CRITERIA DEVELOPMENT FOR THE DATA SELECTION PROCESS TO COMPILE THE ZAMBIAN HYDROPOWER ATLAS

FRANK MUDENDA

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

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DISSERTATION SUMMARY

CRITERIA DEVELOPMENT FOR THE DATA SELECTION PROCESS TO COMPILE THE ZAMBIAN HYDROPOWER ATLAS

FRANK MUDENDA

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Department: Biochemistry, Genetics & Microbiology / Civil Engineering (Joint)

University: University of Pretoria

Degree: Master of Science (Water Resource Management)

Hydropower is a vital source of renewable energy which provides electricity around the world. Zambia's electricity deficit which is characterized by unending daily power cuts has continuously been increasing in recent years. As of 2019, over 1.9 million households (57.6%) had no access to electricity. Furthermore, over 96% of the rural population are still without electricity. This calls for attention and sustainable solutions to electrification, especially the rural population as also reinforced by goal number 7 of the sustainable development goals. Such solutions include the development of a Zambian Hydropower Atlas which can showcase the country's hydropower potential including small-scale technologies which can boost Zambia's electrification by providing electricity to isolated rural households, streets, clinics, schools or industries, buildings and within the existing water infrastructure.

Zambia has not developed a hydropower atlas and therefore, its hydropower potential has not been quantified in detail. Thus, there is a need to develop a hydropower atlas for Zambia, however, there is little technical information and literature regarding the evaluation of hydropower potential and hydropower at existing water infrastructure in Zambia. This study attempted to address this problem by developing data selection criteria and evaluation frameworks to be followed in the development of the Zambia hydropower atlas. The data selection criteria and evaluation frameworks show a step-by-step process to be followed in the evaluation of hydropower potential and the criteria to be met for a site to be included in the Zambian hydropower atlas. Criteria development as a first step was also done by other researchers in the development of other existing hydropower atlases such as the Tanzanian, South African and Madagascar Hydropower Atlases.

The development process of the data selection criteria and evaluation frameworks included conducting a detailed literature review on existing hydropower atlases, existing data selection criteria and the evaluation of hydropower potential, etc. The methodology also included the use of an online Google Forms questionnaire as a tool for the further development of the Zambian hydropower atlas. Institutions in charge of water infrastructures such as Lusaka Water and Sewerage Company and the Mulonga Water and Sewerage Company were visited to obtain data and reports which were used in the development of the data selection criteria. Through these steps, the data and formulas required to evaluate hydropower potential were identified and evaluated to develop the evaluation process in the Zambian context.

This study considered six types of hydropower namely: 1) Run-of-river hydropower, 2) Hydropower generated at dams 3) Hydropower generated from Wastewater Treatment Works (WWTWs), 4) Weir hydropower, 5) Hydrokinetic Hydropower generated from Canals, and 6) Conduit Hydropower generated in Bulk Water Supply Systems. Therefore, six evaluation frameworks were developed in this study. The frameworks were evaluated by applying each framework to a selected case study to show the step-by-step of the frameworks. It has been recommended that the developed evaluation frameworks should be considered only to give a first-order evaluation of hydropower potential. Future research should consider validating the frameworks and updating them.

ABSTRACT

Title: CRITERIA DEVELOPMENT FOR THE DATA SELECTION PROCESS TO COMPILE THE ZAMBIAN HYDROPOWER ATLAS

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The data selection criteria and evaluation frameworks for the evaluation of hydropower potential sites to be included in the Zambian Hydropower Atlas were developed in this study. These were developed for six types of hydropower namely: i) Run-of-river hydropower, ii) Hydropower generated at dams iii) Hydropower generated from Wastewater Treatment Works (WWTWs), iv) Weir hydropower, v) Hydrokinetic Hydropower generated from Canals, and vi) Conduit Hydropower generated in Bulk Water Supply Systems. The frameworks were developed from a detailed literature review and data collection process that was conducted. The selection criteria and evaluation frameworks were applied to selected case studies to show the inclusion or exclusion of some potential sites in the Zambian Hydropower Atlas. It was observed that the development of the data evaluation frameworks is limited by data availability. It was recommended that the developed evaluation frameworks should only be considered to give a first-order evaluation of hydropower potential.

DECLARATION

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- The work contained in this thesis is my own original work;
- I did not refer to work of current or previous students, lecture notes, handbooks, or any other study material without proper referencing;
- Where other people's work has been used this has been properly acknowledged and referenced;
- I have not allowed anyone to copy any part of my dissertation;
- I have not previously in its entirety or in part submitted this dissertation at any university for a degree.

DISCLAIMER:

The work presented in this report is that of the student alone. Students were encouraged to take ownership of their projects and to develop and execute their experiments with limited guidance and assistance. The content of the research does not necessarily represent the views of the supervisor or any staff member of the University of Pretoria, Department of Civil Engineering, and the Department of Biochemistry, Genetics & Microbiology. The supervisor did not read or edit the final report and is not responsible for any technical inaccuracies, statements, or errors. The conclusions and recommendations given in the report are also not necessarily that of the supervisor, sponsors or companies involved in the research.

Frank Mudenda

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ABBREVIATIONS

AC	Alternating Current
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BPC	Botswana Power Corporation
BWSDSs	Bulk Water Supply and Distribution Systems
CEC	Copperbelt Energy Corporation
DEM	Digital Elevation Model
DWRD	Department of Water Resources Development
DWSS	Department of Water Supply and Sanitation
ECOWAS	Economic Community of West African States
ERB	Energy Regulation Board
ELC	Electrical Load Controllers
FDC	Flow Duration Curve
FOSS	Free Open-Source Software
GHG	Greenhouse Gases
GIS	Geographic Information System
GRZ	Government of Zambia
HAZ	HydroAtlas of Zambia
HFO	Heavy Fuel Oil
kW	Kilowatts
kWh	Kilowatt hours
LCOE	Levelized Cost of Energy
LWSC	Lusaka Water and Sewerage Company
MoA	Ministry of Agriculture
MoE	Ministry of Energy
MW	Megawatts
NGOs	Non-Government Organizations
OPPPI	Office for Promoting Private Power Investments
PACRA	Patents and Companies Registration Agency
PAT	Pump-as-Turbine
PRV	Pressure Reducing Value
QGIS	Quantum Geographic Information System
REA	Rural Electrification Authority

SAPP	Southern African Power Tool
STRM	Shuttle Radar Topographic Mission
USD	United States of America Dollars
UNZA	University of Zambia
UP	University of Pretoria
VAT	Value Added Tax
WARMA	Water Resources Management Agency
WSS	Water Supply and Sanitation
WTWs	Water Treatment Works
WWF	World Wide Fund
WWTWs	Wastewater Treatment Works
ZEMA	Zambia Environmental Management Agency
ZDGC	Zambian Distribution Grid Code
ZHA	Zambian Hydropower Atlas
ZMD	Zambia Meteorological Department
ZMW	Zambian Kwacha
ZRA	Zambezi River Authority

1 INTRODUCTION

1.1 BACKGROUND

Hydropower is a vital source of renewable energy which provides electricity around the world. It became a source of electricity in the late 19th century, a few decades after the British-American Engineer James Francis developed the first modern water turbine (Nunez, 2019). Before that, more than 2,000 years ago, hydropower was used as a source of mechanical energy by the Greeks for grinding wheat into flour using water wheels. In the 18th century, hydropower was used extensively for the milling of grain and pumping of irrigation water. Before hydropower, Zambia's small energy requirements were largely supplied by thermal power plants but with the development of the mining industry, the first 18.4 kW hydropower plant was developed in Mulungushi to supply the Zinc-Lead mining complex in Kabwe between 1924 and 1926 (Mihalyi, 1977). Currently, 80.5% of the country's electricity requirements are supplied by hydropower plants which are managed by ZESCO (ERB, 2020).

Electricity plays a vital role in the Gross Domestic Product (GDP) of Zambia, however, the country's electricity deficit which is characterized by unending daily power cuts has continuously been increasing in recent years. With the nation's access to electricity currently averaging at 31 % in total, of which 67 % is of the urban and 4 % is of the rural population, the government still seeks to improve the supply-demand balance which has challenges. Through the vision 2030, it targets to increase the accessibility to 90 % and 51 % in the urban and rural population respectively (USAID, 2018). With the signing of the Paris Agreement on climate change during the United Nations Treaty signing on 20th September 2016, by the President of Zambia, the government committed itself to focus on scaling up the use of renewable energy and energy efficiency (GRZ, 2016). Renewable energy resources include biomass, biogas, solar radiation, wind power, and small hydropower schemes (Department of Energy, 2017).

Previous studies conducted by JICA (2009) in Zambia indicated that the country has the potential of generating about 6,000 MW of hydropower from the river systems, however, only 2,398.5 MW has been tapped largely from a few large hydroelectric power stations and only 0.7 % from small scale hydropower plants (ERB, 2020). Small scale hydropower plants can boost the country's electrification by providing electricity to isolated rural households, streets, clinics, schools or industries, and buildings. Existing facilities like weirs, barrages, canals, waterfalls, dams, or pipelines, can be optimized by installing small turbines for electricity generation (Kumar, et al., 2011). These small installations can generate power ranging from pico (<20 kW), micro (up to 100 kW), to mini (up to 1 MW), to possibly supply a school or clinic, a cultural village centre, or even a whole community (Klunne, 2009). Therefore, it is vital that various potential sources of small-scale hydropower potential are assessed. The identified potential sources and sites could be compiled and added to a hydropower atlas. A hydropower atlas is a tool that is used to showcase a region or country's hydropower potential to the local stakeholders including the private sector, financial sector, and government entities. Furthermore, the hydropower atlas makes aware of the opportunities that small-scale hydropower technologies bring, and the efforts required to get this technology to be successfully implemented.

1.2 PROBLEM STATEMENT

The identification, quantification, and proposing of potential sites for hydropower have many critical roles in the realization of socio-economic development in the entire Southern African region including Zambia. One such role is to provide hydropower to help the countries to meet their growing electricity demand. Zambia has not quantified in detail the hydropower potential and the small hydropower potential is completely unknown. Therefore, there is a need to develop a hydropower atlas that will showcase and quantify the hydropower potential in the country. The first step in this process is the development of the data selection criteria and evaluation frameworks that could be followed in the inclusion of hydropower potential sites in the Zambian Hydropower Atlas.

1.3 HYPOTHESIS

It has been hypothesised that depending on the available data on existing water infrastructure in Zambia, the data selection criteria and evaluation frameworks for hydropower potential could be developed. The developed criteria and evaluation frameworks could provide preliminary guidance in the evaluation of hydropower potential sites that could be included in a Zambian Hydropower Atlas.

1.4 OBJECTIVES OF THE STUDY

The objective of the study is to develop the criteria for the selection process of hydropower potential sites to be included in the Zambian Hydropower Atlas.

The specific objectives of this study are as follows:

- To determine the data required for evaluating the hydropower potential.
- To identify the various available sources of the required data.
- To collect the required data from the various identified sources to ensure easy accessibility of the data for the further development of the Zambian Hydropower Atlas.
- To develop frameworks and criteria to which a specific water infrastructure or river scheme should conform to, to be included in the atlas.
- To evaluate the frameworks and criteria developed for each type of hydropower.

1.5 SCOPE OF THE STUDY

This study entails the development of criteria used to determine the inclusion or exclusion of certain water infrastructure and rivers as potential sites in the Zambian Hydropower Atlas. This implies that hydropower potential existing in rivers, water supply systems, weirs, and dams will be considered during the study.

The following hydropower types will be included in the frameworks to be developed:

- Run-of-river hydropower,
- Hydropower generated at dams,
- Hydropower generated from Wastewater Treatment Works (WWTWs),
- Weir hydropower,
- Hydrokinetic hydropower generated from Canals,
- Conduit hydropower generated in Bulk Water Supply Systems.

Case studies of hydropower atlases of other countries and existing hydropower installations in Zambia will be used during this study to obtain the relevant literature to assist with the development of the criteria.

1.6 METHODOLOGY

The methodology followed in this study is outlined below. This methodology outlines the activities that were done in the development of the data selection criteria and evaluation frameworks:

- A detailed literature review was conducted on the theoretical perspective of hydropower, types of hydropower, data required to evaluate hydropower potential, detailed overview of Zambia's water and energy sectors, existing hydropower installations in Zambia, water infrastructure and river schemes in Zambia, sources of hydropower potential in Zambia, existing selection criteria for different types of hydropower, existing hydropower atlases. Through this step, the formulas and data required to evaluate hydropower potential were identified. Furthermore, data sources were identified.
- Data collection was conducted through the use of online data acquisition tools such as Google Earth Pro, web-based sources, online Google Forms questionnaires, and site visits to the institutions in charge of water infrastructure and river schemes.
- The data selection criteria and evaluation frameworks are developed by assessing and analysing the collected data using GIS tools, hydrology tools, and Microsoft excel. The criteria development also involves the use of existing criteria obtained from the case studies. Where data is unavailable, assumptions are made and validated. The final evaluation frameworks are presented through flow charts.

- Finally, the developed data selection criteria and evaluation frameworks are evaluated by applying them to the selected case studies for each type of hydropower to show the inclusion or exclusion of hydropower potential sites in the Zambian Hydropower Atlas. The weaknesses of the developed data selection criteria and frameworks are also identified and stated.

1.7 ORGANISATION OF THE REPORT

The report consists of the following chapters:

- Chapter 1 serves as the introduction to the dissertation, outlining the background, problem statement, hypothesis, objectives, scope, methodology, and organization of the report.
- Chapter 2 contains detailed literature related to the hydropower concepts which include, an introduction to hydropower, an overview of Zambia's energy sector, aspects of hydropower generation and sources with hydropower potential, the water resources situation in Zambia, aspects of hydropower development in Zambia, case studies and existing data selection criteria.
- Chapter 3 provides a detailed process followed to obtain the relevant data of the water infrastructure and river schemes in Zambia and provides information on the selection of a suitable platform to host the Zambian Hydropower Atlas.
- Chapter 4 Analyses the water infrastructure and river schemes data obtained from the various sources and provides the data selection criteria development process for the evaluation of hydropower potential for each type of hydropower.
- Chapter 5 outlines and discusses the details of the developed data selection criteria and presents the evaluation frameworks for the inclusion of certain water infrastructure or river schemes in the Zambian Hydropower Atlas.
- Chapter 6 includes case studies to evaluate the developed data selection criteria and evaluation frameworks.
- Chapter 7 concludes with a summary of the addressed research objectives, limitations of the study and recommendations for future research activities are also provided.
- The list of references used in this report is given after Chapter 7.
- The report ends with Appendices A, B, C, D and E which contain additional data and information for the report

2 LITERATURE REVIEW

This chapter outlines the literature review that was conducted during the study. The literature review was conducted according to the flow diagram given in Figure 2-1. As can be seen from the flow diagram, the introduction to hydropower is discussed followed by the overview of Zambia's Energy sector. Aspects of hydropower generation are also discussed including the sources with hydropower potential, thereafter, the water resources in Zambia and the available water infrastructure are also evaluated. The chapter also contains a discussion on the case studies and existing data selection criteria. The chapter ends with a summary of the literature review.

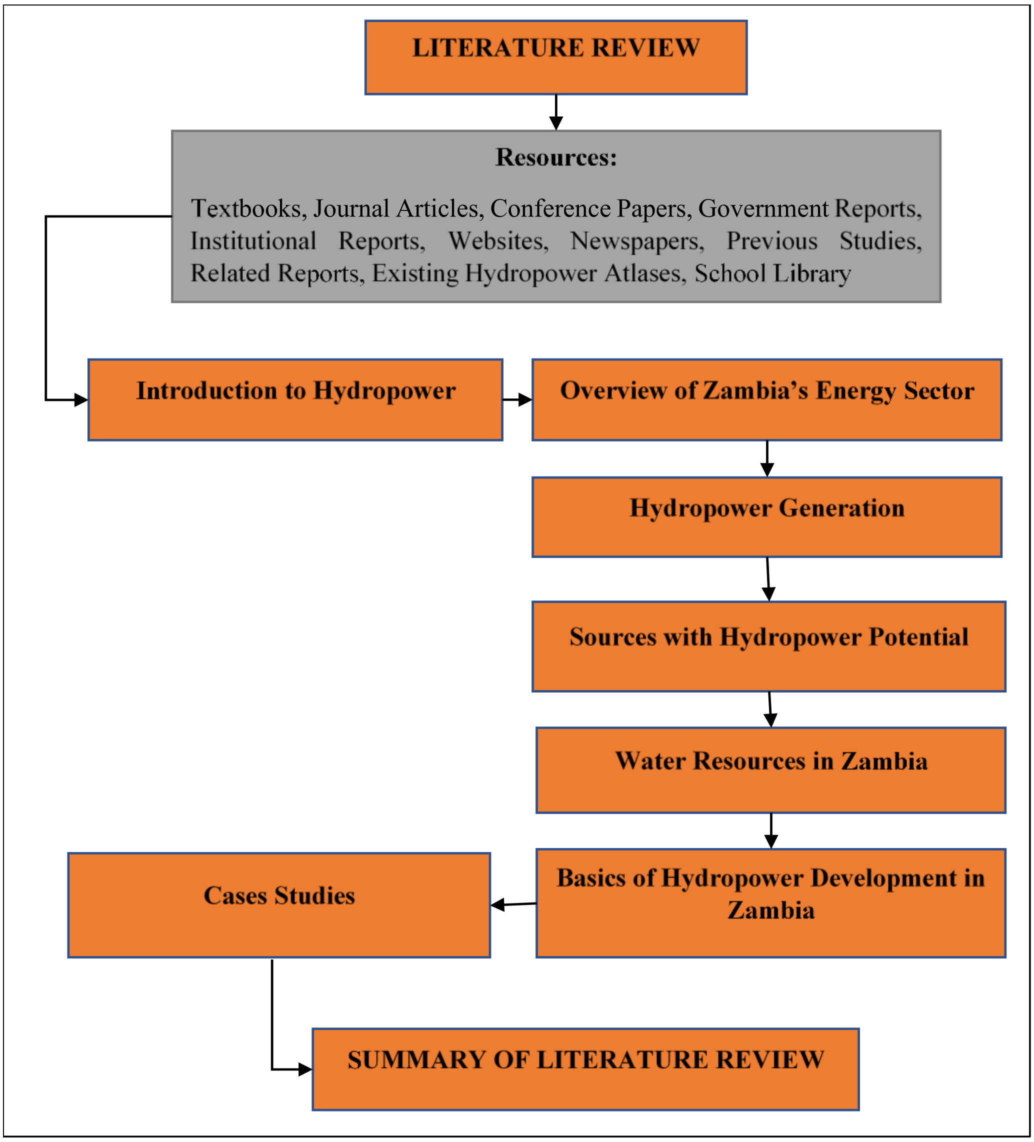


Figure 2-1: Flow Diagram of the Literature review

2.1 INTRODUCTION TO HYDROPOWER

Hydropower is the power generated from water resources such as rivers, dams, lakes, canals, and springs. The water in these resources can be converted to kinetic energy and from there into mechanical energy, which in turn is converted into a useable form of energy called electricity. This form of energy is amazing as it is a reliable, emission-free resource that is renewable through the hydrologic cycle and uses the natural energy of flowing water to provide clean, fast, and flexible electricity (Subhro, et al., 2015). The generated electricity can light up millions of homes and businesses around the world. According to the International Hydropower Association (IHA) 2020 hydropower status report, the world has a total installed hydropower capacity of 1,308 GW which generated over 4,300 TWh of electricity in 2019 making hydropower remain the largest source of renewable energy in the world (IHA, 2020). Figure 2-2 shows the trend of how hydropower generation has been increasing around the world since the year 2000. Through research, further engineering and structural changes have followed, providing for a much more complicated process in designing hydropower plants including the development of easy and flexible small-scale hydropower generating plants (Shrivastava & Srivastava, 2015).

