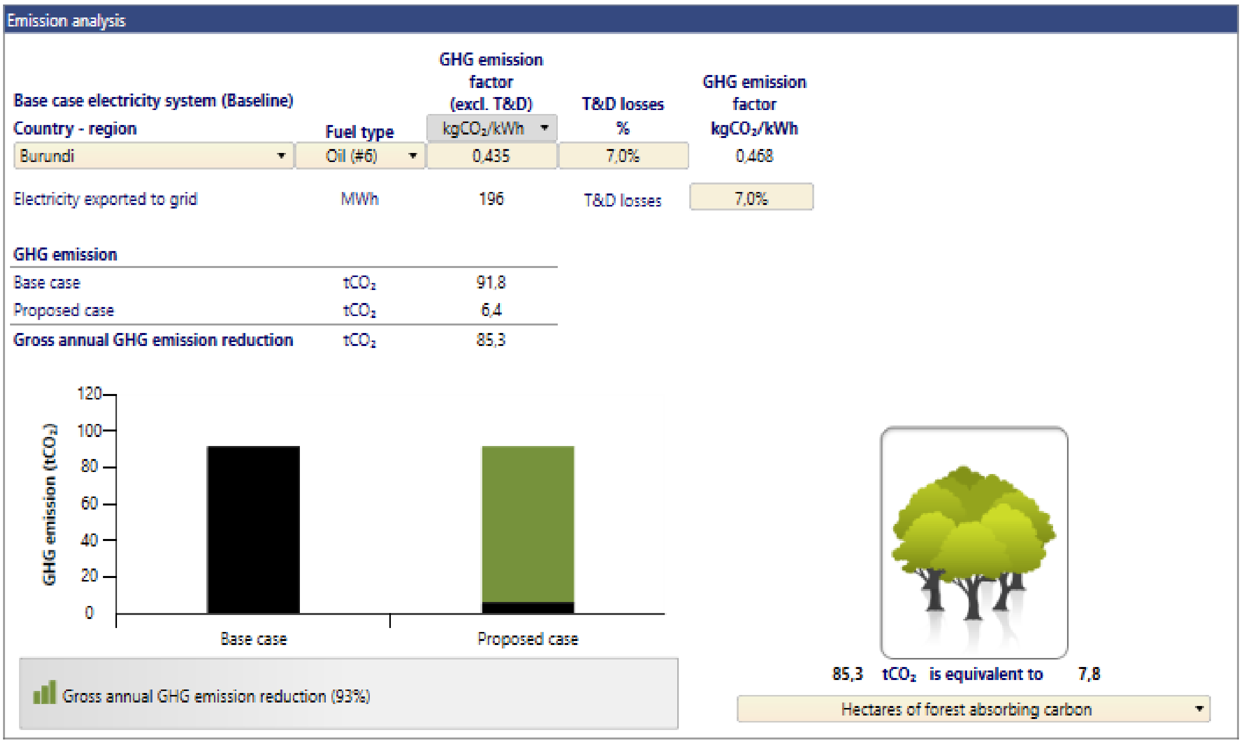
Table 3.9 Summary of the cost analysis

Initial cost	Amount in $	Relative costs
Feasibility study	5000	5.2%
Development	7000	7.3%
Engineering	15000	15.7%
Power system	49284	51.7%
Balance of system and Miscellaneous	19055	17.3%
Total	95339	100 %
Annual Cost		
O&M	16294	
Annual savings	18000	

The power system including power equipment, road construction, transmission line, and power-related energy efficiency measures costs are the largest share (51.7%) of the initial cost. The engineering phase, having a share of 15.7%, includes also the building, mechanical, electrical, and civil design, as well as tenders & contracting, and construction supervision. The development and feasibility study relative costs are respectively 7.3% and 5.2%.

3.3.2.3. Emission Analysis

The Emission Analysis provides the estimation of the greenhouse gas emission reduction potential of the proposed case compare to the base case. For the oil type with 0.435 kgCO_2 and T&D (transmission and distribution) losses of 7%, the GHG emission decrease from 91.8 tCO_2 to 6.4 tCO_2 that is a reduction of 85.3 tCO_2. This is equivalent to 7.8 hectares of forest absorbing carbon.



Emission analysis

Base case electricity system (Baseline) Country - region	Fuel type	GHG emission factor (excl. T&D) kgCO₂/kWh	T&D losses %	GHG emission factor kgCO₂/kWh
Burundi	Oil (#6)	0,435	7,0%	0,468

Electricity exported to grid	MWh	196	T&D losses	7,0%

GHG emission		
Base case	tCO₂	91,8
Proposed case	tCO₂	6,4
Gross annual GHG emission reduction	tCO₂	85,3

Gross annual GHG emission reduction (93%)

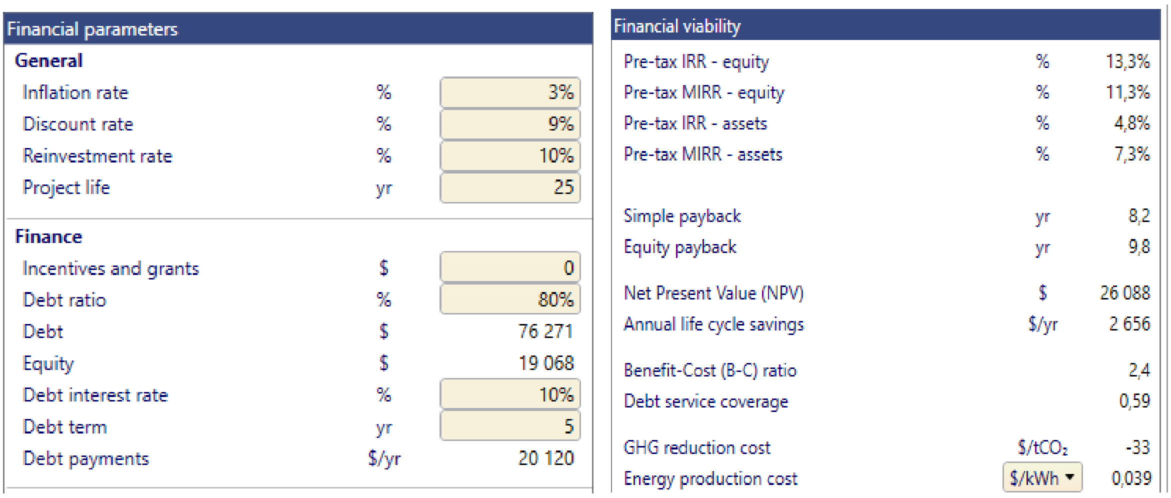
85,3 tCO₂ is equivalent to 7,8

Hectares of forest absorbing carbon

Figure 3.34 Result of the Emission analysis.