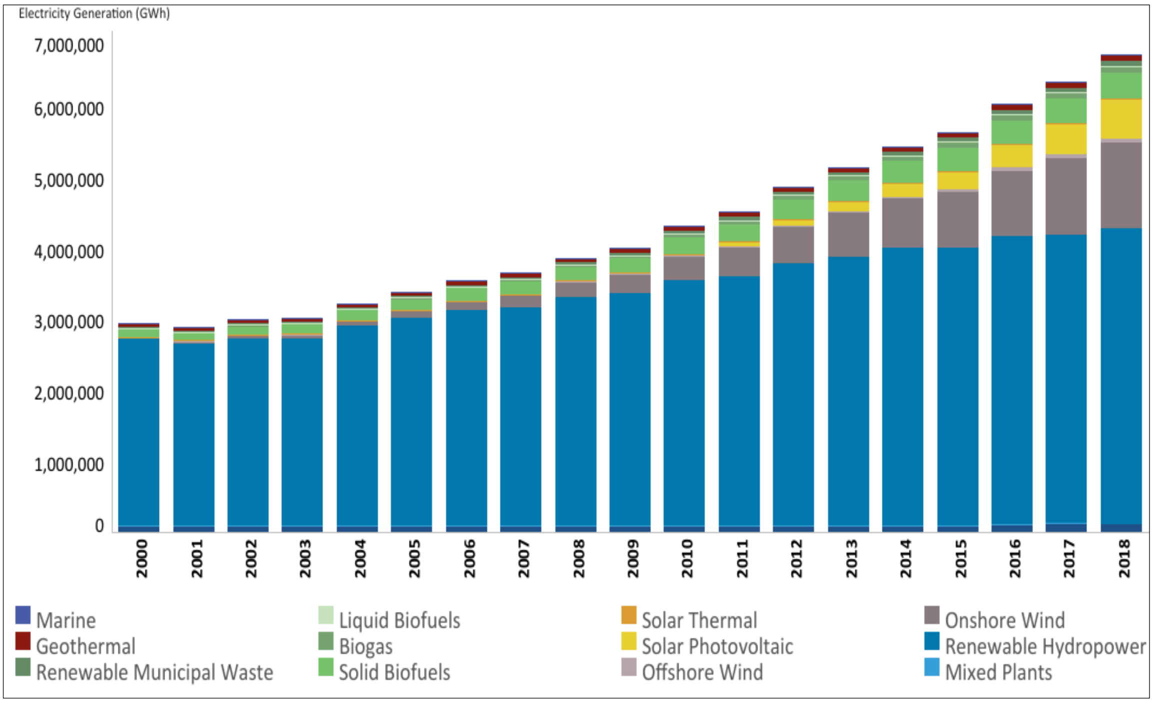


Figure 2-2: Trends in the world renewable energy generation (2000-2018) (IRENA, 2020b)

2.2 OVERVIEW OF ZAMBIA'S ENERGY SECTOR

Zambia's electricity is abundantly sourced from hydropower resources making up to 80.5% of the electricity generation mix as shown in Figure 2-3. Other sources of electrical energy in the order of their contribution are coal-fired thermal, heavy fuel oil(HFO), diesel, and solar. There is also the potential of sourcing electricity from nuclear, biomass, geothermal, and wind. The government of Zambia has plans of developing a fully operational nuclear plant which is expected to add 2,400MW of electricity to the national grid (Mwape, 2019). There is also an ongoing 40MW biomass power project at Zambia Sugar which will utilize sugarcane biomass (Gauri, et al., 2013).

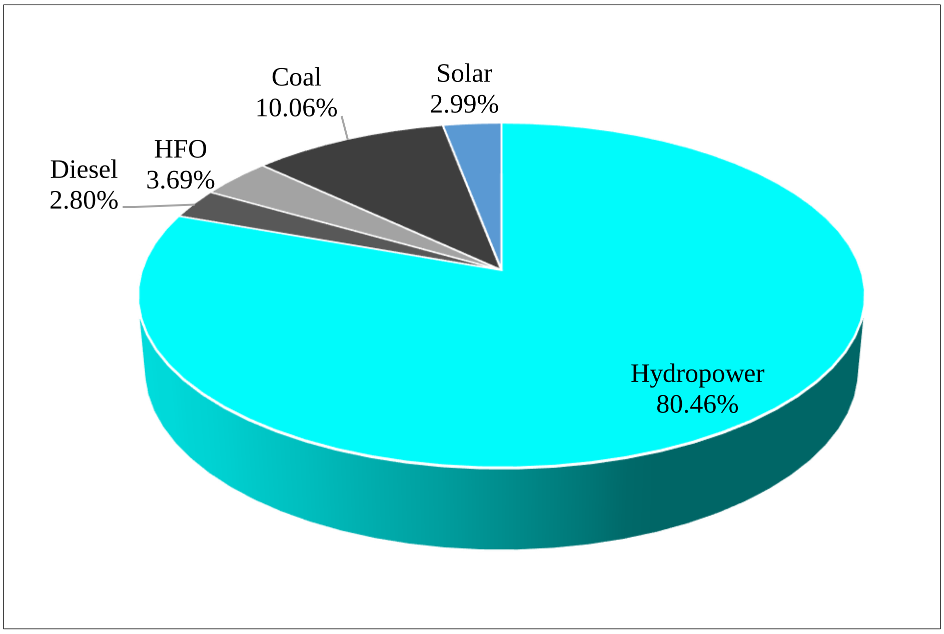


Figure 2-3: Electricity Generation Mix in Zambia (ERB, 2020)

2.2.1 Access to Electricity

According to the survey done by World Bank (2019), 1.4 million Zambian households (42.4 %) had access to electricity through either the national grid or off-grid sources while the remainder 1.9 million households (57.6 %) had no access to electricity (Figure 2-4). Out of the 42.4 % households with access to electricity, 37.7 % of these households are connected to the national grid while the remaining 4.7 % use off-grid solutions. Furthermore, Zambia's access to electricity in terms of the urban and rural population stands at 67 % and 4 % respectively (Kabira, et al., 2019). Therefore, 33 % and 96 % of the urban and rural population are still without electricity. In line with goal number 7 of the sustainable development goals, this calls for attention and sustainable solutions to electrifying, especially the rural population.

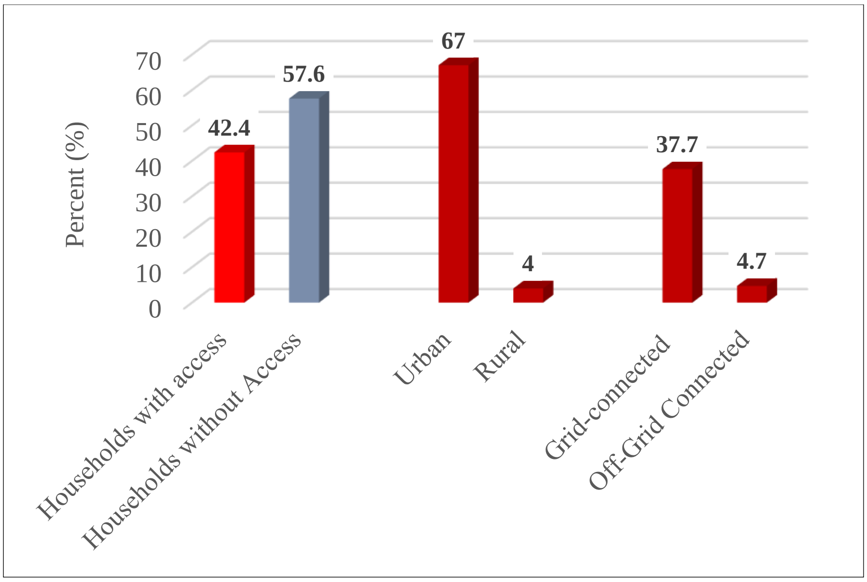


Figure 2-4: Details of Zambia's access to electricity (World Bank, 2019b).

2.2.2 The Electricity Sector

Zambia's electricity is largely generated and distributed by ZESCO, a vertically state-owned utility that owns 77 % of the total installed electricity capacity in the country. The bulk of this electricity generated by ZESCO is from hydropower plants while 0.4 % is generated from diesel plants owned by the utility (ERB, 2020). The remaining 23 % of the installed capacity is generated by IPPs such as Itezhi-tezhi power Ltd, Zengamina Ltd, Lunsemfwa Hydro Ltd, Mamba Collieries Ltd, Ndola Energy Company, Muhanya Solar Ltd, Mugurameno Solar Ltd, and the Copperbelt Energy Corporation (CEC). Investing in these IPPs is promoted by the Office for Promoting Private Power Investments (OPPPI) which is under the Ministry of Energy (MoE). In addition to the IPPs, Zambia imports and exports electricity to the neighbouring power companies such as Eskom and the Botswana Power Corporation (BPC) through the Southern African Power Tool (SAPP).

The hydropower plants owned by the IPPs have connected to the ZESCO main transmission grid for distribution apart from those owned by Zengamina Ltd and CEC. Zengamina Ltd owns and operates a mini-hydropower plant that is connected to an isolated grid for distribution to customers in the North-Western province of Zambia. CEC operates its power plants and also buys more than 50 % of ZESCO's generated electricity and distributes it to mining companies (ERB, 2020). Furthermore, the Rural Electrification Authority (REA) owns a mini solar plant and is responsible for the development and management of all activities related to rural electrification.

The licensing of all the mentioned power companies is done by the Energy Regulation Board (ERB) which is also responsible for the determination of electricity tariffs and the development of standards used by the electricity companies in the country (Kabira, et al., 2019). Figure 2-5 shows the structure of how electricity is generated and supplied in Zambia while Table 2-1 shows the existing power generation plants including their capacities and ownership. The summary of the institutional setup of the Zambian electricity sector is shown in Figure 2-6.

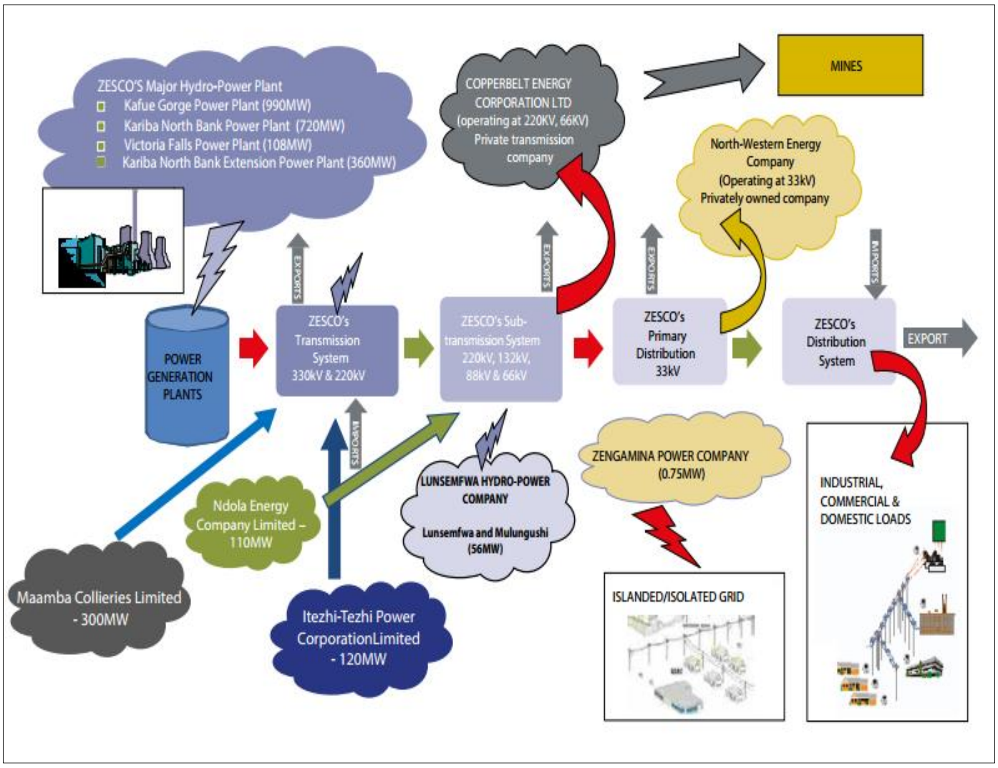


Figure 2-5: Structure of the electricity supply industry in Zambia (ERB, 2020)

Table 2-1: Installed Electricity Generation Capacities in Zambia (ERB, 2020)

Company	Location of Station	Machine Type	Installed Capacity (MW)
ZESCO Limited	Kafue Gorge	Hydro	990
	Kariba North	Hydro	720
	Kariba North extension	Hydro	360
	Victoria Falls	Hydro	108
	Lunzua River	Hydro	14.8
	Lusiwasi	Hydro	12
	Chishimba Falls	Hydro	6
	Musonda Falls	Hydro	10
	Shiwang'andu	Hydro	1

Company	**Location of Station**	**Machine Type**	**Installed Capacity (MW)**
Itezhi-tezhi Power Corporation	Itezhi-tezhi	Hydro	120
Zengamina Limited	Ikelengi	Hydro	0.75
Lusemfwa Hydro Ltd	Mulungushi	Hydro	32
	Lunsemfwa	Hydro	24
	Total Hydro		**2,398.50**
Maamba Collieries Limited	Maamba Power Plant	Coal	300
	Total Coal		**300**
CEC Generation Plants	Bancroft	Diesel	20
	Luano	Diesel	40
	Kankoyo	Diesel	10
	Maclaren	Diesel	10
ZESCO Generation Plants	Luangwa	Diesel	2.6
	Shango'mbo	Diesel	1
	Total Diesel		**83.60**
Ndola Energy Generation Plants	Ndola	HFO	110
	Total HFO		**110**
REA Generation Plants	Samfya	Solar	0.06
CEC	Kitwe	Solar	1
Muhanya Solar Limited	Sinda Village	Solar	0.03
Ngonye Power Limited	LAMFEZ	Solar	34
Bangweulu Power	LAMFEZ	Solar	54
Solera Power	Luangwa bridge	Solar	0.01
Standard Microgrid	Kafue	Solar	0.02
Mugurameno	Chirundu	Solar	0.01
	Total Solar		**89.13**
	Grand Total		**2981.23**

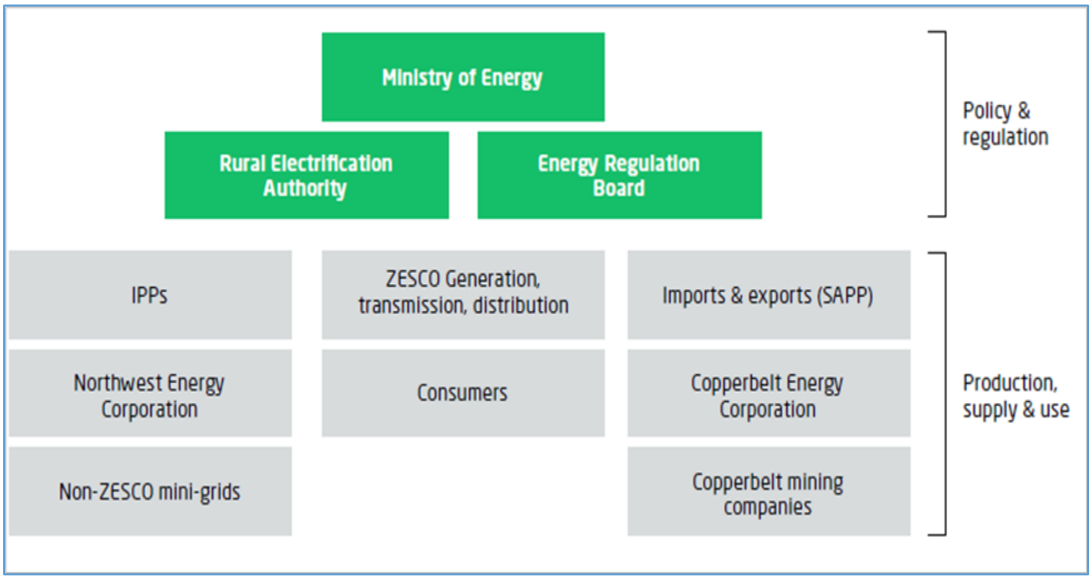


Figure 2-6: The Institutional setup of the Zambian Electricity Sector (Kabira, et al., 2019)

2.2.3 Electricity Consumption

The importance of electricity towards the economy of Zambia cannot be overemphasized, however, the country has experienced a severe electricity supply deficit in the last decade which is driven by the mining sector demand. Zambia's economy is largely dependent on the mining of copper in the Copperbelt and North-Western provinces. According to the ERB (2019) energy status report, the mines are the major consumers of electricity in Zambia consuming more than 50 % of the total electricity generated per year. The report further indicates that the domestic customers are the second consumers of electricity consuming up to 33.20 % of electricity generated per year. Domestic customers are those that consume electricity for home use. Other economic sectors that consume electricity are shown in Figure 2-7.

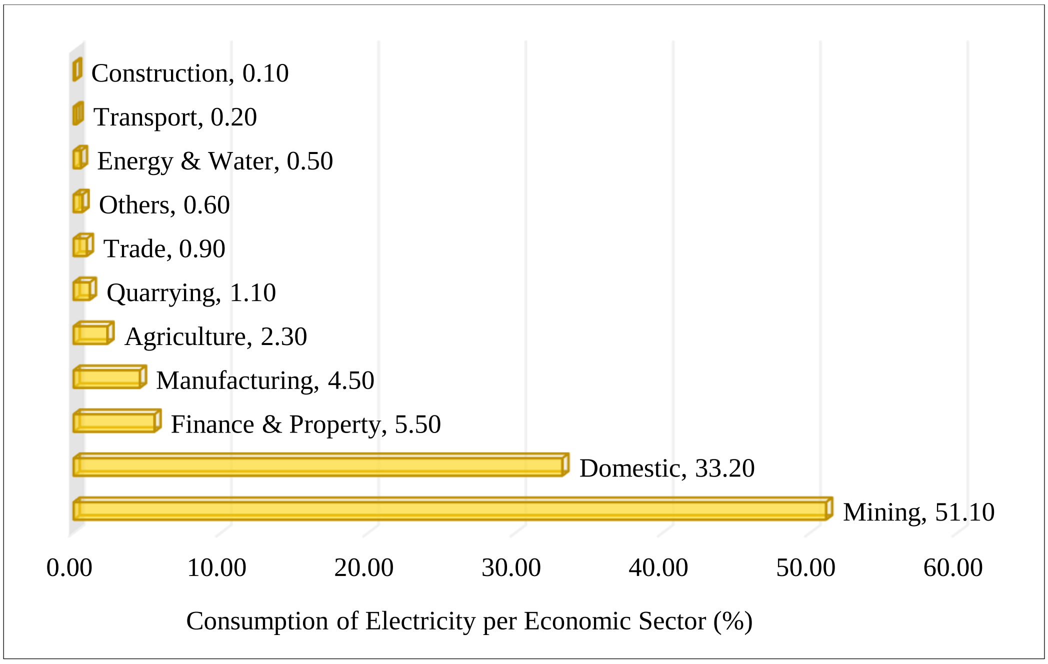


Figure 2-7: Consumption of electricity per economic sector (ERB, 2020)

2.2.4 Electricity Tariffs

Retail electricity tariffs in Zambia are determined by ERB and its decision is final in setting the tariffs. The tariffs in the country have historically been highly subsided by the government leading to a challenging commercial environment for both ZESCO and private investors (Kabira, et al., 2019). Due to this challenging situation, the ERB announced the changes to the electricity tariffs for both domestic and commercial customers in 2019. The changes included the upward adjustments of tariffs and the abolishing of monthly fixed charges for both domestic and commercial customers (ERB, 2019a). Table 2-2 shows the current applicable ZESCO tariff schedule. These ZESCO tariffs, however, are not uniform throughout the electricity suppliers who have their different ERB-approved tariff schedules (Kabira, et al., 2019).

Table 2-2: Current ZESCO Electricity Tariffs in Zambia (ZESCO, 2019)

Tariff Category	Customer Description	Type of Charge	Tariff effective 1 January 2020	
			ZMW	USD
Metered Residential	R1 – Monthly Consumption up to 100 kWh	Energy Charge/kWh	0.47	0.038
	R2- Monthly Consumption 101 to 300 kWh	Energy Charge/kWh	0.85	0.068
	R3- Monthly Consumption above 300 kWh	Energy Charge/kWh	1.94	0.156
Commercial (Capacity up to 15 kVA)	C1- Monthly Consumption up to 200 kWh	Energy Charge/kWh	1.07	0.086
	C2- Monthly Consumption above 200 kWh	Energy Charge/kWh	1.85	0.149
Social Services	Schools, Hospitals, Orphanages, Churches, Water pumping, Street Lighting	Energy Charge/kWh	1.19	0.096
		Fixed Monthly Charge	203.73	16.415
Distribution	Purchasers of power for distribution to retail customers (exchange rate ZMK12.411/USD	MD Charge/kVA/Month	64.02	5.158
		Energy Charge/kWh	0.58	0.047
Maximum Demand Tariffs	Details on Maximum Demand Tariffs are provided by ZESCO (2019)		-	-

Note: Tariffs in the table are exclusive of 3% excise duty and 16% Value Added Tax (VAT)

2.2.5 Renewable energy potential

Renewable energy is taken as a vital aspect of fostering green energy growth and as a way of achieving sustainable economic development. It is the energy extracted from resources that nature will replace. This includes energy generated from hydro, solar, geothermal, wind, and biomass resources (Malama, et al., 2018). With the ever-growing requirement of energy in the world and the need to fight global warming, the extraction of energy from renewable energy sources is being encouraged around the world. This is because renewable energy is clean, plentiful in supply, and cheap. Zambia has joined the rest of the world and Africa in particular in taking advantage of the benefits of renewable energy including reducing greenhouse gas (GHG) emissions. Climate change in Zambia is a reality with Greenhouse Gases emissions being one of its major contributing factors. According to the Fossil CO_2 and GHG emissions of all world countries 2019 Report by Crippa, et al. (2019), Zambia emitted an estimated amount of 18.99 million tonnes of GHG in 2010. This is expected to reduce by 25% in 2030 through Zambia's vision 2030 policy (USAID, 2018).

According to the Zambia Renewables Readiness Assessment Report by Gauri, et al. (2013), Zambia is also aware of how renewable energy can assist in achieving the Millennium Development Goals by ensuring access to modern energy services for the majority of the rural communities. Small-scale renewable energy systems can provide affordable energy to the poor, help with creating employment by powering enterprises for increased production, and produce cleaner energy for cooking and heating. For these reasons, the Government of Zambia established REA and the rural electrification fund through the Rural Electrification Act to give impetus to the rural electrification agenda. REA strives to fulfil its vision, "Electricity for all rural areas by the year 2030", by designing and offering smart subsidies for capital costs, to developers and operators that are selected on a competitive basis, for projects to supply energy for the development of rural areas (Gauri, et al., 2013).

Zambia is well endowed with renewable energy sources which have great potential for electricity production, predominantly hydro. The country is considered as one of the water-rich countries in Southern Africa with an estimated hydropower potential of more than 6,000 MW. Out of this, 2,398.5 MW has been exploited mainly through large hydropower plants (ERB, 2019a). This is expected to increase after the completion of the Kafue Gorge Lower (KGL) hydropower plant which will add 750 MW of electricity. Furthermore, Zambia has few installed mini-hydropower plants which include Zangemina (0.75 MW) and Shiwang'andu (1 MW) hydropower.

According to JICA (2009), the development of mini-hydropower plants in Zambia has shown a clear contrast as with the case of large hydropower plants that are connected to the national grid. The mini-plants are located in remote areas far from the ZESCO national distribution grids and supply power to local schools, clinics, hospitals, rural residences, and farms. Therefore, the development of small-scale hydropower plants is considered as an option to enhance rural electrification in remote areas of Zambia. REA has so far identified 29 small-scale hydropower potential sites in the Northern, Luapula, Western and North-Western provinces of Zambia that may supply power to rural areas. As of December 2018, REA had concluded feasibility studies for nine of the potential sites as a process of increasing electricity access in the targeted Zambian rural areas (ERB, 2020). There are also plans in the private sector to develop off-grid hydropower projects which include Chavuma (15 MW), West Lunga (3 MW), and Chitokoloki mission(150 kW) (Gauri, et al., 2013). These projects are expected to increase Zambia's dependency on hydro renewable energy. Other renewable energy technologies in Zambia are solar, biomass, geothermal, and wind. Their current status and potential are outlined below,

- **Solar**: Zambia has average solar insolation of 5.5 kWh/m^2/day, with approximately 3,000 sunshine hours annually, providing good potential for solar thermal and photovoltaic applications. This solar potential was realised through the development of the solar resource atlas for Zambia by the world bank. The solar resource and photovoltaic atlas for Zambia is included in Appendix A. However, this technology has been underexploited with only 1.1 MW of installed capacity.
- **Biomass**: Zambia has a total biomass resource and economic bioenergy potential of 2.15 million tonnes, and 498 MW, respectively (Gauri, et al., 2013). This potential has not been exploited in Zambia. There is only 1 biomass project going on in Zambia which is being undertaken by Zambia sugar in the Southern province and is expected to generate 40MW once completed.
- **Geothermal**: Over 80 hot and mineralized springs have been identified in Zambia with over 35 having potential for electricity generation (Malama, et al., 2018). There is no current installed geothermal power generation plant in Zambia. In 1986 the Zambian Geological Survey in conjunction with the Italian aid determined that the hot springs in the Northern province of Zambia were favourable for commercial power generation with a capacity of over 2MW. The Government of Zambia is currently exploring options for undertaking these hot springs for power generation.
- **Wind**: Opportunities for the development of large-scale wind power plants in Zambia are low due to low wind speeds which average 3m/s at 10 m height above the ground (Gauri, et al., 2013). This speed is not suitable for power generation but is appropriate for irrigation and domestic water pumping. Malama, et al., (2018), suggested that a wind atlas for Zambia would help determine the full potential of wind energy in Zambia. Other authors also suggested that higher wind speeds may exist at higher heights (eg. 70 - 100 m) and thus needs to be explored in directing strategies to develop wind in Zambia.

The availability and utilization of the renewable energy sources in Zambia already described are summarized in Table 2-3.

Table 2-3: Availability and utilization of renewable energy sources (Gauri, et al., 2013)

Renewable Energy	Opportunities for	Resource Availability	Potential Energy Output
Solar	Thermal (water heating), electricity (water pumping, lighting, refrigeration)	6-8 sunshine hours	5.5 $kWh/m^2/day$
Small-scale Hydro	Small grids for electricity supply	Reasonably extensive	Requires elaboration and quantification, 29 potential sites identified on small rivers
Wind	Electricity, mechanical, water pumping	Average 3 m/s at 10 m height	Modest potential, especially for irrigation, Wind atlas required
Biomass	Electricity generation	Agro-waste, forest waste, sawmill wastes, animal waste, wastewater, sugarcane	Reasonably extensive but requires elaboration and quantification
Geothermal	Electricity generation	Hot springs	Requires elaboration and quantification, More than 80 hot springs have been identified.

2.3 HYDROPOWER GENERATION

Hydropower generation takes place at facilities called hydropower plants. These facilities are located on rivers and streams but for more reliability, a dam is required to store enough water (Subhro, et al., 2015). Hydropower generation could also be developed at existing water infrastructure facilities such as water supply system infrastructure, wastewater treatment works (WWTWs), weirs, and irrigation canals. At hydropower plants, flowing water turns the blades in a turbine – this changes the kinetic energy to mechanical energy, the turbine then rotates the generator rotor which then converts the mechanical energy into electricity (Osman, et al., 2018).

The electricity is transmitted to the places where it is needed via electrical transmission lines. The hydropower plants are categorized based on their capacity. In Zambia, they fit in any one of the four category ranges listed below (UNIDO, 2019).

- Micro-hydro (generates less than 500 kW),
- Small-hydro (500 kW – 20 MW),
- Medium-hydro (generates above 20 MW – 100 MW),
- Large-hydro (generates above 100 MW).

2.3.1 The Hydropower Potential

The law of conservation of energy states that energy can never be created nor destroyed but it can change from one form to another. In generating electricity, no new energy is created, but energy is converted from one form to another. Fundamentally, water moves by gravity from a high elevation point to a lower elevation point (Subhro, et al., 2015). The available energy of this flowing water is given by the product of its weight and the height so-called effective head through which the water drops. Therefore, the hydropower potential of a water resource is the function of the head and the water discharge and is given by equation 2.1.

$$P = \rho g Q H \eta \qquad \text{(Equation 2.1)}$$

Where:

P = the Hydropower potential (W)

ρ = the density of water (1,000 kg/m^3)

g = the acceleration due to gravity (9.81 m/s^2)

Q = the discharge (m^3/s)

H = the effective head (m)

η = the efficiency of the turbine (%).

2.3.2 Basic Components of a Hydropower Plant

According to Kumar, et al. (2011), there are typically four types of hydropower plants namely run-of-river, dam based outlets and spillways, pumped storage, and instream hydropower on existing water infrastructure such as canals. The basic components that make up each of these types of hydropower plants are depicted layouts shown in Figures 2-8, 2-9, 2-10, and 2-11 respectively. Usually, some components are common to all the types of hydropower while some are only available in specific types of hydropower. The components described in this section make up a typical hydropower plant.

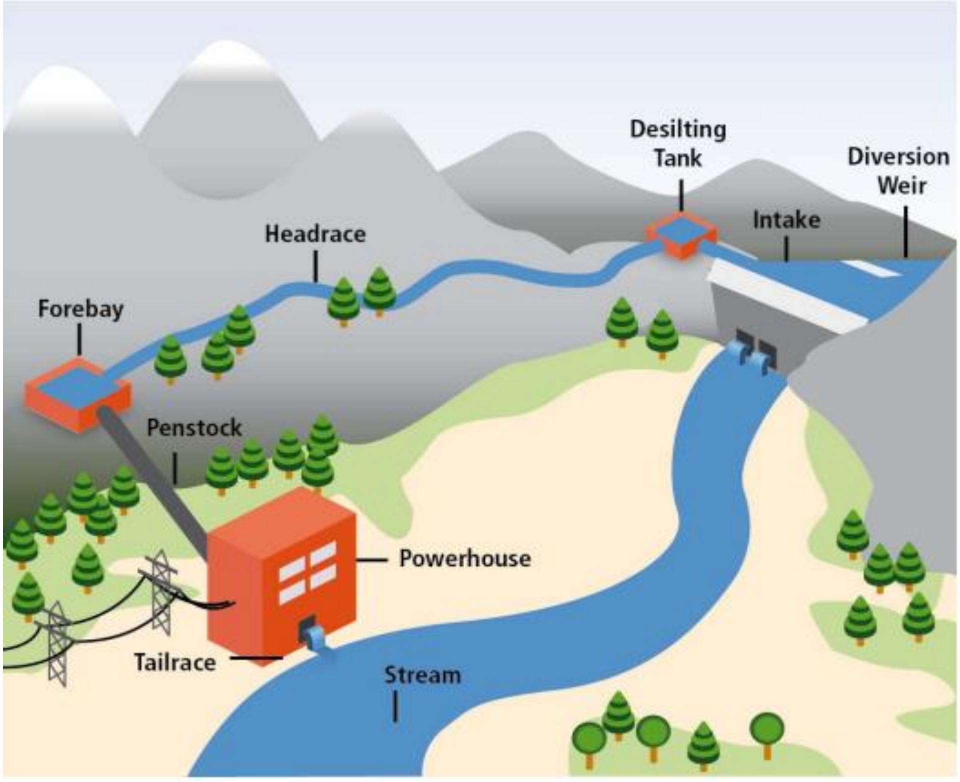


Figure 2-8: Typical Layout of a Run-of-River Hydropower Plant (Kumar, et al., 2011)

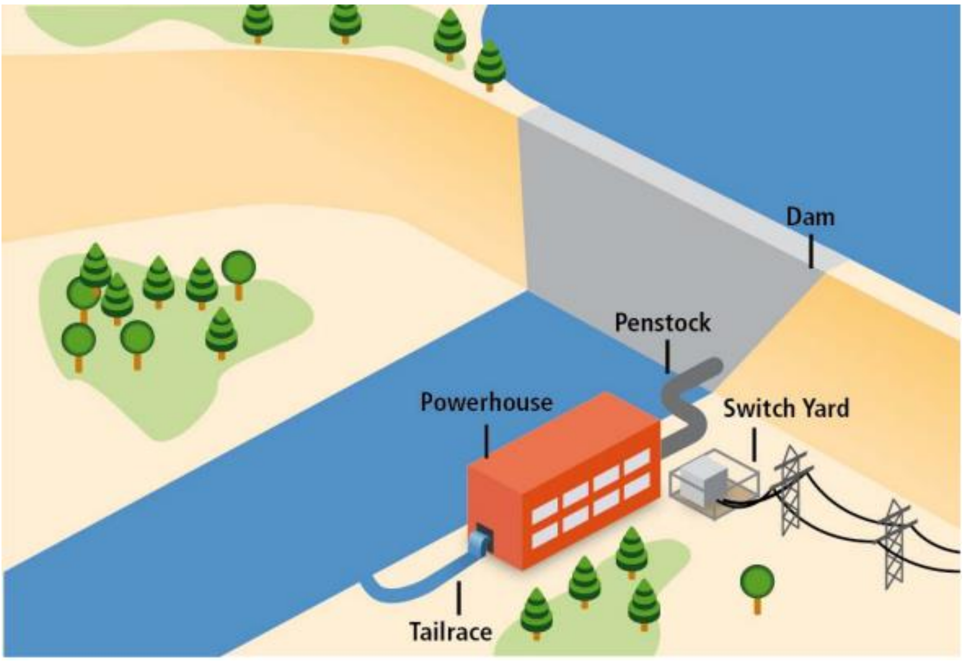


Figure 2-9: Typical Layout of a Dam Based Outlets and Spillways Hydropower Plant (Kumar, et al., 2011)

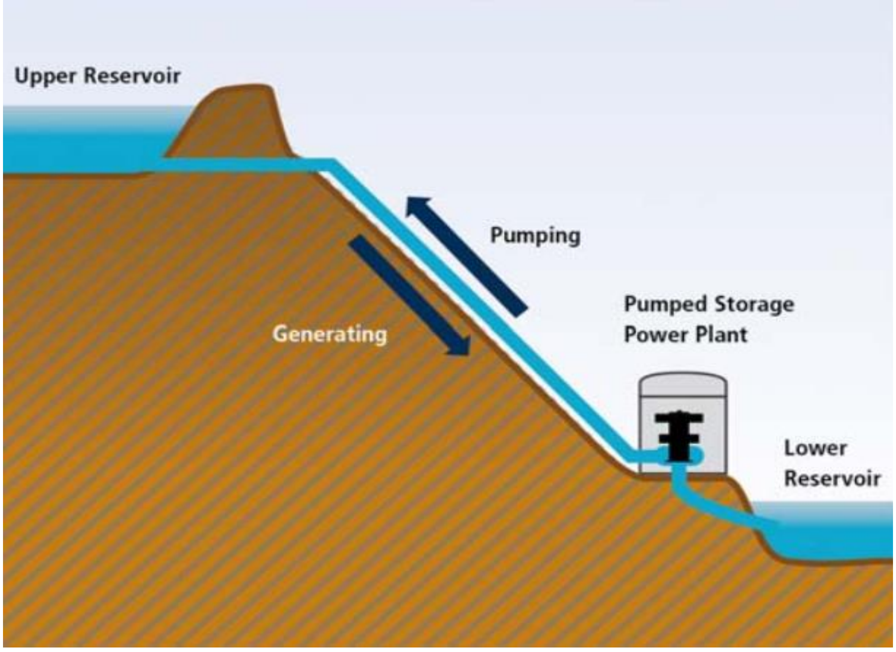


Figure 2-10: Typical Layout of a Pumped Storage Hydropower Plant (Kumar, et al., 2011)

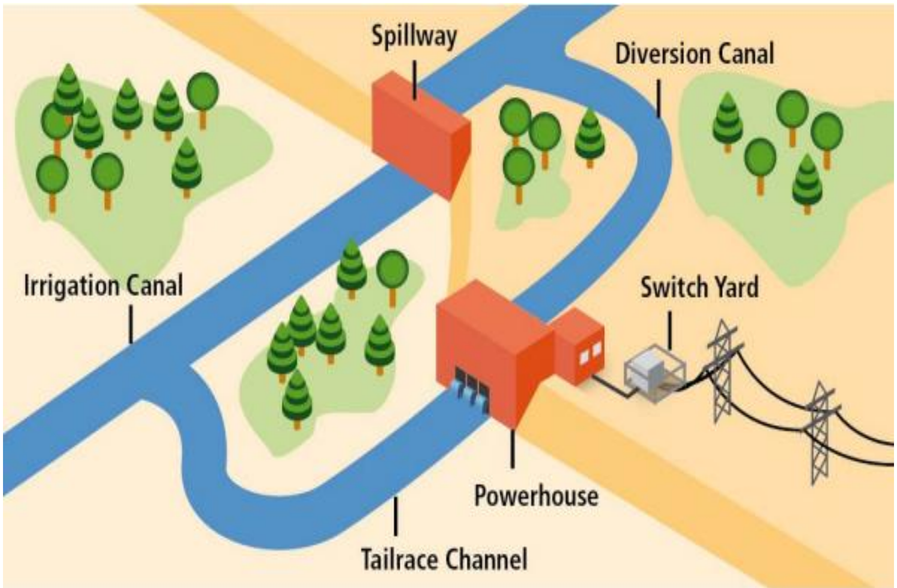


Figure 2-11: Typical Layout of an Instream Hydropower Plant on an existing canal (Kumar, et al., 2011)

2.3.2.1 Civil Works Components

Civil works components are structures that control the water that runs through a hydropower plant system. According to CETC (2004)**,** the civil structures must be located in suitable sites and designed for optimum performance and structural stability. Furthermore, other factors such as the use of local materials, local labour, and appropriate technology must be considered to reduce the cost and ensure a reliable system. These civil structures are described in Table 2-4.

It is also important that these structures are selected in such a way that they are cost-effective and environmentally friendly.

Table 2-4: Civil works components of a hydropower system (adapted from CETC, 2004)

Civil work structure	Description
Powerhouse	The powerhouse is a building that houses the turbine, generator, and controller units. Although the powerhouse can be a simple structure, its foundation must be solid and firm. All design parameters for hydraulic structures must be considered including geotechnical investigations and landslide slide treatment.
Intake	This is the structure that conveys the required flow of water from the source stream or dam and diverts it into the powerhouse. It has to be designed and located precisely to ensure that the full design flow rate goes to the turbine. In run-of-river systems, a low-head dam or weir could be used to hold back the water to provide a steadier flow of water.
Outlet (Tailrace)	A tailrace is a channel that allows the water to flow back to the river or stream after it has passed through the turbine.
Headrace Canal	The headrace canal carries the design flow from the intake to the forebay. The cross-section of the canal and alignment should be designed for optimum performance and economy to reduce losses due to leakage. An open channel or pipeline could be used as a headrace.
Forebay Tank	The forebay tank connects the channel and the penstock. The tank allows fine silt particles to settle before the water enters the penstock. A fine trash rack is used to cover the intake of the penstock to prevent debris from entering and damaging the turbine.
Penstock Pipe	The penstock pipe transports water under pressure from the forebay or dam to the turbine where the potential energy of the water is converted into kinetic energy to rotate the turbine. This is often the most expensive item in the project budget. It is, therefore, worthwhile to optimize its design to minimize its cost.