3.3.2.4. Financial Analysis

In the Financial Analysis, the financial parameters (discount rate, debt ratio, etc.) are considered as input items. The financial viability output items (IRR, simple payback, NPV, etc.) are then calculated. The financial parameter, annual revenue the cost-saving-revenue are displayed respectively in Figure 3.35 and 3.36.



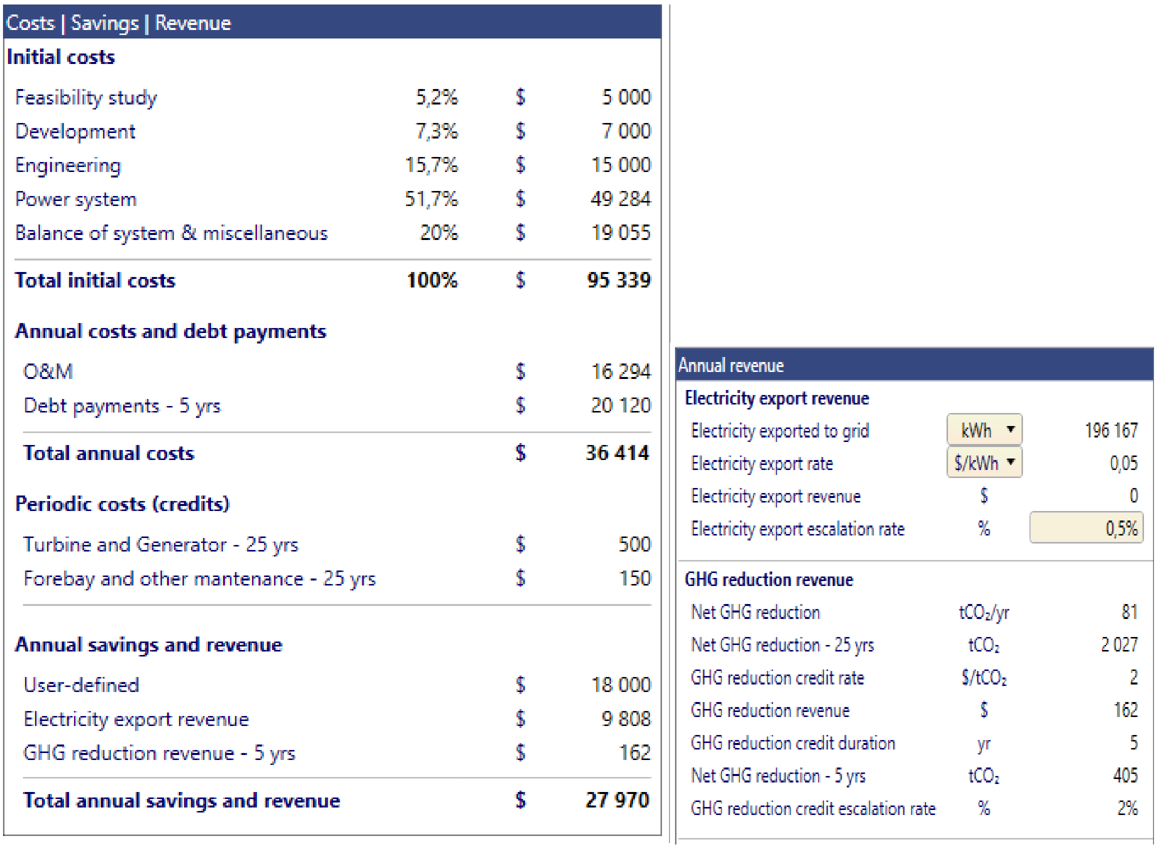
Financial parameters

General		
Inflation rate	%	3%
Discount rate	%	9%
Reinvestment rate	%	10%
Project life	yr	25
Finance		
Incentives and grants	$	0
Debt ratio	%	80%
Debt	$	76 271
Equity	$	19 068
Debt interest rate	%	10%
Debt term	yr	5
Debt payments	$/yr	20 120

Financial viability

Pre-tax IRR - equity	%	13,3%
Pre-tax MIRR - equity	%	11,3%
Pre-tax IRR - assets	%	4,8%
Pre-tax MIRR - assets	%	7,3%
Simple payback	yr	8,2
Equity payback	yr	9,8
Net Present Value (NPV)	$	26 088
Annual life cycle savings	$/yr	2 656
Benefit-Cost (B-C) ratio		2,4
Debt service coverage		0,59
GHG reduction cost	$/tCO₂	-33
Energy production cost	$/kWh	0,039

Figure 3.35 Input financial parameter and the output financial viability.



Costs | Savings | Revenue

Initial costs

Feasibility study	5,2%	$	5 000
Development	7,3%	$	7 000
Engineering	15,7%	$	15 000
Power system	51,7%	$	49 284
Balance of system & miscellaneous	20%	$	19 055
Total initial costs	**100%**	**$**	**95 339**

Annual costs and debt payments

O&M	$	16 294
Debt payments - 5 yrs	$	20 120
Total annual costs	**$**	**36 414**

Periodic costs (credits)

Turbine and Generator - 25 yrs	$	500
Forebay and other mantenance - 25 yrs	$	150

Annual savings and revenue

User-defined	$	18 000
Electricity export revenue	$	9 808
GHG reduction revenue - 5 yrs	$	162
Total annual savings and revenue	**$**	**27 970**

Annual revenue

Electricity export revenue

Electricity exported to grid	kWh ▾	196 167
Electricity export rate	$/kWh ▾	0,05
Electricity export revenue	$	0
Electricity export escalation rate	%	0,5%

GHG reduction revenue

Net GHG reduction	tCO_2/yr	81
Net GHG reduction - 25 yrs	tCO_2	2 027
GHG reduction credit rate	$/$tCO_2$	2
GHG reduction revenue	$	162
GHG reduction credit duration	yr	5
Net GHG reduction - 5 yrs	tCO_2	405
GHG reduction credit escalation rate	%	2%

Figure 3.36 Output of the financial analysis.