2.3.2.2 Turbines

A turbine is a unit that consists of a runner connected to a shaft that converts the potential energy in the falling water into mechanical or shaft power. The turbine is connected either directly to the generator or is connected utilizing belts and pulleys depending on the speed required for the generator. Turbines are categorized as either reaction or impulse turbines. A reaction turbine is a horizontal or vertical wheel that operates with the wheel completely submerged, a feature that reduces turbulence (Subhro, et al., 2015). This is the most widely used type of turbine. An impulse turbine, on the other hand, is a horizontal or vertical wheel that uses the kinetic energy of the water jet striking its buckets or blades to cause rotation. The wheel is covered by a turbine housing and rotates after the water strikes the buckets or blades. The water then falls to the bottom of the wheel housing and flows out. While there are only two types of turbines as already stated, there are many variations whose descriptions are given as follows:

- **Pelton Turbine:** These turbines function by directing one or more jets of water tangentially onto a runner with split buckets. This type of turbine is usually used for higher head installations, but some manufacturers do supply small turbines for low head applications (Loots, et al., 2015). The typical example of the Pelton turbine is shown in Figure 2-12.

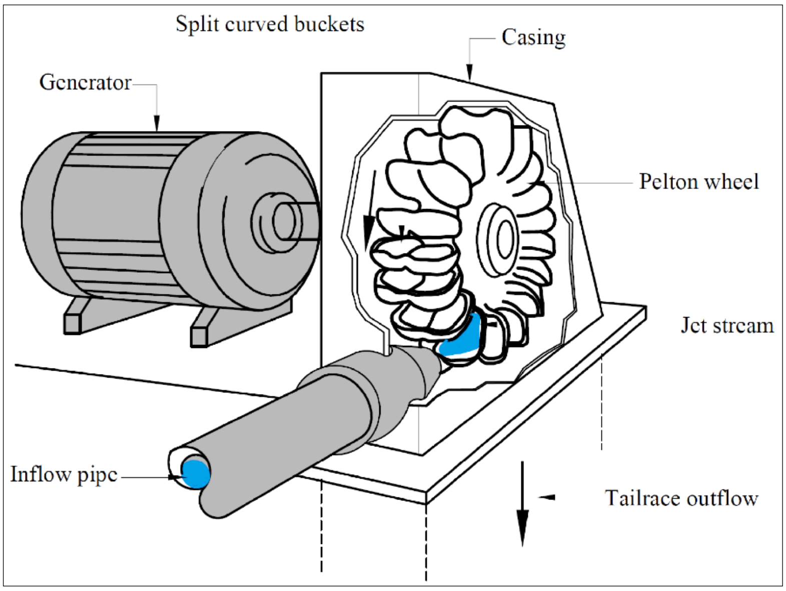


Figure 2-12: Typical Pelton Turbine (Loots, et al., 2015)

- **Cross-flow turbines:** these are turbines that are constructed with two disks joined together using inclined blades. With this turbine, water enters from the top and passes through the blades twice and after hitting the blades twice it falls into the tailrace with ideally no residual energy (Loots, et al., 2015). The cross-flow turbines are regularly used when large flow-rate variations are anticipated because their efficiency does not drop much when the flow rate change. Figure 2-13 shows a typical cross-flow turbine.

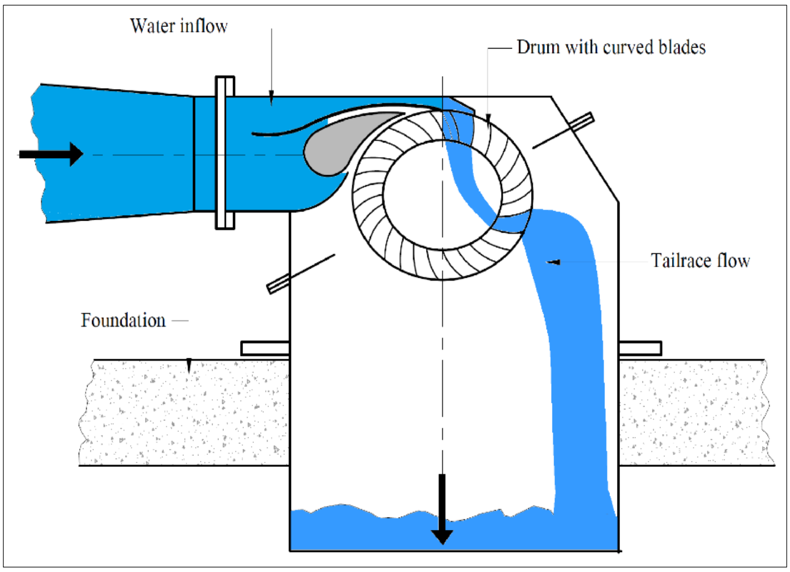


Figure 2-13: Typical cross-flow turbine (Loots, et al., 2015)

- **HydroEngine Turbines**: These turbines (Figure 2-14) are typically constructed with two shafts connected to blades moving in an elliptical path with power transfer in the linear motion portion of the blade travel (Natel Energy, 2018). These turbines are similar to the cross-flow turbines in that water passes through the turbine twice, but is used in similar circumstances as Kaplan turbines, except where Kaplan turbines often require sub-surface installation to avoid cavitation on the blades, there is no cavitation potential with the hydroEngine turbines. Furthermore, hydroEngine turbines can be installed anywhere between tailwater and headwater elevation, potentially simplifying civil works (Loots, et al., 2015).

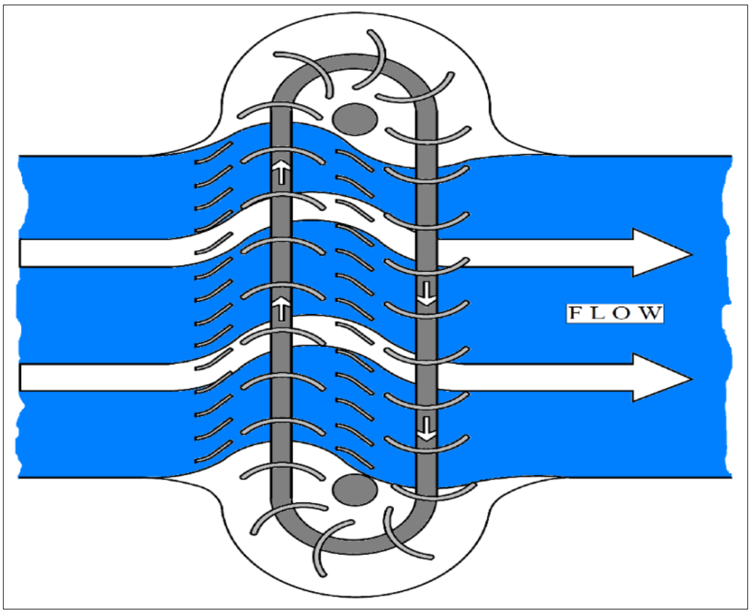


Figure 2-14: Typical HydroEngine Turbine (Loots, et al., 2015)

- **Hydrodynamic screw-type turbine (Archimedean principle):** According to the study by Loots, et al. (2015), screw-type turbines are based on the principle of an Archimedes screw pump in reverse that operates by utilizing the hydrostatic pressure difference across the blades. The article further states that in terms of capital cost the Archimedes' screw turned out to be 22 per cent cheaper than an equivalent Kaplan turbine. This type of turbine is also less harmful to fish (Lubitz & Doost, 2020). Figure 2-15 shows the typical design of a screw-type turbine.

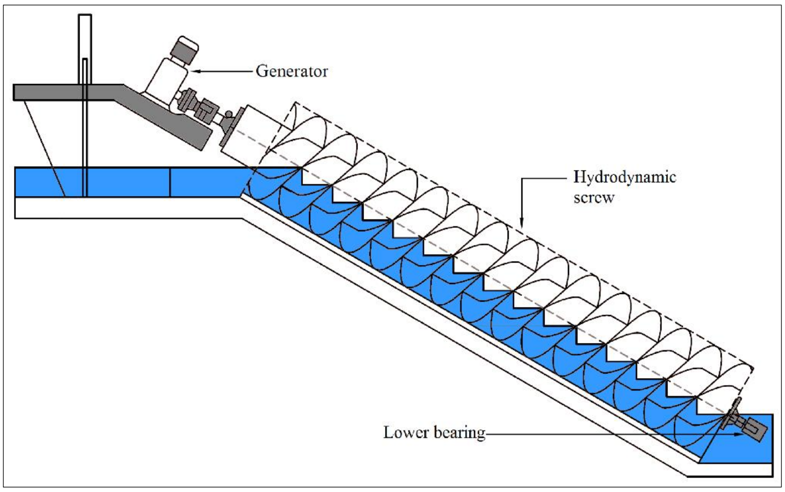


Figure 2-15: Screw-type turbine design (Loots, et al., 2015)

- **Water wheels**: Water wheels are vertically mounted wheels rotating about a horizontal axle. They are used as a traditional way of generating electricity in small quantities. Water wheels are less efficient due to significant losses by friction and the incomplete filling of the buckets (AET, 2010). However, they are practical in certain cases as they are simple to control, easy to construct, maintain, and aesthetically pleasing (Loots, et al., 2015). Water wheels are classified by how the water is applied to the wheel, relative to its axle. Figure 2-16 shows some types of water wheels based on this classification.

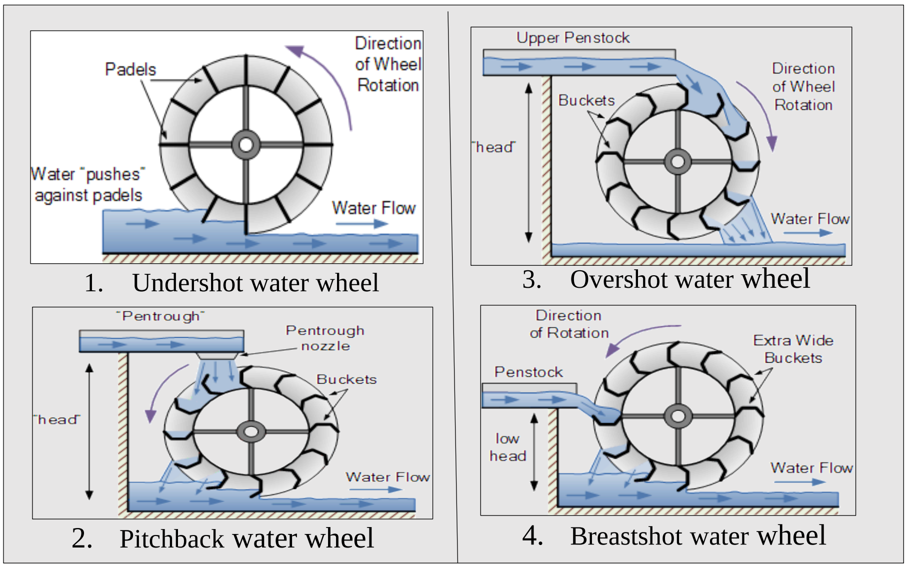


Figure 2-16: Types of Water wheels (AET, 2010)

- **Kaplan, bulb, and propeller turbines:** These turbines use the axial flow of water to develop hydrodynamic forces that rotate the runner and unlike the impulse turbines, they are completely submerged in water (Loots, et al., 2015)**.** Kaplan turbines are generally used for low heads and large flows. Figure 2-17 shows the typical Kaplan turbine.

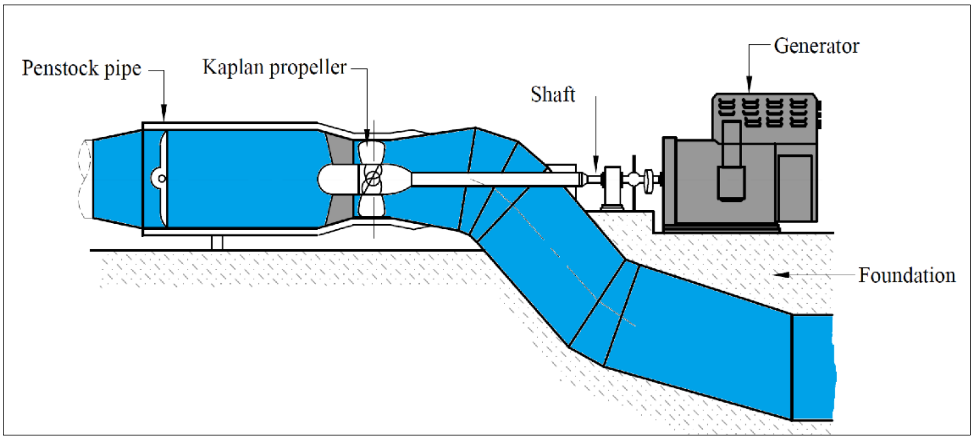


Figure 2-17: Kaplan turbine (Loots, et al., 2015)

- **Vortex turbine:** The vortex turbine uses both kinetic and static potential energy (head) principles. It is capable of generating energy using a low hydraulic head and its design is based on a round basin with a central drain that forms a vortex at the centre and rotates the turbine, thereby, generating electricity (Loots, et al., 2015). The vortex turbine promises to provide a power generation system (a micro hydropower plant) resulting in minimum interference with the river and aquatic life (Rycroft, 2018). Figure 2-18 shows a typical vortex turbine design.

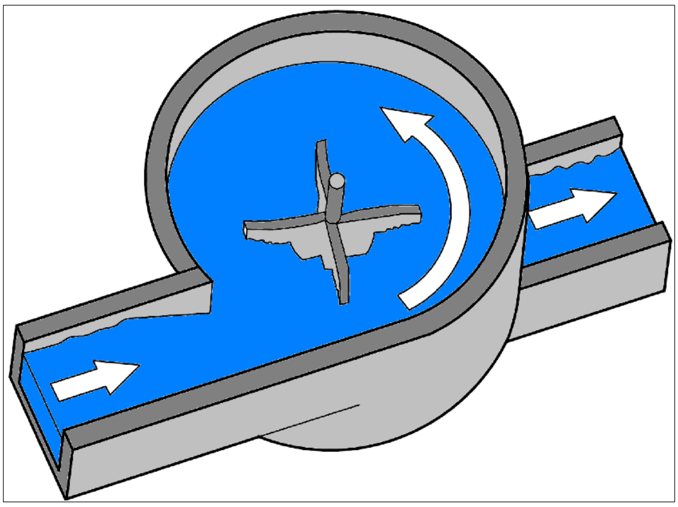


Figure 2-18: Typical vortex turbine design (Loots, et al., 2015)

- **Francis turbine:** A Francis turbine (shown in Figure 2-19) has radial runners that guide the water to exit at a different radius than the inlet radius. The flow enters the turbine in a radial direction, flowing towards its axis, but after striking and interacting with the turbine blades it exits along the direction of that axis (Trivedi, et al., 2020).

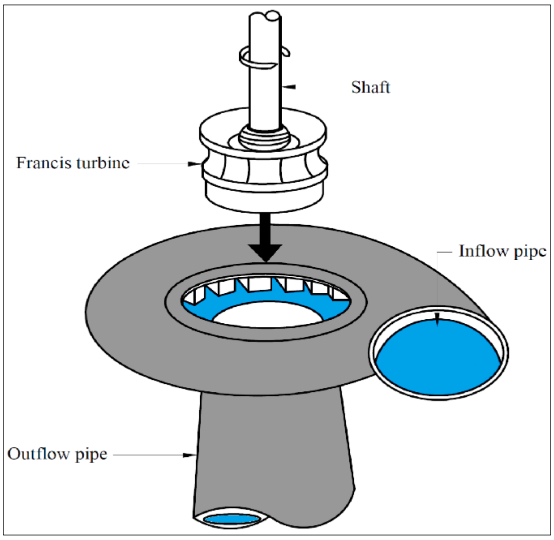


Figure 2-19: Francis turbine (Loots, et al., 2015)

- **Siphon turbines:** Siphon turbines (Figure 2-20) have propeller blades, similar to the blades found in Kaplan turbines which are connected to a turbine shaft that turns a generator. These turbines are an attractive type of small-scale hydropower turbines because they can be retrofitted into existing structures such as weirs, dams, and canals where there is already a drop in water elevation (Martinez, et al., 2019).

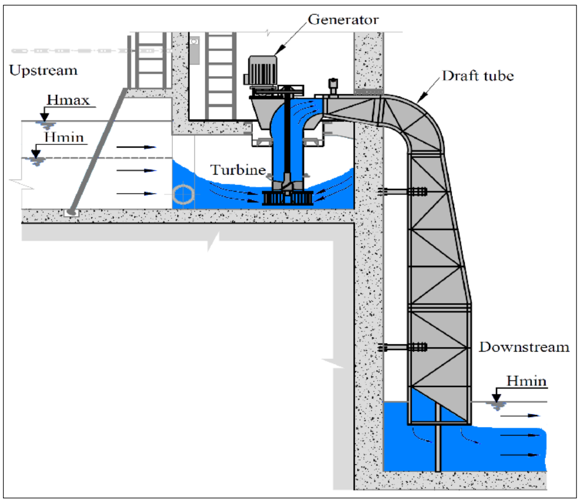


Figure 2-20: A siphon turbine (Loots, et al., 2015)

- **Inline turbines:** These turbines include spherical and ring turbines which are installed directly in the primary conduit of a pressured system (Figure 2-21). Furthermore, these turbines do not need to be installed in a bypass and are generally applicable in pico-and micro-hydropower installations.

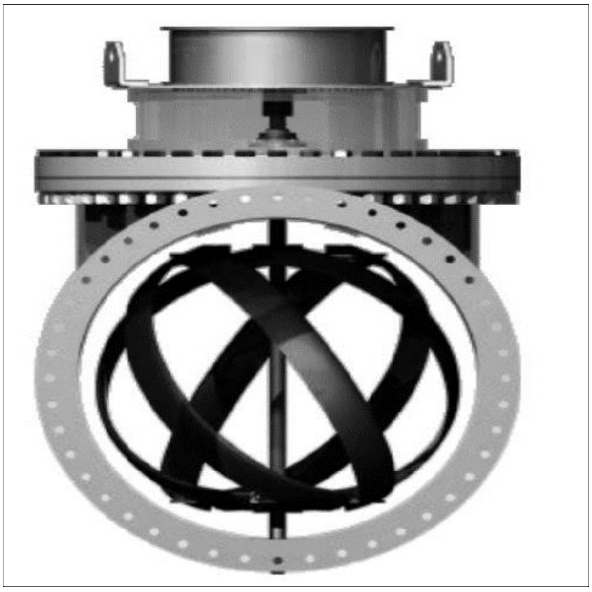


Figure 2-21: Inline turbine (Loots, et al., 2015)

- **Pump-as-Turbine (PAT):** A Centrifugal pump can be used as a hydraulic turbine (called Pump-as-Turbine) when it is run in reverse. PATs are more readily available and less expensive because pumps are mass-produced than turbines. However, for adequacy performance, a micro-hydropower site must have a fairly constant head and flow because PATs have poor partial-flow efficiency. Full efficiency from PATs can be obtained by installing multiple units, where they can be turned on or off depending on the availability of water in the river or stream (CETC, 2004). An example of a PAT is shown in Figure 2-22.

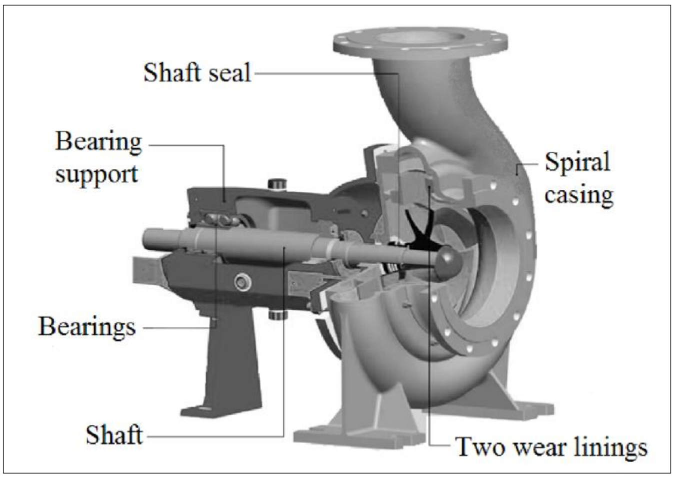


Figure 2-22: An example of a Pump-as-Turbine (Loots, et al., 2015)

- **Hydrokinetic turbines:** Hydrokinetic energy is the energy generated from the moving water in oceans, rivers, and artificial water channels (Chica, et al., 2015). Hydrokinetic turbines have been developed to extract this energy. They do not require a dam or diversion. There are two common types of rotors used as shown in Figure 2-23. These rotors can be placed either horizontally or vertically. Horizontally placed rotors have some beneficial features which make them more suitable than vertical axis turbines since they are easier self-starting, have less torque fluctuation, higher efficiency, and larger speed operation (Chica, et al., 2015).

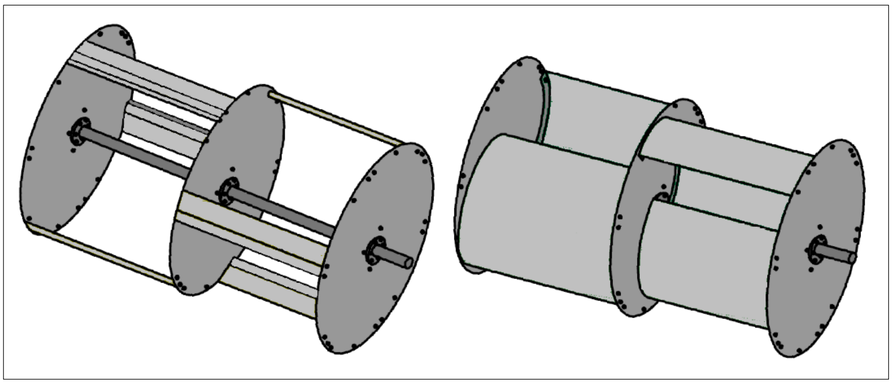


Figure 2-23: Darrieus (left) and Open Savonius (right) rotors (Loots, et al., 2015)

According to Mundon & Goldsmith (2014), the power that a hydrokinetic turbine can extract from the kinetic energy of flowing water is given by equation 2.2 below,

$P = 0.5 \times \rho \times A \times V^3 \times C_P$ (Equation 2.2)

Where:

P = power (in Watts)

V = velocity of the water in the channel (m/s)

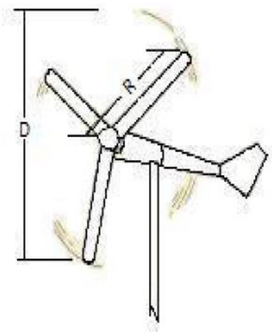
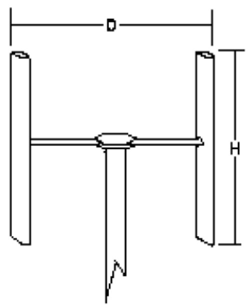
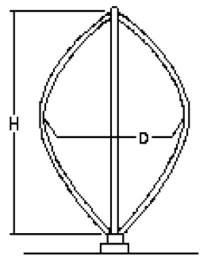
ρ = density of water (1,000kg/m^3)

A = swept area of the turbine blade (m^2)

C_P = power coefficient of the hydrokinetic turbine.

From equation 2.2, higher values of C_P are preferred over lower C_P values. The values of C_P are specified by the manufacturer of the hydrokinetic turbine and may vary with its size. However, it has a maximum possible value of 0.593 which is referred to as the Betz limit and is only experienced when the velocity of the water leaving the turbine is one-third of the velocity entering the turbine (Chica & Ainhoa, 2017). The swept area of the hydrokinetic turbine depends on the rotor configuration and can be calculated according to Table 2-5 for the circular type (conventional), the Darrieus, and the H-Darrieus rotors.

Table 2-5: Swept area expressions for different turbine configurations (Chica & Ainhoa, 2017)

Rotor blade	Conventional rotor	H-Darrieus rotor	Darrieus rotor
Turbine Configuration			
Swept area (A_t)	$A = \pi R^2$	A = DH	A = 0.65DH

Note: R is the turbine radius (m), D is the turbine diameter (m) and H is the turbine height (m)

2.3.2.3 Generators

Generators convert the mechanical (rotational) energy produced by the turbine to electrical energy; this is the heart of any hydro-electrical power system. The principle of the generator operation is quite simple: when a coil of wire is moved past a magnetic field, a voltage is induced in the wire thereby generating electricity. Generators are also called alternators when they are alternating current (AC) generators (CETC, 2004). Alternators produce AC electricity by varying voltages above and below the zero voltage.

There are two types of generators: synchronous and asynchronous. Synchronous generators are standard in electrical power generation and are used in most power plants. They have efficiencies ranging from 75% to 90%. Asynchronous generators on the other hand have efficiencies that vary from as low as 65% to 75% and are more commonly known as induction generators. Both generators are available in three-phase or single-phase systems. System capacity, type of load, and length of the transmission dictate whether a single- or three-phase generator should be used (CETC, 2004). However, asynchronous generators are more suitable for small hydropower plants, and they are generally cheaper than synchronous generators.

2.3.2.4 Drive Systems

Drive systems are used to transmit power from the turbine to the generator shaft in the required direction and at a required speed so that electricity is generated at a stable voltage and frequency. Drive systems used in micro-hydropower plants include direct-drive systems, wedge belts and pulleys, timing belts and sprocket pulley, and Gearbox (Dametew, 2016). A direct drive system is more advantageous as compared to other types because of its low maintenance, higher efficiency, and low cost. The wedge belts and pulleys are more commonly used in micro-hydropower plants. The timing belt and sprocket pulley drives are also commonly used in micro-hydropower plants; however, they are more efficient in small system drives (less than 3kW) where efficiency is critical. Gearboxes are suitable for use with larger machines where the belts would be inefficient.

2.3.2.5 Electrical Load Controllers

Electrical turbines vary in speed as the load is applied or removed. This variation in speed affects the frequency and voltage output from a generator which could damage it when there is high power or over-speeding under no-load conditions. Electrical Load Controllers (ELCs) are solid-state electronic devices designed to regulate the output power of a hydropower plant by automatically varying the amount of power dissipated in a resistive load. ELCs can also be used as a load management system by assigning a predetermined prioritized secondary load such as heating (CETC, 2004).

2.3.2.6 Transmission Network

Electricity is commonly transported from the powerhouse to homes via a network of overhead cables whose size and type depend on the amount of electrical power to be transmitted and the length of the power line to the homes. Underground cables are also used to transmit power in cases where environmental and geographical conditions are favourable in terms of cost and safety (Valenzuela, et al., 2019). The construction of transmission lines and their components must follow national and local electrical codes and should be undertaken by qualified and certified professionals. For instance, the Zambian Distribution Grid Code (ZDGC) must be followed when setting up a transmission network in Zambia.

2.3.3 Basics of Hydraulics in Hydropower

As already discussed, hydropower potential exists at locations where there is a presence of the two parameters: head and flow. For hydropower generation in water supply and distribution systems, these parameters have a dependence on the characteristics of the pipe network. Furthermore, as discussed under the description of the hydrokinetic turbine, the hydropower potential that a hydrokinetic turbine can extract from the kinetic energy is dependent on the velocity of the water in the canal or stream channel.

2.3.3.1 Pipe flow and pressure head

The flow of water in a pipe is dependent on its diameter and volume of water. The effective pressure head is dependent on hydraulic head loss encountered in the pipe system. In mathematical terms, the effective pressure head is given by equation 2.3 below.

$$H_n = H - (H_f + H_k) \qquad \text{(Equation 2.3)}$$

Where:

H_n = the effective pressure head (m)

H = the gross head (m)

H_f = the major head loss (m)

H_k = the minor head loss

The major head loss is the loss in the head due to frictional effects in the pipe. This may be calculated using the Darcy-Weisbach equation given below.

$$H_l = f\frac{l}{d}\frac{V^2}{2g} \qquad \text{(Equation 2.4)}$$

Where:

f = frictional factor which depends on Reynold's number (R_e) and relative roughness(ε/d),

l = the length of the pipe (m)

d = diameter of the pipe (m)

V = average velocity (m/s) of the water in the pipe

g = acceleration due to gravity (9.81 m/s^2).

The frictional factor can be obtained from the Moody diagram (Figure 2-24) by computing the relative roughness (ε/d) of the pipe and its Reynold's number (Re). According to the equation presented in Figure 2-24, Re depends on the density (ρ) and the viscosity(μ) of the fluid as well as its average velocity (V) and diameter of the pipe. The symbol ε is the roughness of the pipe and depends on the material of the pipe. The friction factor also depends on the change in pressure in the pipe as can be seen in the equation presented in Figure 2-24.

In addition to the major head loss, in any pipe system, there are minor losses that are raised by the additional components in the straight pipeline network. The additional components include bends, elbows, tees, valves, sudden expansions or contractions, gradual expansions or contractions, and pipe entrances or exits. These minor losses are calculated using equation 2.5,

$H_k = K_l \frac{V^2}{2g}$ (Equation 2.5)

Where:

H_k = minor head loss (m)

K_l = the local loss coefficient

v = the average velocity (m/s)

g = the gravitational due to gravity (9.81 m/s^2)

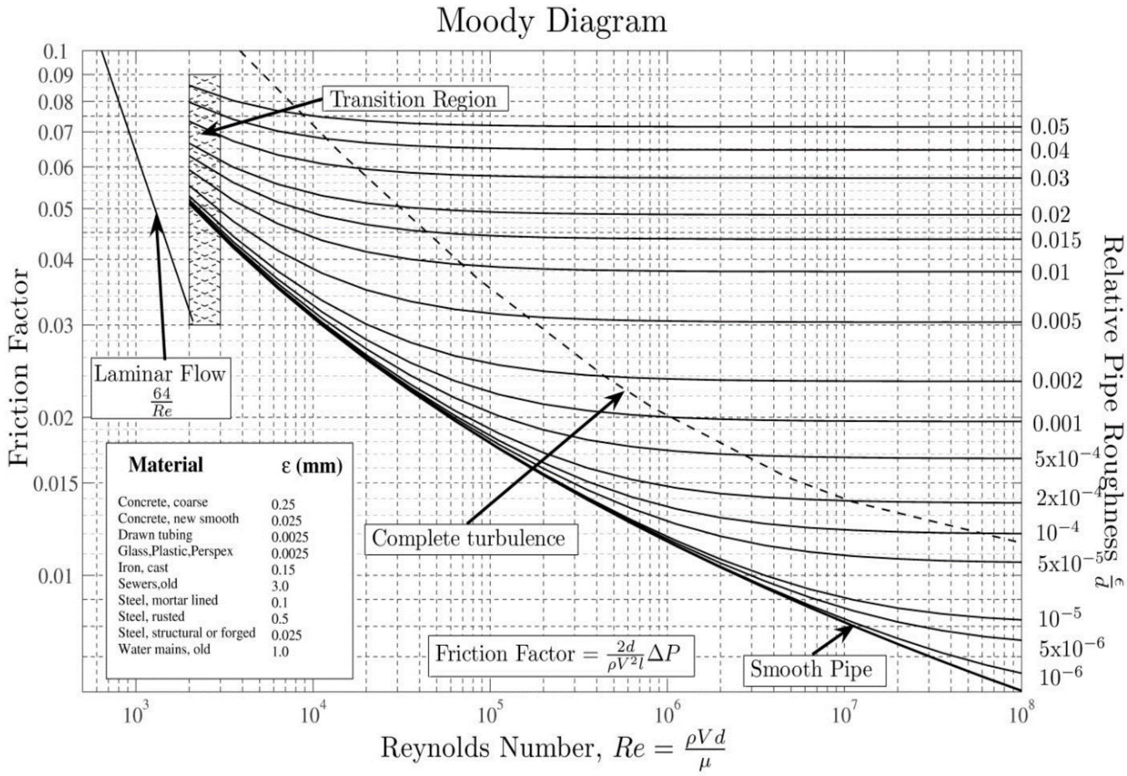


Figure 2-24: Moody Diagram (Edward & Brewington, 1997)

2.3.3.2 The Velocity of Water in Open Channels

The velocity of water in an open channel can be calculated using manning's equation given below,

$V = \frac{1}{n} R_h^{2/3} (S_0^{1/2})$, (Equation 2.6)

$R_h = \frac{A}{P}$ (Equation 2.7)

Where:

v = the average velocity (m/s)

n = manning's roughness number ($s/m^{1/3}$)

R_h = hydraulic radius (m)

S_0= slope of the channel (m/m)

A = cross-sectional flow area of the channel (m^2)

P = wetted perimeter of the channel (m)

Determination of manning's roughness number (n) at a particular site is the greatest difficulty encountered when using equation 2.6 (Phillips & Tadayon, 2007). This is due to its extreme dependence on numerous variables which includes the specific flow conditions in a given period, water-flow depths, and channel bed type and configuration. Recommended values of n for different channel conditions are given in USACE (2010). The hydraulic radius (R_h) depends on the cross-sectional shape of the channel. This can be easily obtained for regular-shaped channels (Engineering Toolbox, 2005). However, natural channels are of irregular shape and thus require the engineer's or hydrologist's much attention when estimating the hydraulic radius. However, according to Maidment (2015), the shapes of natural channels vary from approximately parabolic to approximately trapezoidal.

2.4 SOURCES WITH HYDROPOWER POTENTIAL

Where there is hydropower potential, there should be the presence of volumetric water flow and hydraulic head. As per equation 2.1, the more the volumetric flow and head, the more the hydropower potential, however, it is generally better to have more of the available head than the flow because less water will be needed to produce a given amount of power with less and smaller equipment (CETC, 2004). Hydropower potential also exists in locations where there is a presence of suitable velocities for hydrokinetic turbine installations. This section describes locations where opportunities for hydropower potential exist.

2.4.1 Dams

Dams offer opportunities for Large hydropower projects. They create a reservoir to store water for later consumption. A reservoir is known to provide the highest level of hydroelectricity supply services (Egre & Milewski, 2002). However, the construction of a large dam results in significant alteration of the natural and human environment which greatly affects the ecosystem, biodiversity, and seasonal patterns of the river flow including water temperature. Therefore, the suitable site for dam construction needs to be thoroughly studied ensuring that the most effective avoidance action limits the extent of flooding based on technical, social, and environmental considerations (Kumar, et al., 2011).

The study conducted by Loots, et al. (2015) in South Africa indicated that there exist opportunities to retrofit existing dams and reservoirs with low head hydropower plants which can be used to meet the base or peak electricity demands. The existing dam facilities and weirs may be optimized by installing small hydro turbines for additional hydropower generation.

Furthermore, opportunities for hydropower generation through hydrokinetic turbine installations exist in fast-flowing water channels downstream of dams (Egre & Milewski, 2002).

At an existing dammed-storage hydropower scheme with suitable site conditions, a pumped storage hydropower scheme can be set up (Florian & Relly, 2015). During times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine, generating electricity. This method is considered a commercially important means of large-scale grid energy storage and improves the daily capacity factor of the generation system. However, it is important to note that the method has special site requirements, specifically, it needs both geographical height and water availability. Hilly or mountainous areas and areas of potentially outstanding natural beauty are the likely suitable sites (Florian & Relly, 2015). Therefore, social, and ecological considerations are a requirement.

2.4.2 Rivers

Hydropower potential exists in rivers due to the available natural flow of the river. A run-of-river can be set up where a portion or all of the river flow is diverted to a channel or pipeline to convey the water so that it passes through a hydraulic turbine which is connected to an electric generator. A run-of-river scheme has no storage; therefore, power generation follows the hydrological cycle of the river basin. This means that generation depends on precipitation and runoff and may have daily, monthly, or seasonal variations. Hydrokinetic turbines can also be installed in river channels to generate electricity by utilizing the river's water velocity.

Run-of-river systems require that the design discharge be known to determine the hydropower potential of the site. This is done by plotting the flow duration curve (FDC) of the river discharge at the site. The river discharge can be obtained by accessing field measured flow data records for gauged stations (World Bank, 2015). Discharge at ungauged stations can be estimated using data from nearby gauged stations or through hydrological modelling of the river network using GIS and tools such as the SWAT model (Vincenzo, et al., 2019).

2.4.3 Wastewater Treatment Works (WWTWs)

WWTWs offer opportunities for implementing on-site hydropower generation systems when there is a presence of a high flow effluent that is discharged to nearby water bodies by gravity. Low head hydro turbines such as the Kaplan type can be utilized to generate power in such applications due to the difference in elevation and high flow rates (Almad, et al., 2018). The generated power can be used to meet the electricity demand at the WWTWs, or it can be sold back to the supplier. The utilization of WWTWs to generate electricity has fewer water licensing requirements as with other water flows. This gives it an advantage (NYSERDA, 2011).

2.4.4 Canals

Substantial potential for the development of small hydropower schemes exists within existing manmade infrastructure such as irrigation canals (Kyutae, et al., 2016). Suitable locations exist within the irrigation canals where electrical energy can be captured from the flows either by a diversion or by the canal itself via installing hydrokinetic turbines. Tapping electricity through this method has benefits which include elimination of fish concerns due to the presence of pre-existing screens, low environmental concerns due to pre-existing manmade infrastructure, and reduced licensing complexity since the irrigation structures are frequently located on private property than public land (Kyutae, et al., 2016). A study conducted by Loots, et al. (2015) in South Africa discussed five (5) potential sites for low head hydropower development within the irrigation canal systems. These are summarized below:

- **Diversion structures:** Diversion structures may be ideal sites for the implementation of low head hydropower projects, firstly because the existing infrastructure can be used to lower construction costs and secondly because many diversion structures span right across rivers, allowing for the utilization of all the flow for a hydropower plant. If the gradient is steep, vertical drop structures are constructed. These drop structures can in many cases be used to house a turbine, typically a siphon turbine, HydroEngine, or Kaplan turbine.
- **Concrete lined chutes and drop structures:** Chutes are regularly used for water transportation downhills. Depending on the head available at a certain chute, it can either be bypassed using a pipe and conventional turbine or the existing structure can be used in conjunction with a hydrodynamic screw, inline or similar turbine.
- **Bridges:** Vehicle, cattle, and pedestrian bridges may provide many opportunities for easy installation of low head turbines in irrigation canals. These structures can provide anchorage for various types of hydrokinetic turbines.
- **Flow gauging stations:** Opportunity for pico or micro hydropower generation exists within most irrigation canals that have a flow measuring station. Important to note here is that the flow measuring structure should not be influenced to guarantee effective flow measurement results.
- **Open lengths on irrigation canals:** Water wheels and hydrokinetic turbines can be installed along sections of concrete-lined canals if there is a need for electricity nearby. The main drivers to determine the suitability of these sites are flow volumes, flow velocities, and reliability of flow.