The yearly cash flow graphs are plotted in Figure 3.37. The pre-tax is initially negative due to the high equity investment. At a negative cash flow is recorded. In the next 6 years, the cumulative annual savings and revenue overtake all the equity, annual and periodic cost such that the cash flow becomes positive. It is shown on the graph of the cumulative cash flow that a positive cash flow starts at the 10th year of the life cycle of the hydropower project.

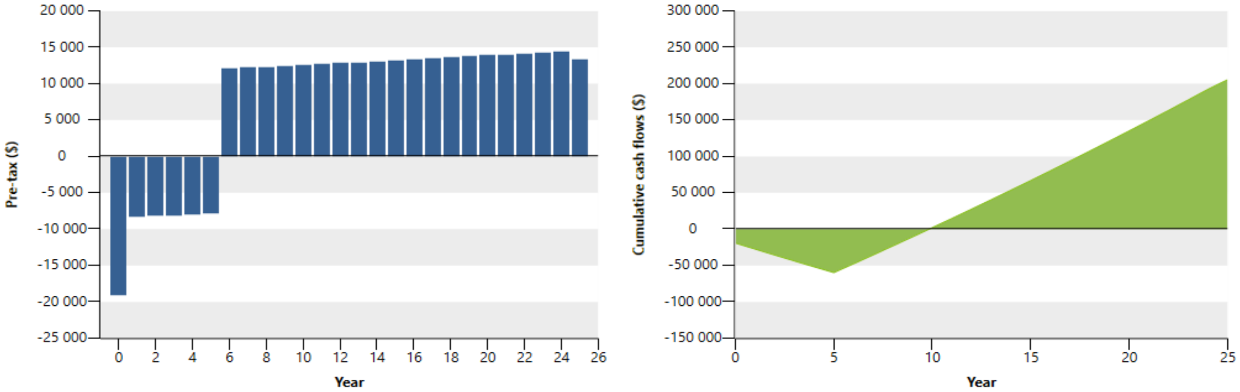


Figure 3.37 Year cash flows over the life time of the project.

3.3.2.5. Sensitivity Analysis

The sensitivity of important financial indicators (Net Present Value, the Energy Production cost and the Equity Payback) in relation to key and financial parameters (initial cost, O&M, debt ratio, debt interest ratio. Table 3.10 gives the parameters which have the greatest impact on the financial indicators.

Table 3.10 Sensitivity analysis.

		Financial Parameters				
		Initial Cost	O&M	Debt ratio	Electricity export rate	Debt interest rate
Financial indicators	Equity payback	★	★	★★		★★★
	Net present Value	★★	★★★		★★★	★
	Pre-tax IRR -equity	★★★	★★	★	★	
	Energy Production cost	★	★			

It is shown in Table 3.10 that the debt ratio and the debt interest rate have a great impact on the equity payback, while for the Net present value it is the O&M and the electricity export rate. The pre-tax IRR –equity and the energy production cost are more sensitive to the initial cost and the O&M.

3.3.2.6. Risk Analysis

The risk analysis is performed for four financial indicators namely the pre-tax IRR - equity, equity payback, NPV and Energy production cost (see Figure 3.38 and 3.39).

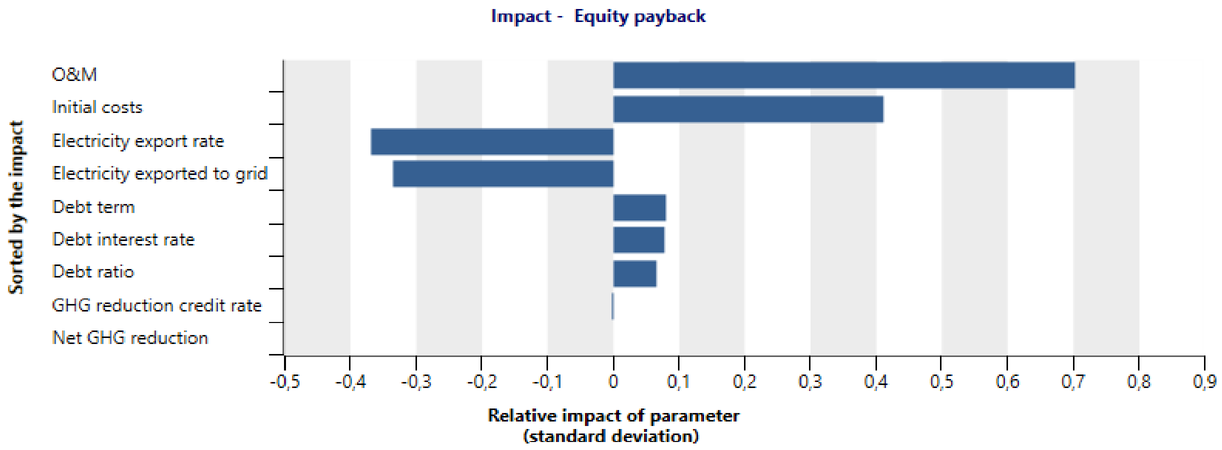


Figure 3.38 Risk Analysis with the selected financial indicators.

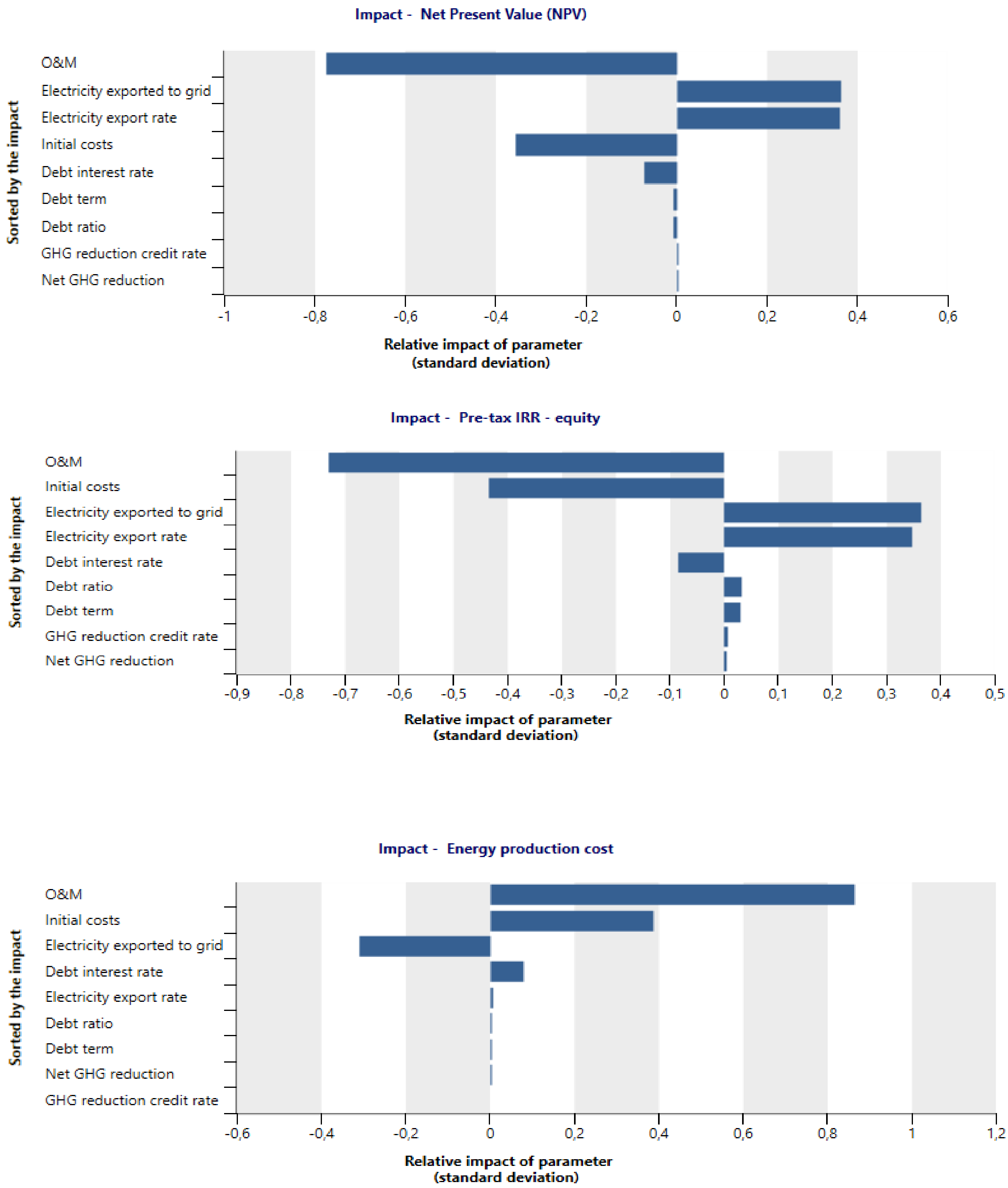


Figure 3.39 Risk Analysis with the selected financial indicators.

The histograms displayed in Figure 3.38 and 3.39 help to assess the relative impact of each of these individual parameters in order to identify the important ones that influence a great variability of the financial indicators. The greatest impact on the financial indicator implies that efforts need to be done as to reduce the uncertainty associated with the financial parameter.

For each parameter, the longer the horizontal bar the greater is the impact of the input parameter on the variability of the financial indicator. The financial parameters which contribute to the most variability of the financial indicator are sorted from the top to the bottom. In addition, the direction of the horizontal bar (positive or negative) provides an indication of the relationship between the financial parameter and the financial indicator. A positive relationship indicates a direct proportion between the financial parameter and the financial indicator. As the indicator increases the financial parameter increase as well. A negative relationship indicates a direct proportion between the financial indicator and the financial parameter. As the parameter increases the financial indicator decreases.

Taking this into account, a clear interpretation of Figure 3.38 and 3.39 can be inferred. For the equity payback, the initial cost and O&M have the highest impact. Moreover, an increase in the electricity export rate and electricity exported to the grid results in the reduction of the equity payback. The impact of the debt term, debt ratio and debt interest ratio are is very significant.

In the case of the NPV, O&M, electricity export rate, electricity exported to the grid and the initial cost have the highest impact. In addition, an increase in the initial cost and O&M results in the reduction of the NPV. In contrary, the greater the electricity export rate and electricity exported to the grid, the higher is the NPV.

Similarly, the higher the initial cost and O&M, the bigger is the electricity production cost. However, an increase in electricity exported to grid results in the diminution of the electricity exported to the grid.

In summary, for the four financial indicators, the initial cost, O&M and electricity export rate are the most important input parameter which has to be considered in order to take further analysis such as the performance analysis. This is due to the high impact which might influence the outcomes of the NPV and/or the equity payback.

3.3.3. Sustainability assessment of the proposed project

This sustainable assessment model used in this section was developed by Bandhari et al. in (Bhandari, Saptalena, & Kusch, 2018) in order to determine the overall score of each sustainability dimensions corresponding to the MHP project. As recommended by the IHA’s Hydropower Sustainability Assessment Protocol report, the scoring of the respective indicator is from 1 to 5. The gradation is divided into the following level in the Hydropower Sustainability Assessment Protocol (IHA, 2018):

- Level 5: Suitable, adequate and effective assessment with no significant opportunities for improvement.
- Level 4: Suitable, adequate and effective assessment with only a few minor gaps.
- Level 3: Suitable adequate and effective assessment with no significant gaps.
- Level 2: A significant gap in assessment processes relative to basic good practice.
- Level 1: Significant gaps in assessment processes relative to basic good practice.

The indicators are regrouped into a theme. The themes are also regrouped into dimensions. The indicators and themes used here were adapted from (Bhandari et al., 2018). There are four sustainability assessment dimensions related to each specific subject:

- Economic dimension
- Social dimension
- Technical dimension
- Environmental dimension.

The themes are categorized into each dimension in Table 3.11 (adapted from (Bhandari et al., 2018)).

Table 3.11 Sustainability assessment Dimensions.

Sustainability Assessment			
Technical	**Economical**	**Environmental**	**Social**
Electricity use	Investment	Legislation	Community involvement
Reliability	Community contribution	Aquatic ecosystem	Affordability
Efficiency	Employment remuneration	Land use	Accessibility
Technology	Project Benefit	Climate change and GHG emission	Communication

The score for the technical, economic, environmental and social sustainability dimension are respectively given in the following tables.