2.4.5 Bulk Water Supply and Distribution Systems (BWSDSs)

As shown in Figure 2-25, opportunities for hydropower generation exist in BWSDSs due to the elevation difference between the water source and the discharge areas. According to Loots, et al., (2014), there are 4 basic areas where hydropower generation can occur in a BWSDS. These are summarized in Table 2-6.

Table 2-6: Potential areas in BWSDSs where electricity can be generated (Loots, et al., 2014)

No.	Potential area	Description
1	Dam releases	In this area, conventional hydropower can be generated.
2	Water Treatment Works (WTWs)	Electricity can be tapped from the bulk pipeline from the water source to the WTWs.
3	Potable Water	Electricity can be generated at the inlets to service reservoirs where pressure-reducing stations are utilized to dissipate the excess energy.
4	Distribution network	Electricity can be generated by recapturing excess energy in the pressure-reducing valves (PRVs).

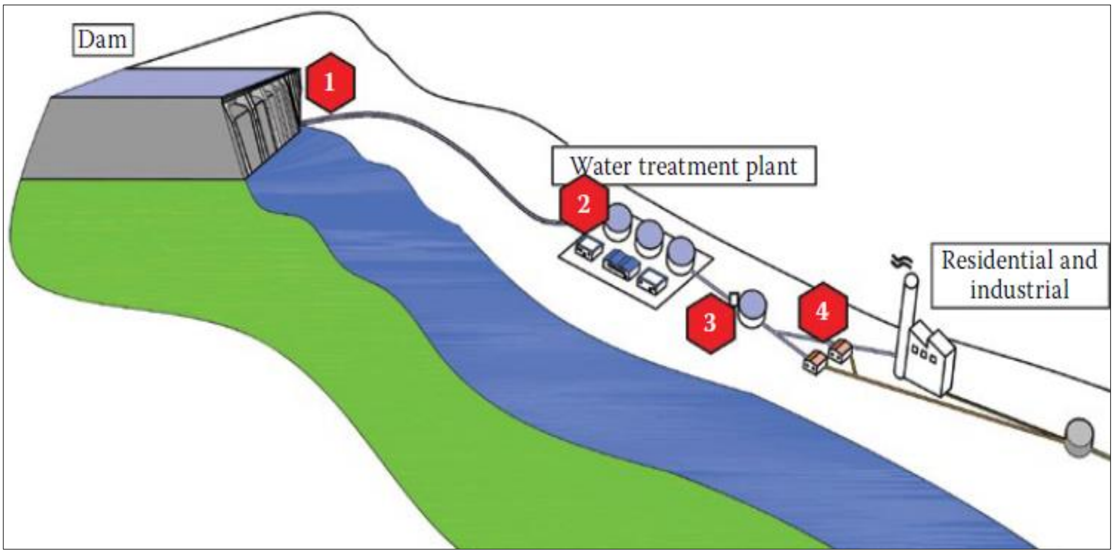


Figure 2-25: Locations in a BWSDS where opportunities for hydropower generation exist (Loots, et al., 2014)

According to Choulot, et al., (2012), excess energy at PRVs can be recaptured via conduit hydropower turbines. This can be done by replacing the existing PRV with a small turbine or by connecting it in parallel with a small turbine (Loots, et al., 2015). Generating hydropower in water distribution systems, however, requires that electricity be generated without affecting the required water pressure and flow on the customer side. The generated electricity may be inserted in the regional electricity grid or used for self-consumption at the local grid level of the water infrastructure (Samora, et al., 2016).

2.4.6 Existing Weirs

There is hydropower potential at existing weirs which are built to regulate discharge and water levels in water channels. When a weir is constructed to keep the upstream water level constant, electricity can be generated by passing the water through a turbine when flowing downstream (Marence, et al., 2016). Tapping electricity in this way has advantages which include a minimized influence on existing neighbouring plant structures, reduced environmental impact, and a simplified licensing process due to the pre-existing regime of operations (Marence, et al., 2016).

2.5 WATER RESOURCES IN ZAMBIA

Water resources are sources of water that are useful or potentially useful to humans. Zambia is well endowed with water resources that exist in two forms namely, surface water and groundwater. These two forms are important because they are needed for recreation, hydropower generation, household purposes, industrial purposes, and agricultural purposes. Zambia generates an estimated 100 km^3/year of surface water and an estimated annual renewable groundwater potential of 49.6 km^3/year (MEWD, 2010). The groundwater serves as a major source of base flow in the perennial rivers and contributes about 30 to 90% of the total flows of natural rivers (GRZ, 2011). The highest use of surface water is hydropower generation followed by agriculture (Figure 2-26). It should be noted that hydropower use is not a consumptive use. The same water may be used for agriculture downstream of the hydropower plant. The surface water resource is poorly distributed across the country while groundwater is fairly well distributed. In any case, most of this water needs to be developed to meet present and future demand for the mentioned purposes.

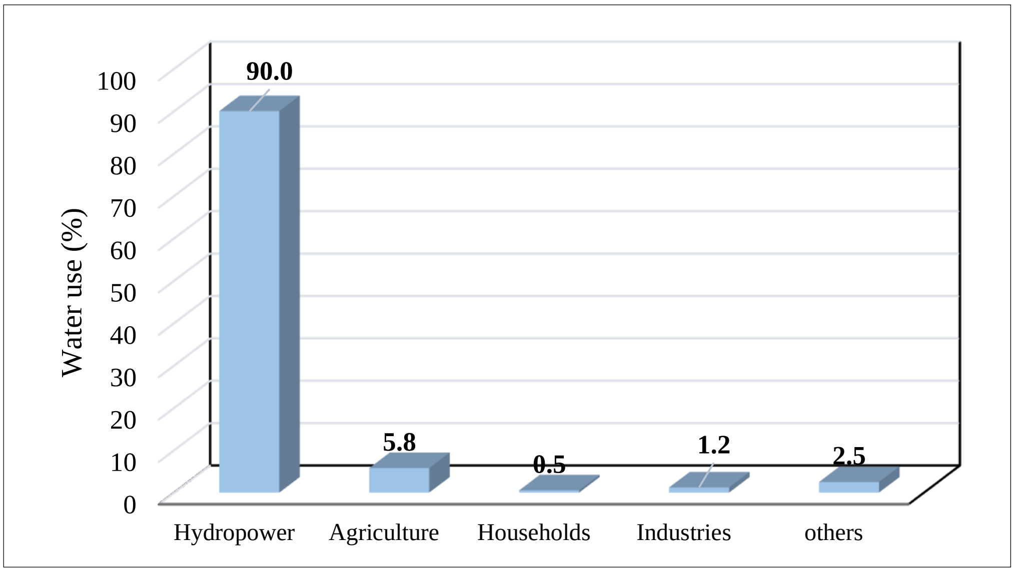


Figure 2-26: Water use in Zambia by per cent (JICA, 2003)

Zambia has two main river basins namely the Zambezi and Congo River basins. The Zambezi river basin is the largest and is comprised of three main catchments namely the upper Zambezi, Kafue, and Luangwa catchments. The Congo basin is also comprised of three catchments namely the Chambeshi, Luapula, and the Tanganyika catchments which are situated in the northern part of Zambia (MEWD, 2010). The six catchments together are the institutional water resources management entities that relate to the efficient management of the water resources in specific areas of Zambia including carrying out water flow and rainfall measurements (WARMA, 2018). The six main rivers of these catchments are namely, the Zambezi, Kafue, Luangwa, Chambeshi, Luapula, and Lufubu Rivers. The flows of these rivers and tributaries largely follow the seasonal rainfall patterns experienced in Zambia. Therefore, high flows are experienced in the northern part of the country where rainfall received is generally higher, however, the southern part of the country has more water flows due to the presence of large rivers such as the Zambezi, Kafue, and Luangwa (MEWD, 2010). Table 2-7 shows a summary of the catchment area, the length of the main rivers, and the estimated historical runoff. The locations of the catchments and Zambia's river systems are shown in Figure 2-27 and Figure 2-28 respectively.

Table 2-7: Average flow, length, and area of the six main river catchments of Zambia (MEWD, 2010)

River Catchment	**Main River**	**River Length* (km)**	**Catchment area* (km^2)**	**Average flow**(m^3/s)**
Zambezi	Zambezi	1,700	268,235	2,981
Kafue	Kafue	1,576	156,034	320
Luangwa	Luangwa	867	145,690	661
Luapula	Luapula	627	113,323	1,116
Chambeshi	Chambeshi	579	44,400	185
Tanganyika	Lufubu	250	17,096	65

*River length and Catchment area within Zambia only.
**Average flow is based on a 30-years period

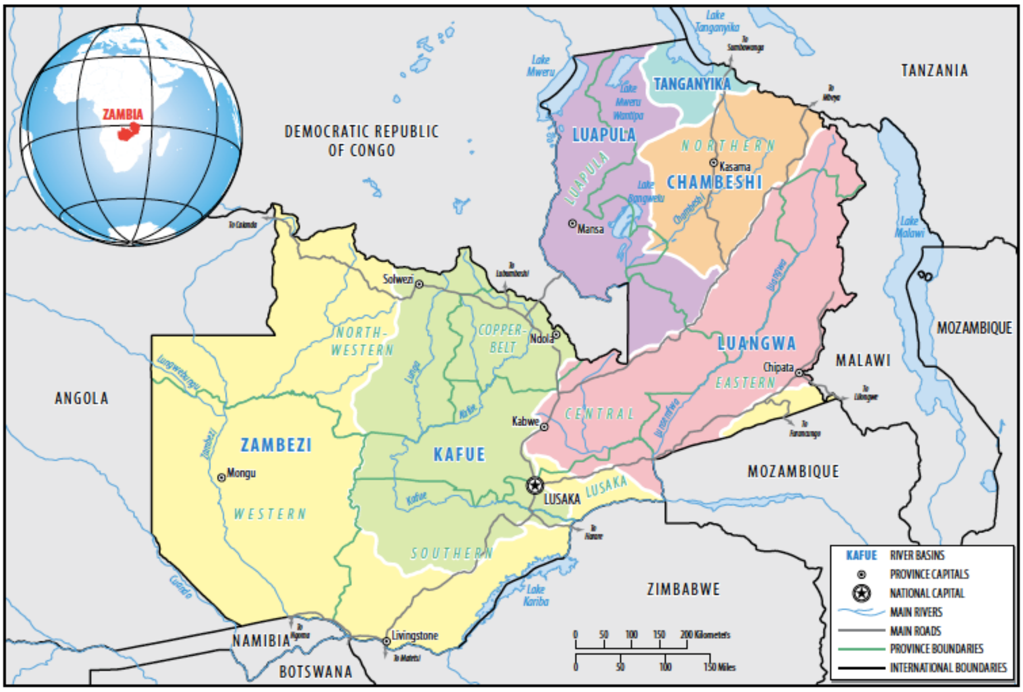


Figure 2-27: The Six River Catchments of Zambia (MEWD, 2010)

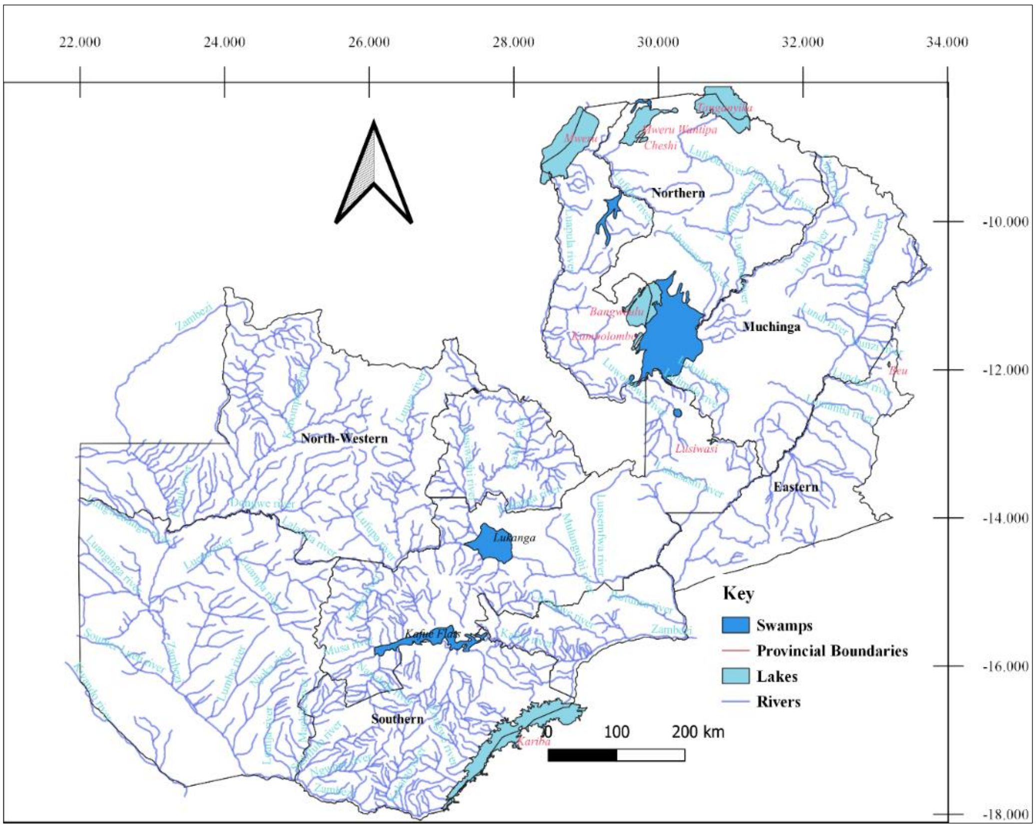


Figure 2-28: Surface water distribution in Zambia - Rivers, Streams, Lakes, and Swamps (WWF, 2019b)

2.5.1 Rainfall Situation

Zambia is located near the equator which gives the country its tropical climate. Zambia receives moderate rainfall ranging from an average of 600 mm per year in the southern areas to 1400 mm/year in the northern areas (MEWD, 2010). The rainfall regime in the country is uni-modal occurring mainly between October and April (Figure 2-29). The highest rainfall is received in December and January. In recent years, Zambia has experienced recurrent cycles of drought and floods which have had adverse effects on the water flow of rivers, streams, and infrastructure. The poor rainfall or droughts generally resulted in low water levels in Zambia's large dams especially those located in the southern parts of the country (Koppen, et al., 2015).

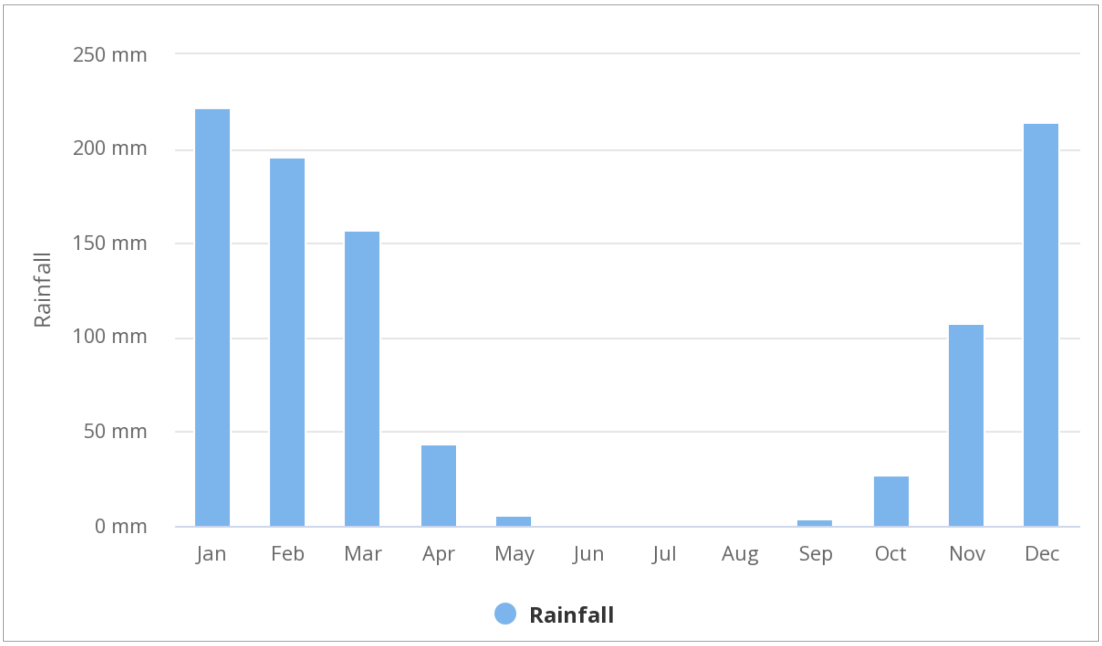


Figure 2-29: Average Monthly Rainfall Variation of Zambia for 1901 – 2016 (Harris & Jones, 2017)

2.5.2 Institutional, Legal and Policy Framework of the Zambian Water Sector

Zambia's water sector is made of up two subsectors, namely, the Water Supply and Sanitation Subsector and the Water Resources Management and Development Subsector (WARMA, 2018). Under the 2010 National Water Policy and the Water Supply and Sanitation Act No. 28 of 1997, the Ministry of Water Development Sanitation and Environmental Protection (MWDSEP) has the responsibility for Water Supply and Sanitation (WSS) in the country. The MWDSEP provides policy guidance, technical and financial control, and facilitates mobilization of foreign and local funds for capital development through the Department of Water Supply and Sanitation (DWSS). MWDSEP has the overall mandate to coordinate WSS to all water users through local municipalities (NWASCO, 2018b). There are presently 103 local municipalities in Zambia, and these are overseen by the ministry of local government and housing.

The local municipalities have the authority for the management of WSS to commercial water utilities and private schemes which have been established by the formation of joint ventures among the local municipalities. There are currently 11 commercial utilities and 6 private schemes licensed to provide WSS services in the 10 provinces of Zambia (NWASCO, 2018a). These utilities and private schemes are regulated by the National Water Supply and Sanitation Council (NWASCO). Adherence to the water quality standards and environmental protection in the WSS system is regulated by the Zambia Environmental Management Agency (ZEMA) which is under the MWDSEP, Department of Environmental Management (NWASCO, 2018b). Therefore, ZEMA ensures that the utilities and private schemes provide water to the users within acceptable standards and that effluents from industries and WWTWs are discharged into water bodies within acceptable water quality standards. ZEMA also ensures that environmental flow in rivers is provided from dam infrastructure. Figure 2-30 shows the institutional set-up of the Zambian water sector and Table 2-8 shows the commercial utilities and private schemes responsible for WSS service in Zambia.