Table 3.12 Scoring of Technical Dimension.

Themes	Weighting of themes within dimension	Indicators	Score	theme score
Electricity use	0.3	Serviceability performance of energy supply	4	3.5
		Design of the gird	3	
Reliability	0.2	Maintenance program	2	3
		Quality of power	4	
Efficiency	0.15	capacity factor	3	3
		grid & machinery efficiency/expansion possibility	3	
Technology	0.35	Program of asset upgrades	2	3
		Replication of program	4	
Technical dimension score				3.15

Table 3.13 Scoring of Economic Dimensions.

Themes	Weighting of themes within dimension	Indicators	Score	theme score
Investment	0.35	Grant of funding	4	3
		payback period	3	
		repair and maintenance	2	
Community contribution	0.15	Villager contribution	4	4
		Activities on the MHP	4	
Employee remuneration	0.2	Salaries	4	4
Project benefit	0.3	General income	3	3.3
		Employment opportunity	4	
		New income activities	4	
Economic dimension score				3.44

Table 3.14 Scoring of Environmental Dimension.

Themes	Weighting of themes within dimension	Indicators	Score	theme score
Legislation	0.15	Compliance with legislation	4	4
Aquatic ecosystem	0.25	interference with fish population	3	3
		share of water taken from river	3	
Climate change	0.35	Fossil fuel avoided	4	4
Land use	0.35	Erosion	3	3.5
		Sedimentation	4	
Environmental dimension score				3.975

Table 3.15 Scoring of Social Dimension.

Themes	Weighting of themes within dimension	Indicators	Score	theme score
Commitment involvement	0.35	Training of community members and local operators	3	3.3
		Equality	4	
		Sense of ownership, self-governance	4	
Affordability	0.2	income spent on electricity	4	4
Accessibility	0.2	Grid access	4	3.5
		ease of grid connection	3	
Communication	0.25	Electricity use for communication purposes	4	3.5
		Computer usage	3	
Social dimension score				3.53

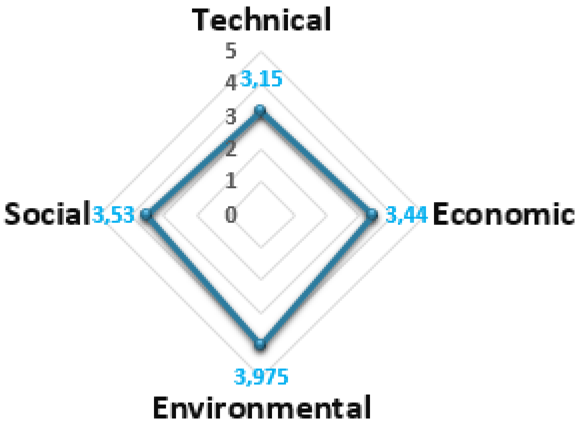


Figure 3.40. Scoring of the four sustainability assessment dimensions.

From the result found in this previous table, taking into account technical economic, environmental, and social sustainability dimensions, it has been revealed that the environmental dimension displays the best score of 3.975, followed by social (3.53), economic (3.44), and technical dimensions (3.15). If the technical and the social dimension are chosen to have a weight of 30% (highest priority) and the environmental and economic dimension 20%, the final score of the project is 3.487.

3.3.4. Ownership and operational option

In the case of MHP schemes, four main ownership options can be considered:

- Community Ownership: Consumers within the community, with the help of generous funding, manage to build the system and all incomes go back to the community.
- Entrepreneur Ownership: One or many investors pay for the scheme and receive the all the profit from sales of power.
- Government Ownership: The scheme is state-owned and the net income goes to the municipality.
- Cooperative Ownership: An association of few consumers (with a compulsory membership fee to join) own the system and an administrative committee elected by the whole cooperative is in charge of all the activities monitoring.

Generally, private forms of ownership such as entrepreneurship ownership are more often financially and technically sustainable. However, they tend to focus on generating more incomes and neglect the poor population. In contrary, municipal schemes such as community ownership are less financially sustainable and tend to neglect the maintenance of the scheme, therefore, are less technically sustainable. But they tend to cover the whole community.

The cooperative ownership has been chosen as a suitable option in remote and rural communities. This kind of ownership is the more convenient if we take into consideration the financial constraint and the low percentage of literate in rural communities. The scheme will be owned by a few number citizens which choose to join the cooperative and an administrative committee will be monitoring the finances and maintenances of MHP system.

In addition to the administrative committee which is responsible to all the decision-making process, a technical team of four technicians will be in charge of the operation and maintenance of the MHP system. Together with the technical team, a financial officer with three assistants will be responsible of collecting all the incomes from the consumers. An audit consultant should be hired every three months in order to ensure enough transparency in the execution of all the activities.

3.4. Key findings and Discussions

3.4.1 Micro hydropower system

In this study, the first step was to identify a suitable site for an easy and rapid implementation of a MHP system. During the field investigation, many reliable sites was eligible for a MHP project. However, the other target was to identify site which does not need huge investment cost for the purpose of making the project economically feasible for a developing country like Burundi. Knowing that a hydropower system requires two parameters: sufficient flow rate and available pressure head. Therefore, a good site of MHP schemes correspond to a low head and high flow rate or a high head and low flow rate. The second case, which does not necessitate high financial cost, was considered for the identification of the suitable site. Hence, the present study aimed to explore hydropower potential characterized by relatively high pressure head and low flow rate.

The result of field investigation shows that the western region of Burundi near the Tanganyika Lake presents considerable sites with a reliable potential of a MHP scheme.

The site for this study was selected in the Central West of Burundi, in the province of Burundi more specifically in Muhuta Commune. The characteristic of the site is an available gross head of 84m and flow rate of 0.0736 m^3/s. The approximated power output under the site condition calculated was 36.5 kW.

The suggested MHP system aimed to supply Gitaza, a near small centre which does not have access to the national grid. The estimated annual energy consumption was approximated at 179.5 MWh. The output power of the proposed system has been found to cover this electricity demand.

The site condition suggested, during the turbine selection, that a Pelton turbine was to be used as the best choice of the hydraulic turbine. The specific speed of 24.67 also confirmed the choice of a Pelton turbine. The design computation of Pelton turbine has suggested a turbine of 17 buckets, 34cm of wheel diameter and 72 mm of jet diameter. Simulations obtained using SolidWorks revealed that the main energy was transmitted in the radial axis (Z-axis) of the turbine which proved the good performance of the turbine.

In addition to the design of the Pelton turbine, the design of the civil structure was developed. Following the parametrization of each component, the major component of the civil structure was found to be the penstock due to its relatively long length evaluated to 380m. The penstock of 208 cm of inner diameter and 2.4 mm of thickness.

A synchronous generator using a brushless type of exciter and an Automatic Voltage Regulator as regulator was suggested to be used for the MHP system.

3.4.2. Feasibility of study of the MHP

The feasibility study of the proposed system was developed using the Retscreen software. The first step was to assess the hydropower energy potential of the selected site. With no available data of the flow rate on the river where the MHP is to be implemented, a simple approximation of the available flow rate was achieved using the rainfall data, the seepage and an approximated evapotranspiration of the chosen area. Hence, the flow duration curve which is an input data in the RETscreen software was derived.

The feasibility analysis was developed in five major steps.

Firstly, the Energy model has revealed a turbine peak efficiency of 83.5% and a turbine efficiency at design flow of 81.6%. The hydro system power capacity calculated by the software was 34.6kW with a capacity factor of 64.8%. The annual electricity export revenue was found to be $9,808.

Secondly, the Cost Analysis has given an approximation of a feasibility study cost of $5,000, development cost ($7,000), engineering cost ($15,000), power system cost ($49,284) and balance of system ($19,055). The total cost was evaluated at $95339. The annual cost was approximated to $16,294 and the annual savings of $18,000.

Thirdly, the emission analysis has provided an estimation of a reduction of 85.3 tCO_2 equivalents to 7.8 hectares of absorbing carbon.

Fourthly, the financial analysis has predicted a simple payback of 8.2 years and an equity payback of 9.8 years if a project life of 25 years. The NPV was approximated to $26,088 and the annual life cycle savings to $2,656. The energy production cost per kWh was evaluated at $ 0.039. The cumulative annual savings and revenue have shown a positive cash flow in 10 years. Therefore, this project is assumed to be financially viable.

Lastly, the O&M and initial cost were found to be the two most important parameters which have a significant impact on the financial indicator such as the NPV, equity payback and energy production cost in the sensitivity and risk analysis.

A sustainability assessment has been achieved on the proposed project using four sustainability dimensions namely the economic, environmental, social, and technic dimension. It has been revealed that the overall score of the project is 3.487 with the environmental dimension having the best score of 3.975. The sustainability assessment score found infers that the proposed project is relatively sustainable.

Assuming the financial situation of the selected centre Gitaza, the cooperative ownership was chosen to be the most suitable type of ownership to be applied.

3.4.3. Advantages and Disadvantages of the proposed MHP system

3.4.3.1. Advantages of the MHP system

The suggested MHP system has many advantages compared to other decentralized systems. These advantages are due to mainly the nature of the energy source, the way of energy conversion and the small interaction of the system with the environment.

First of all, The MHP system is an efficient system. The system takes a small amount of water from the river which goes back to the river after going through the MHP scheme. Moreover, the overall efficiency of the system is 61.2% which is reasonably very high compared to other energy systems such as diesel generators or solar PV systems.

Then, the MHP system is a reliable system if we consider the fact that the flow is available all along the day and throughout the whole year. This represents a huge advantage for a small scale system knowing the intermittencies related to other decentralized energy systems such as wind and solar PV systems.

Next, the MHP is a run-of-river system which implies that there is no impoundment required. The construction of the civil structure does not include large dams but a small diversion weir. Therefore, the financial resource to build such a system reduce considerably compare to other hydropower system. In addition to this, there is no or very small environmental impact as a result of the absence of dams and reservoirs.

Last, for a developing country like Burundi, the low initial and maintenance cost of the system represents an important driver for a rapid replication of similar system in all the remote areas inasmuch as there is many MHP potential site in the rural area.

3.4.3.2. Disadvantages of the MHP system

Firstly, the limited amount of available flow rate does not allow a high extension of the system to generate more power. Consequently, an increase in electricity demand would require a construction of another MHP system at a close distance.

Secondly, many MHP potential sites are characterized by a very small discharge during the dry season which may affect the output power in the case of an implementation of a similar system.

The development of MHP systems need specific site condition which should be assessed at the beginning of the project to accomplish a sustainable system such as the technical, social and economic assessment. These specifications might change from one site to another which makes the MHP project more complex.

Chapter 4. CONCLUSION AND RECOMMENDATION

The aim of this research was to develop a simple, viable and reliable MHP system to electrify a remote center located in a rural area in Burundi. Therefore, the study was undertaken to design the mechanical and civil component of the MHP. The guideline of the design construction was to keep the system technically and economically achievable under the constraints of the selected site. The second aim of this study was to assess the feasibility of this proposed system in order to ensure the sustainability of the project. The purpose of the study was to contribute to the enhancement of the electricity access in rural areas of Burundi.

This study has identified several MHP potential site mostly in the western region of Burundi and a selected site was chosen in the central region in Rumonge Province more precisely in Muhuta. The results of this field investigation have shown that the site condition was characterized by a gross head of 84m and 0.0736m^3/s of flow rate. The output power of 36.5 kW can be extracted at the site. From the turbine selection, the Pelton turbine has emerged as the suitable turbine to be used under similar condition.

The results of this feasibility study indicate that the MHP project is viable with an equity payback of 9.8 years. The O&M and initial cost are the important parameters which should be more investigated due to their high impact on the financial indicator such as the NPV, equity payback and energy production cost. The contribution of this study has been to confirm that a decentralized energy system such as the MHP system is technically feasible and can be easily implemented in rural areas where there is no access to the national grid using low cost compare to other alternatives.