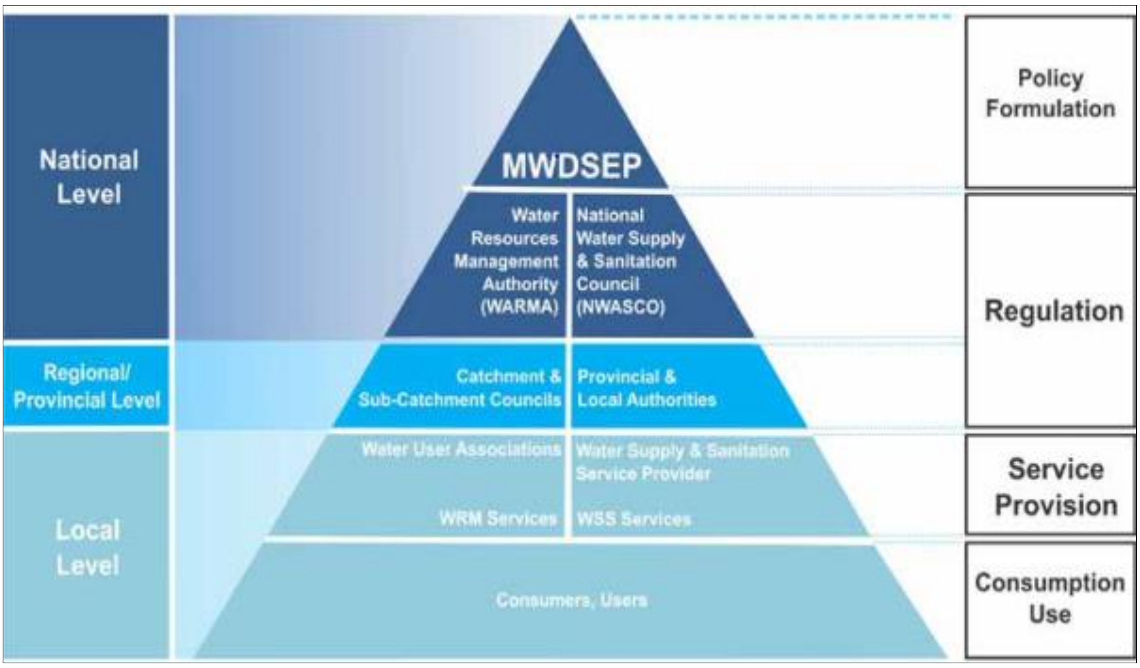


Figure 2-30: The Institutional set up of the Zambian water sector, source: (WARMA, 2018)

Table 2-8: Commercial utilities and Private schemes responsible for WSS in Zambia

Source: (NWASCO, 2018a)

Provider		**License Number**	**Location**
Commercial Utilities			
1	Lukanga Water & Sewerage Co. (LGWSC)	L57	Central Province
2	Southern Water & Sewerage Co. (SWSC)	L34	Southern Province
3	Lusaka Water & Sewerage Co. (LWSC)	L22	Lusaka Province
4	Kafubu Water & Sewerage Co. (KWSC)	L15	Copperbelt Province
5	Nkana Water & Sewerage Co. (NWSC)	L30	Copperbelt Province
6	Mulonga Water & Sewerage Co. (MWSC)	L25	Copperbelt Province
7	North Western Water & Sewerage Co. (NWWSC)	L31	North Western Province
8	Eastern Water & Sewerage Co. (EWSC)	L14	Eastern Province
9	Chambeshi Water & Sewerage Co. (CHWSC)	L46	Muchinga/Northern Province
10	Western Water & Sewerage Co. (WWSC)	L45	Western Province
11	Luapula Water & Sewerage Co. (LPWSC)	L11	Luapula Province
Private Schemes			
12	Kafue Sugar	L13	Kafue, Lusaka Province
13	ZESCO	L35	Livingstone, Southern Province, Kafue Gorge, Lusaka Province, Itezhi-Itezhi, Central Province
14	Lafarge Cement-Chilanga (LCC)	L36	Chilanga, Lusaka Province
15	Konkola Copper Mines Plc (KCM)	L44	Nampundwe, Central Province
16	Kaleya Small Holding Co. (KSH)	L17	Mazabuka, Southern Province
17	Zambia Sugar Plc.	L47	Mazabuka, Southern Province

Furthermore, all functions related to the Water Resources Management and Development in Zambia are also the responsibility of MWDSEP through the Department of Water Resources Development (DWRD) and the Water Resources Management Authority (WARMA). DWRD is responsible for policy formulation and guidance as well as internationally shared rivers.

WARMA acts as the regulatory body in the management and development of water resources in the whole country except for the internationally shared river segments (GRZ, 2011). It is responsible for regulating the construction of surface and groundwater infrastructure such as dams, weirs, gauging stations, and boreholes in the catchment areas including the issuing water rights. The authority is also responsible for managing and monitoring the use of all the existing water infrastructure in Zambia. WARMA owns more than 66 flow gauging stations across the country and records hydrological information through its catchment officers for planning and monitoring of surface water resources. It also checks the hydrology and hydraulic analyses, and design procedures on water projects in the catchment areas (WARMA, 2018). WARMA also works with the Department of Planning and Research (DPR) and other research institutions such as the University of Zambia (UNZA), Copperbelt University (CBU), and the Natural Resources Development College (NRDC) to undertake water-related research activities.

In addition to the institutional setup, there is also the Zambezi River Authority (ZRA) which is responsible for the operation and maintenance of the Kariba dam complex and all irrigation schemes on the internationally shared stretches of the Zambezi River. The ZRA also investigates and develops new dam sites and is responsible for issuing water rights on the Zambezi River (ZRA, n.d.). The Authority is also responsible for analysing and distributing hydrological and environmental information concerning the Zambezi River and Lake Kariba. The ZRA owns a network of 13 hydrometric stations that are used for the control of day-to-day operations of the Kariba dam water levels and the monitoring of the flow of the Zambezi river. The ZRA and ZEMA are responsible for assisting, conducting, and approving the Environmental and Social Impact Assessments (ESIA) for new projects requiring an ESIA such as hydropower plants.

2.5.3 Water Infrastructure in Zambia

Zambia develops its water resources through weirs, dams, reservoirs, boreholes, wells, WWTWs, WTWs, and canals. Zambia has 5 large dams and approximately 3,000 small dams (0.5 m – 15 m high) which are owned by various key players which include the local communities, individuals, private organizations, and government institutions such as the ZRA, DWRD and the Ministry of Agriculture (MoA) (AWF, 2012; MEWD, 2010). Table 2-9 shows the existing large dams in Zambia. The small dams are mainly situated in the drought-prone areas of the country such as the Southern, Eastern, and Central Provinces. Figure 2-31 shows an inventory of the dams including small dams located in Zambia.

According to the country report by Akayombokwa, et al., (2015), there are gravity-fed irrigation canals and weirs scattered across Zambia which contribute to an estimated irrigated area of 155,992 hectares per year. The canals and weirs have been developed by the government, commercial farmers, and private organizations such as Zambia Sugar ltd (which owns the Nakambala irrigation schemes). Figure 2-32 shows the distribution of gravity-fed irrigation schemes across the country.

Table 2-9: Details of the five existing large dams in Zambia

Compiled from Tshenyego, et al. (2019), World Bank (2018), ZRA (n.d.) & Blight (2013)

	Name of Dam	**River**	**Dam height (m)**	**Reservoir capacity (Million m^3)**	**Dam type**	**Owner/Developer**
1	Kariba	Zambezi	185	185,000	Concrete -Arch	ZRA
2	Kafue gorge lower	Kafue	140	112	Concrete face-Rockfill	ZESCO
2	Itezhi-tezhi	Kafue	65	6,000	Earth-rockfill	ZESCO
3	Kafue gorge upper	Kafue	32	785	Earth-rockfill	ZESCO
4	Mita hills	Lunsemfwa	49	679	Rockfill	Lunsemfwa hydro ltd
5	Mulungushi	Mulungushi	46	272	Rockfill	Lunsemfwa hydro ltd

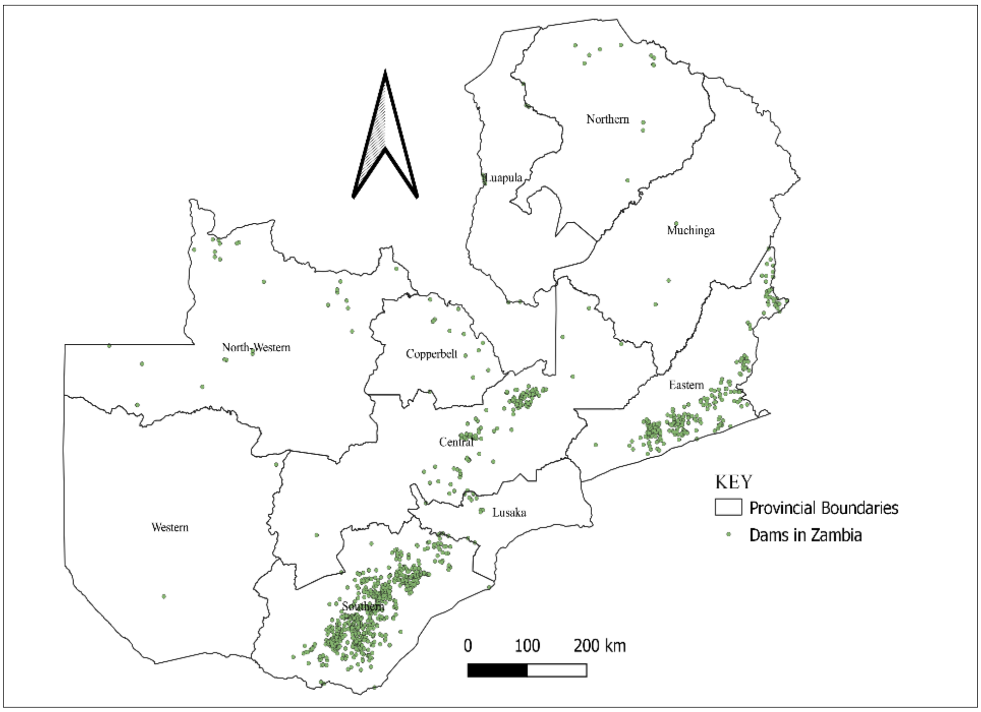


Figure 2-31: Small dams in the Southern Province of Zambia.

Modified after (World Bank, 2018a; WWF, 2019a)

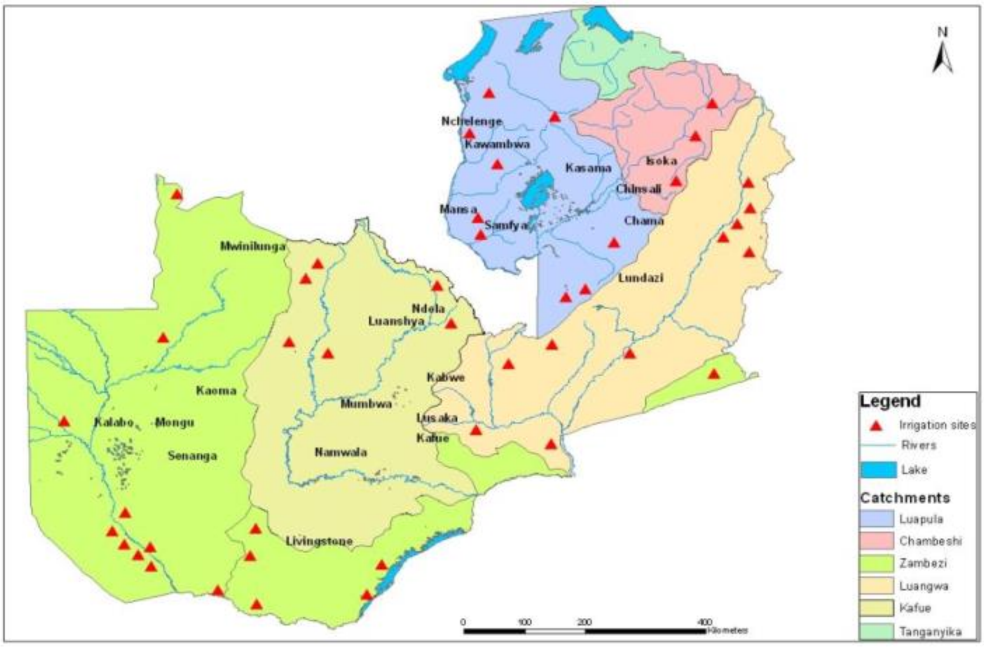


Figure 2-32: Distribution of irrigation schemes in Zambia (Akayombokwa, et al., 2015)

Furthermore, the commercial utilities and private schemes in the 103 municipalities have BWSDSs service infrastructure (which include WTWs, Storage Reservoirs, WWTWs, and bulk pipelines in their respective catchment areas). For instance, according to LWSC, (2011), the Lusaka Water and Sewerage Company (LWSC) operates 4 WTWs, 7 WWTWs, and more than 23 Water storage reservoirs in the city of Lusaka. The utility draws raw water from the Kafue

River via the Iolanda WTWs located 45 km away from Lusaka city and transports the water through a bulk water supply pipeline which has a capacity of 111,000 m^3/day. Furthermore, there are a total of 20 WTWs operated by the KWSC (8 WTWs), MWSC (8 WTWs), and NWSC (4 WTWs) in the Copperbelt Province (MWSC, 2017; KWSC, 2020; NWSC, 2018). There are also 12 WWTWs in the Copperbelt province operated by the KWSC (5 WWTWs) and NWSC (7 WWTWs) (KWSC, 2020; NWSC, 2018). Other utilities and private schemes need to be investigated to find out the existing water service infrastructure in their BWSDSs systems. An example of the water supply and distribution system is given in Figure 2-33 in the case of NWSC.

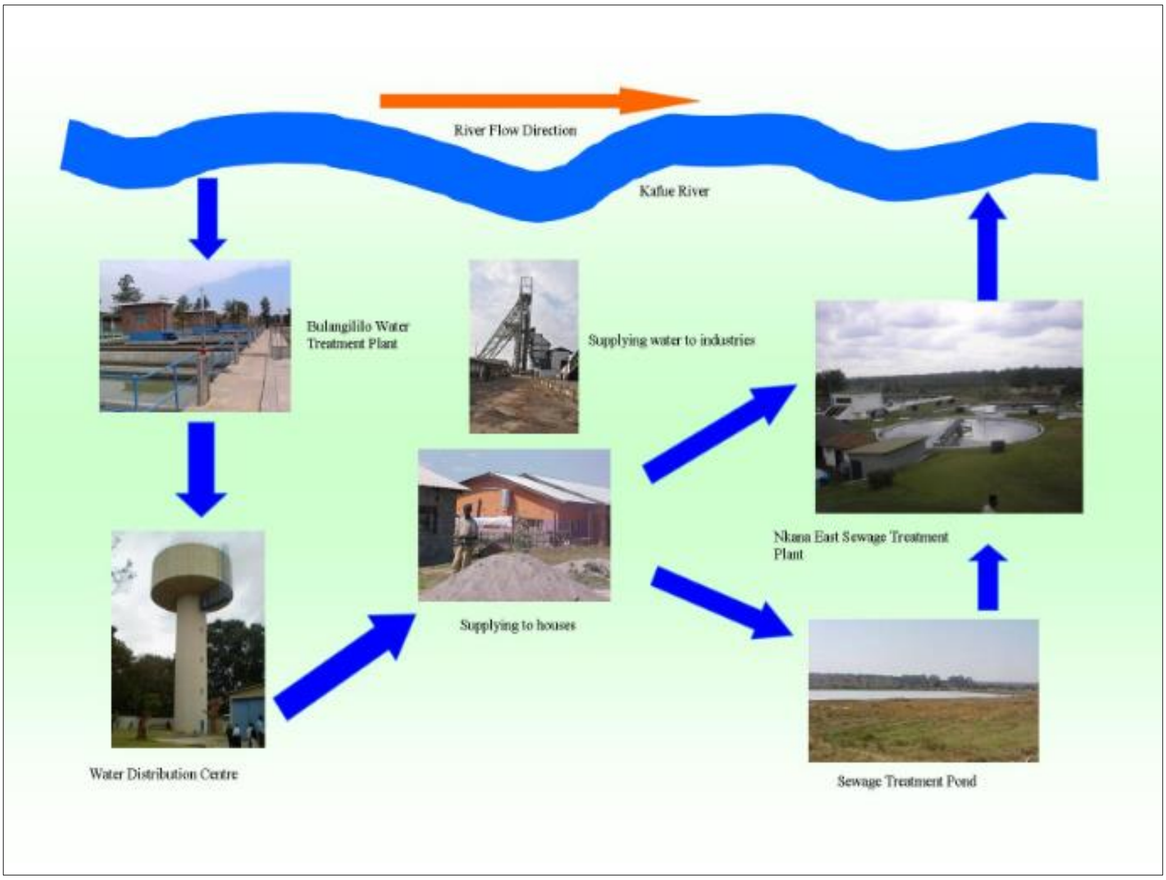


Figure 2-33: Layout of the NWSC bulk water supply and distribution system (NWSC, 2018)

2.6 BASICS OF HYDROPOWER DEVELOPMENT IN ZAMBIA

2.6.1 Policies and Regulations

The liberation and creation of a market economy in 1991 by the Government of the Republic of Zambia (GRZ) led to the promulgation of the first National Energy Policy (NEP) in the year 1994 (Mwaba, 2005). The NEP of 1994 was formed with the main objectives which included the restructuring of the power industry to open it up to the private sector, improving and promoting electricity access to more productive areas, and cost-effective development of hydropower generating plants. The policy also set the institutional framework under which these policy objectives would be implemented. This included the establishment of the ERB which regulates among others, against monopolistic tendencies of energy undertakings in Zambia (Cristian, 2018). The documents presented in Table 2-10 outline the current legal and regulatory framework of the power sector in Zambia.

Table 2-10: The Legal and Regulatory framework applicable to Hydropower projects in Zambia

Legal Document	Document Description
National Energy Policy (NEP) of 2019	This policy acts as a guide to policymakers, decision-makers and development managers in the government, private sector, Non-Government Organisations (NGOs), and civil societies on GRZ's intended actions in the energy sector, regional and international environments (Cristian, 2018). It repeals and builds on previous NEP of 1994 and 2008 and is anchored on the Seventh National Development Plan and Vision 2030 (MoE, 2019b). The NEP of 2019 emphasizes the consideration of climate change mitigation and adaptation while advancing sustainable development of the energy sector.
Electricity Act of 2019 (repeals and replaces the Electricity Act of 1995 and its amendments)	This Act formulates the principles of electricity generation, transmission, and distribution in Zambia. This Act also gives the ERB's mandate to issue electricity generation, transmission, and distribution licenses to both public and private undertakings. The electricity act defines the undertaking as any commercial enterprise, whether public or private, for production, generation, transmission, distribution, or supply of energy (GRZ, 2019a).
The Energy Regulation Act of 1995 (amended in 2003)	This Act formulates the roles of the ERB and defines its powers and functions (GRZ, 1995a; GRZ, 2003a).
Rural Electrification Act of 2003	This Act gives REA its mandate to oversee and implement the rural electrification program in Zambia (GRZ, 2003b).
The Seventh National Development Plan 2017 - 2021	In this document, GRZ focuses on adjusting electricity tariffs and fuel prices in a phased manner to reach cost-effective levels which attracts private investments. The government also focuses on gradually adjusting fossil fuel prices to reflect the negative impacts of pollution and also promoting alternative clean or improved cooking energy (MNDP, 2017).

Legal Document	Document Description
Zambia Grid Code (ZAGC) of 2006	All participants in the electricity supply industry in Zambia are required through Statutory Instrument No. 79 of 2013, of the laws of Zambia to adhere to the provisions of the ZAGC (Mfuni, 2018). Under the ZAGC regulations a "Grid Code participant" is defined as a Generator, End-user Customer, Distributor, Supplier, Transmission Network Service Provider, Embedded Generator, System Operator, or a Regional Operator and an end-user Customer is a consumer of electricity connected to the Transmission System or supplied directly by a Transmission Network Service Provider (ERB, 2016).
Distribution Grid Code of 2016	This code establishes the basic rules, procedures, requirements, and standards that govern the operation, maintenance, and development of the Zambian electricity distribution systems to ensure the safe, reliable, and efficient operations of the distribution systems (Cristian, 2018).
Standards	All the standards which deal with the transmission, distribution, metering, power reliability, power quality, and safety of appliances are published by the Zambia Bureau of Standards (ZABS) and are required to be followed (Kabira, et al., 2019).
The Rural Electrification Master Plan (REMP) (2008)	The document indicates a target of 51% rural electricity to be achieved by 2030. The REMP was developed by REA together with the Japanese government for the period from 2008 to 2030. The document lists small-scale hydropower plants and mini solar plants as options to enhance rural electrification in some remote areas of Zambia (JICA, 2008).
Vision 2030	This document references the achievement of universal access to clean, reliable, and affordable at the lowest total economic, financial, social, and environmental cost consistent with the national development by 2030 (GRZ, 2006).