Besides, some limitations need to be acknowledged. The study did not take into account the design of transmission of the generated power and a detailed specification of the generator including the regulator of the MHP system. Therefore, a further study could assess these two components. It would be also interesting to investigate the quality of the generated power on an isolated grid

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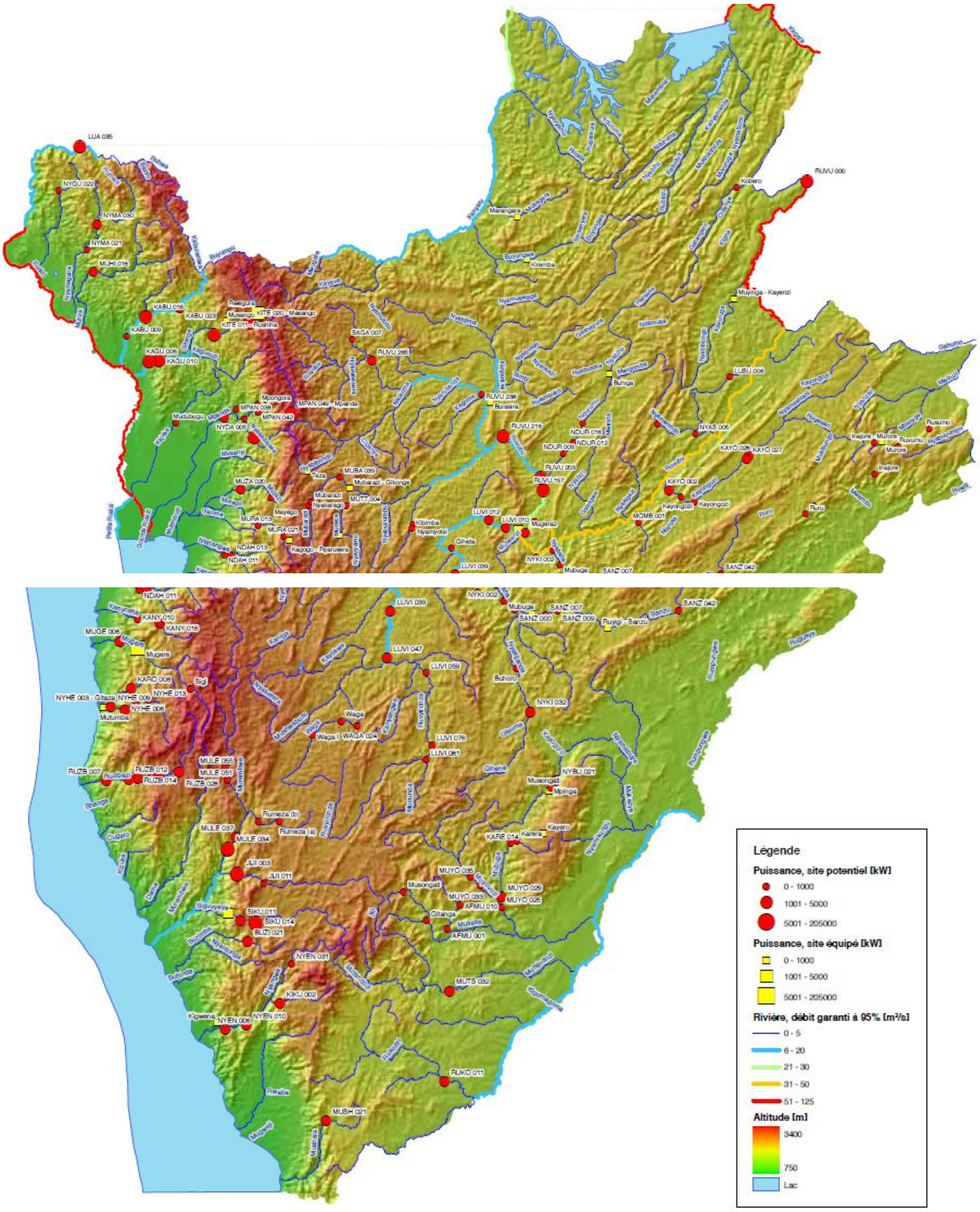
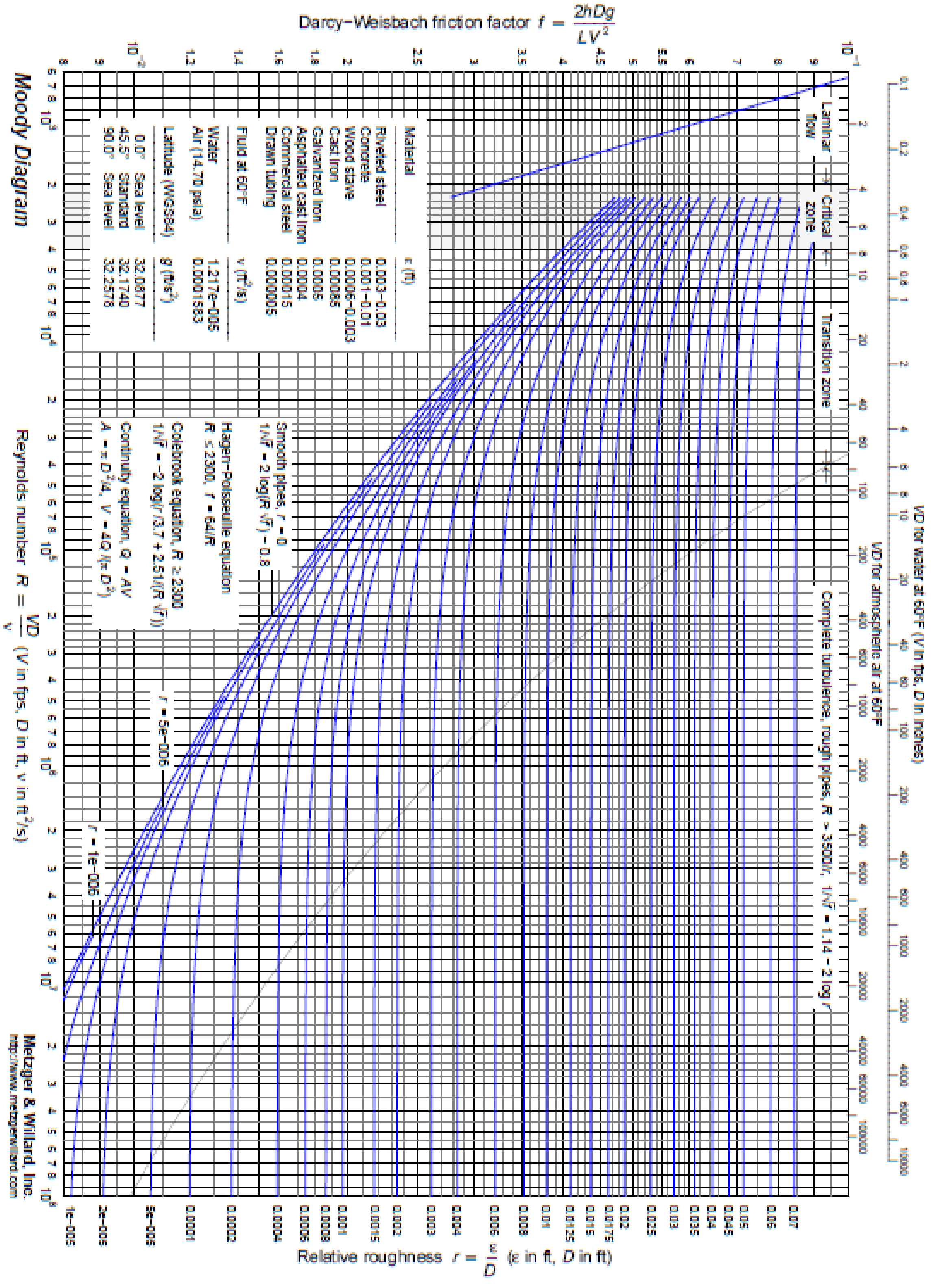
APPENDIX A: Small Hydropotential of Burundi



APPENDIX B: Moody Diagram



APPENDIX C: Rainfall data

Site	Year	Month	rainfall(mm)	Number of days	Average temperature
MUHUTA	2017	12	233	15	28
MUHUTA	2017	11	273,5	19	28
MUHUTA	2017	10	143	14	28
MUHUTA	2017	9	140,5	9	27
MUHUTA	2017	8	60,5	4	30
MUHUTA	2017	7	7,5	2	29
MUHUTA	2017	6	21,5	3	29
MUHUTA	2017	5	115,6	11	29
MUHUTA	2017	4	157,2	17	29
MUHUTA	2017	3	222,1	22	30
MUHUTA	2017	2	289,1	19	30
MUHUTA	2017	1	277,2	19	31

APPENDIX D: NASA data of the temperature and insolation

year	month	date	Tmax	Tmin	Tmean	insolation (kwh/m2/day)
2017	1	1	25,3	18,44	21,87	2,53
2017	1	2	23,51	18,05	20,78	4,38
2017	1	3	25,31	17,64	21,475	5,57
2017	1	4	27,54	17,86	22,7	5,69
2017	1	5	28,01	18,89	23,45	5,74
2017	1	6	27,62	19,26	23,44	6,17
2017	1	7	27,22	18,96	23,09	6,11
2017	1	8	20,78	18,89	19,835	4,04
2017	1	9	26,39	17,84	22,115	5,37
2017	1	10	21,56	18,65	20,105	3,71
2017	1	11	24,57	18,42	21,495	4,34
2017	1	12	27,35	18,41	22,88	6,67
2017	1	13	25,51	17,88	21,695	2,73
2017	1	14	24,07	18,6	21,335	3,35
2017	1	15	23,67	18,06	20,865	5,47
2017	1	16	23,76	18,73	21,245	5,12
2017	1	17	26,92	17,41	22,165	5,1
2017	1	18	27,55	19,06	23,305	3
2017	1	19	26,46	18,51	22,485	3,89
2017	1	20	25,68	18,44	22,06	2,8
2017	1	21	24,17	18,55	21,36	6,73
2017	1	22	25,69	17,37	21,53	3,32
2017	1	23	26,48	18,36	22,42	5,59
2017	1	24	27,66	19,47	23,565	6,55
2017	1	25	27,39	18,83	23,11	3,5
2017	1	26	24	19,13	21,565	3,92
2017	1	27	23,99	18,18	21,085	6,64
2017	1	28	24,08	17,67	20,875	5,22
2017	1	29	23,8	17,69	20,745	5,62
2017	1	30	24	17,85	20,925	5,07
2017	1	31	25,39	18,48	21,935	3,83
2017	2	1	24,77	18,15	21,46	5,98
2017	2	2	25,45	18,15	21,8	4,13
2017	2	3	21,34	17,92	19,63	3,27
2017	2	4	26,13	17,15	21,64	6,02
2017	2	5	26,03	18,34	22,185	5,7
2017	2	6	27,13	18,22	22,675	5,16
2017	2	7	26,95	18,4	22,675	6,29
2017	2	8	26,53	19,86	23,195	5,25
2017	2	9	23,58	19,05	21,315	3,68
2017	2	10	27,6	19,12	23,36	5,72
2017	2	11	26,3	19,08	22,69	3,52
2017	2	12	24,61	19,37	21,99	5,35
2017	2	13	26,97	18,39	22,68	6,41
2017	2	14	27,86	19,36	23,61	6,56
2017	2	15	27,24	19,85	23,545	5,95
2017	2	16	24,18	19,32	21,75	4
2017	2	17	21,89	17,78	19,835	1,78
2017	2	18	22,67	16,81	19,74	4,61
2017	2	19	22,91	18,04	20,475	3,26
2017	2	20	22,34	17,77	20,055	4,73
2017	2	21	26,54	16,57	21,555	2,66
2017	2	22	22,62	17,8	20,21	5,15
2017	2	23	26	17,3	21,65	3,98
2017	2	24	22,49	18,38	20,435	3,71
2017	2	25	23,97	18,29	21,13	4,52
2017	2	26	23,38	17,97	20,675	4,73
2017	2	27	23,4	17,83	20,615	2,59
2017	2	28	24,02	18,58	21,3	4,97

APPENDIX E: Budget report

No	ITEM	Description	Cost in local currency	COST in USD
1	International Transport	Flight Fees Alger-Kigali, Kigali-Alger	150330	1380
2	Local Transport	Transport during Internship	800000	432
		Excursion for field Investigation	900000	487
		Data collection	700000	378
4	Research Expenditures, Equipment, Materials and tools	Printing and Photocopies (including bindings)	315000	170
		Hammer	45000	24
		Wire (or rope)	16000	9
		Nails	12000	6
		Measuring tape	12000	6
		Nail puller	20000	11
5	Communication and Internet Subscription	Credit	180000	97
	TOTAL			3000

The table above shows the detail description of how the research grant has been used during the period of internship and data collection. The largest share of the financial resource used is in the international transport and the local transport (46% and 43%). The remaining financial resource has been used for the Research, Equipment, Materials and the Communication and Internet Subscription.