2.6.2 Electricity Licensing

Under the Electricity Act of 2019, all undertakings in Zambia, whether public or private for production, generation, transmission, distribution, or supply of energy must be licensed by ERB. However, it should be noted that the Act also provides for two possible license exemptions which are (i.) mini-grids with an installed capacity of less than 100kW which is solely for own use and (ii.) a micro-generation installation that is connected at a distribution voltage level with a name-plate capacity of up to 10kVA single phase and 30kVA three-phase. However, the developer still needs to obtain all other applicable licenses and permits according to the steps given in Figure 2-34. For all non-exempt undertakings, the ERB issues the licenses under the categories and periods of validity listed in Table 2-11.

Table 2-11: License categories and period of validity in Zambia (Kabira, et al., 2019)

Category	Period of Validity (Years)
Generation	30
Transmission	30
Distribution	15
Supply	5
Combined with all above	20

Requirements for hydropower project licensing in Zambia include the Patents and Companies Registration Agency (PACRA) certificate, a consent from the National Heritage Conservation Commission (NHCC) confirming the site not to be a national or cultural heritage, and other pre-requisite permits which include environmental, water and land permits. These permits are described in Table 2-12. The licensing steps followed in Zambia for obtaining a license for combined generation, distribution, and supply of electricity for hydro off-grid systems with an installed capacity of less than 100 kW, and higher than 100 kW selling electricity to connected consumers are shown in Figure 2-35 and 2-36 respectively.

Table 2-12: Environmental, Water and Land approvals in Zambia

Compiled from GRZ (1995) & Kabira, et al. (2019)

Permit type	Description
Environmental	Under the Environmental Management Act of 2011, all hydropower projects for which an Environmental Project Brief (EPB) or an Environmental Impact Statement (EIS) is required, must be approved by ZEMA. It should be noted that the environmental permit is a pre-requisite for other permits such as the water permit.
Water use	Under the Water Resources Management Act of 2011 of the laws of Zambia which governs water resource use and management, hydropower projects need to obtain a water use permit for hydroelectric purposes from WARMA. The license for hydropower is usually given for a period of 25 or 30 years.
Land use	The Lands Act of 1995 of the laws of Zambia categorizes lands into two categories namely: state lands and customary lands. For hydropower projects on state lands, approvals must be obtained from the Ministry of Lands and Natural Resources (MLNR) and require the approval of the Commissioner of Lands and other relevant authorities such as district councils. For projects on customary lands, the area chief's permit is needed. It should be noted that local banks in Zambia do not often finance projects on customary lands.

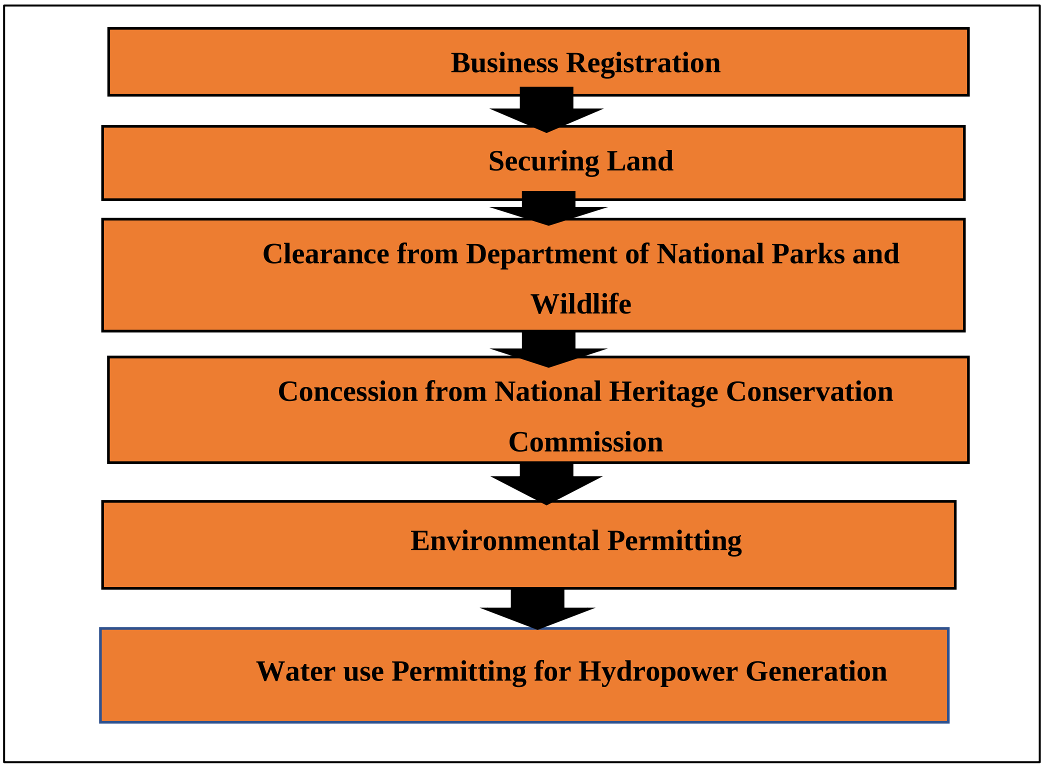


Figure 2-34: The licensing steps applicable to hydropower plants meant for own use (ERB, 2019b)

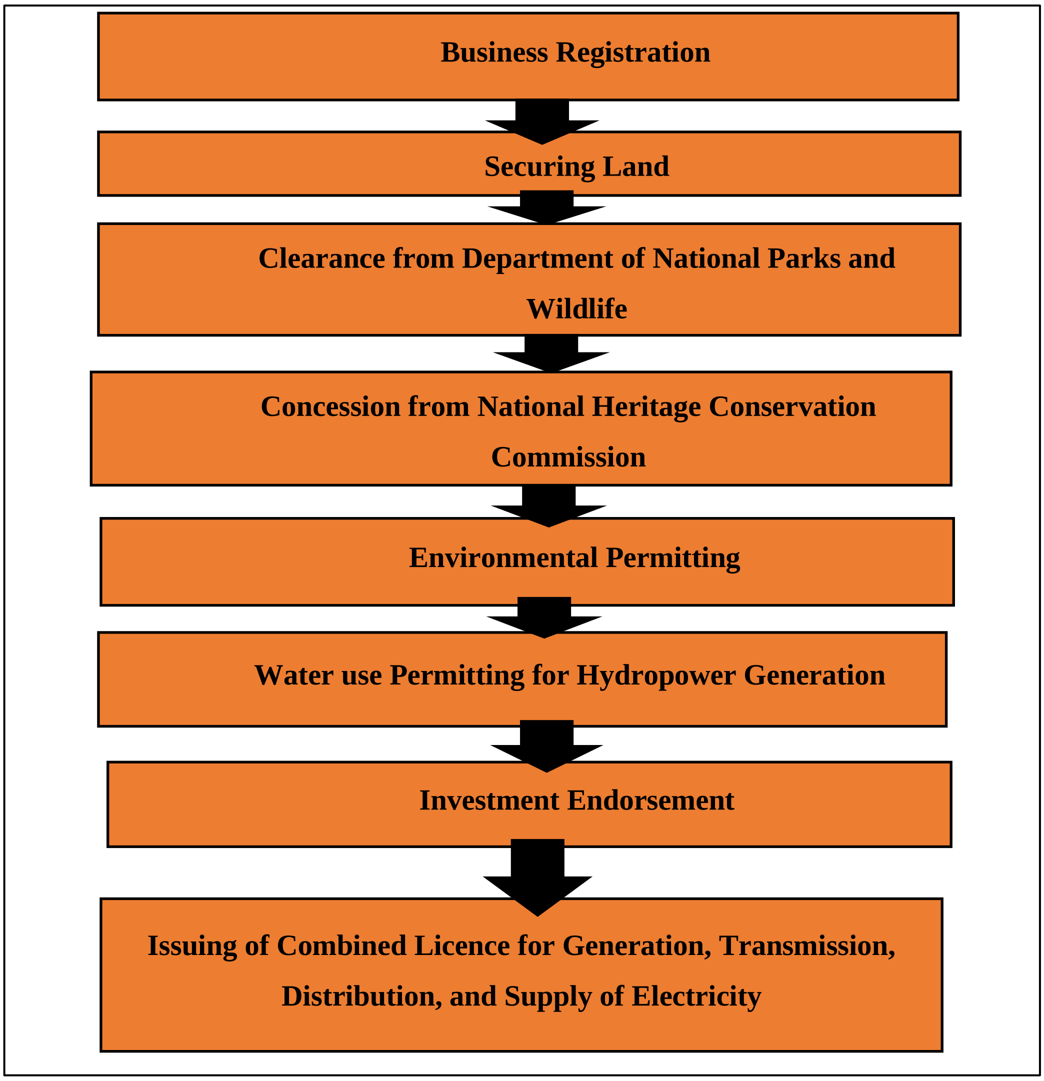


Figure 2-35: The steps for obtaining an electricity license for hydropower capacity of less than 100 kW (ERB, 2019b)

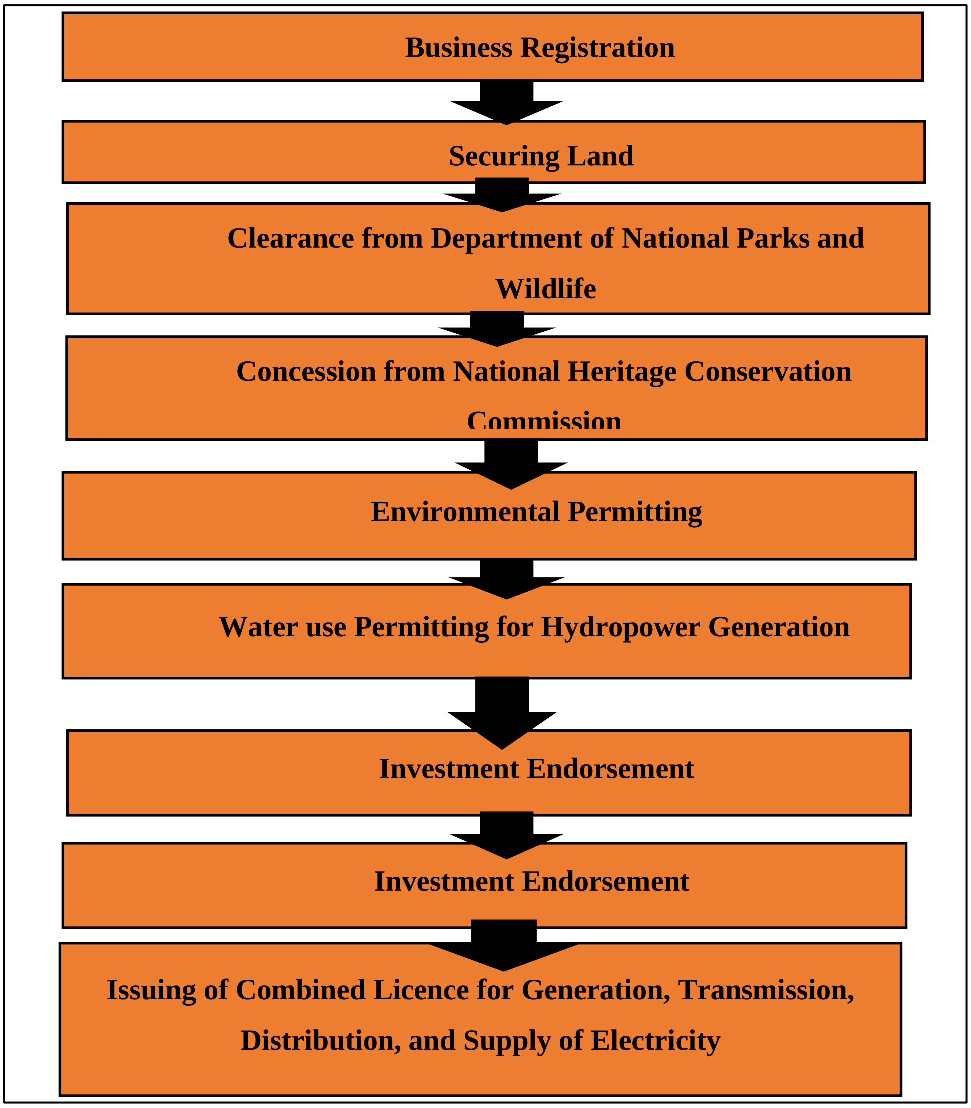


Figure 2-36: The steps for obtaining an electricity license for hydropower capacity of more than 100 kW (ERB, 2019b)

2.6.3 Protected areas

Protected areas are considered environmentally sensitive areas and siting of hydropower projects in these areas is discouraged because the areas are heavily managed through various national regulations. Zambia has a high density of protected areas which comprise approximately 40% of its inland area. The protected areas consist of a vast domain that encompasses 20 national parks, 3 wildlife and bird sanctuaries, 36 game management areas (GMAs), and several other categories such as wetlands and fisheries (GRZ, 2005; GRZ, 2014). National parks are primarily limited to tourism; human settlement and hunting are not permitted. GMAs act as buffer zones for national parks and are used to control the hunting of wild animals through a licensing system. Human settlement and economic activities are permitted in GMAs where these activities are not harmful to wildlife (Lindsey, et al., 2014).

The activities are regulated by the Zambia Wildlife Authority (ZAWA) which is mandated by law to manage the protected areas. Figure 2-37 shows the network of Zambia's protected areas.

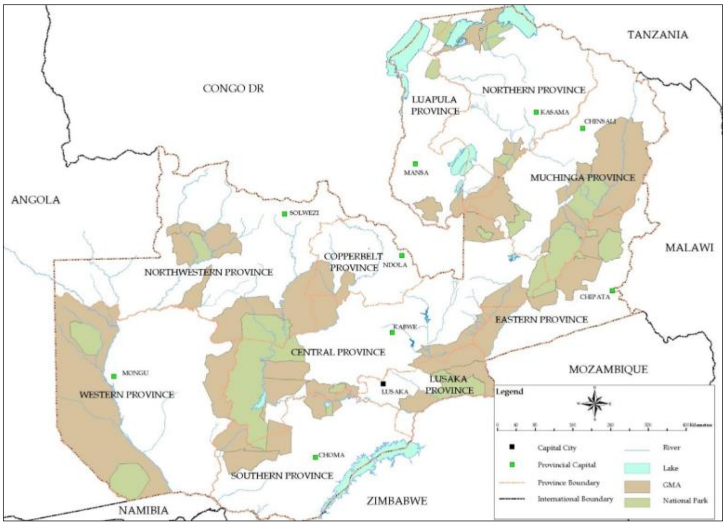


Figure 2-37: The Zambian Network of protected areas (GRZ, 2014)

2.6.4 Cost aspect

Hydropower is a capital-intensive technology that has long lead times for development and construction due to the significant feasibility, planning, design, and civil engineering works required (IRENA, 2020a). Various cost components add up to the total cost of setting up a hydropower plant. These are discussed in Table 2-13.

Table 2-13: Installation Cost of Hydropower Plants (IRENA, 2020a)

Cost Component	Description
Civil Works Costs	This consists of the engineering, procurement, and construction of the dam, reservoir, tunnelling, canal, penstock, intakes, and powerhouse. They also consist of the cost of building the site access infrastructure and components of the grid connection. As an example, Table 2-14, gives the actual price of some Civil works units for the existing Zengamina mini-hydropower plant in Zambia in the year 2008 and inflated prices in the year 2022. The prices were inflated using the consumer price indexes (CPI) for the years 2008 and 2022.;
Electro-magnetic equipment costs	This includes the cost of turbines, generators, transformers, cabling, and control systems. This cost is strongly correlated with the capacity of the hydropower plant because a proposed capacity of a hydropower plant can be achieved by a combination of a few large turbines or many small turbines and generating units. The cost of electro-magnet equipment is a high percentage (30 – 40%) of a small hydropower budget.

Cost Component	Description
Project Development Costs	This includes the costs of planning and feasibility assessments, environmental impact and social analysis, licensing fees, fish and wildlife measures, development amenities, water quality monitoring, and historical and archaeological mitigations. In Zambia, the environmental impact fees charged by ZEMA are shown in Table 2-15 and the water licensing fees charged by WARMA for hydroelectric use are shown in Table 2-16.

Table 2-14: Actual prices of civil works units used in the construction of the Zengamina hydropower plant in Zambia (JICA, 2008; ZamStats, 2022)

Item	Unit Price (2008) CPI = 81.3	Unit Price (2022) CPI = 344.9
Masonry	USD 150 /m^3	USD 636 /m^3
Concrete	USD 600 / m^3	USD 2,545 / m^3
Rebar	USD 1,400 / tonne	USD 5,939 / tonne
Tunnel boring	USD 1,000 /m	USD 4,242 /m
Common Excavation	USD 10 /m^3	USD 42 /m^3
Rock Excavation	USD 60 /m^3	USD 255 /m^3
Steel Structure	USD 2,800 /tonne	USD 11,878 /tonne
Access Road	USD 30,000 /km	USD 127,269 /km
Road Maintenance	USD 3,000 /km	USD 12,726 /km
33 kV distribution line	USD 36,000 /km	USD 152,723 /km

Table 2-15: Environmental license fees in Zambia (GRZ, 1997; ZEMA, 2022)

Type	Project Cost (USD)	Fee units	ZMW	EUR
EPB	-	43,333	12,999.90	651.0
EIS	Less than 100,000	43,333	12,999.90	651.0
	100,000 – 500,000	216,665	64,999.50	3255.2
	500,000 – 1,000,000	541,662	162,498.60	8137.9
	1,000,000 – 10,000,000	1,083,324	324,997.20	16275.9
	10,000,000 – 50,000,000	2,166,650	649,995.00	32551.7
	Greater than 50,000,000	3,249,975	974,992.50	48827.6

Note: i) As of 2022, each fee unit is equal to 0.30 ZMK (ZEMA, 2022)

ii) 1 ZMW = 0.05008 EUR (updated rates are available at https://www1.oanda.com/currency/converter/)

Table 2-16: Hydropower projects water permit fees in Zambia (GRZ, 2018b; WARMA, 2022)

Item	Fee unit	ZMW	EUR
Application for permit for usage up to 10 MW	16,666.67	5,000	250.4
Application for Permit for Additional usage from 10-250 MW	3,333.33	999.99	50.1
Annual access charge per kW of installed capacity	2.529976	0.75899	0.038
Use per kWh generated	0.003069	0.00092	0.00005
In a cascade of any installed capacity per kWh generated	0.002534	0.00076	0.00004

Note: i) As of 2022, each fee unit is equal to 0.30 ZMK (WARMA, 2022)

ii) 1 ZMW = 0.05008 EUR (updated rates are available at https://www1.oanda.com/currency/converter/)

2.6.5 Financing

Funding opportunities for hydropower projects in Zambia are available both from domestic and international donor funders. Domestic funding opportunities for the private sector are limited especially for small-scale hydropower because of their markets, technologies, and business models which are still unknown to local commercial banks (Kabira, et al., 2019). This is so because local commercial banks consider conventional hydropower to be highly profitable and less risky than small-scale hydropower. On the other hand, the international-donor-related funding opportunities for small-scale hydropower are increasing in Zambia and developers may access them (Cristian, 2018). Table 2-17 describes and lists the available funding opportunities (both domestic and international) for hydropower projects in Zambia.

Table 2-17: Funding opportunities available for hydropower related projects in Zambia

Adapted from Cristian (2018)

Funding opportunity	**Period from**	**Funded by**	**Fund available to,**
Africa Clean Energy (ACE) Business Programme.	2017	DFID	Enterprises across Africa supply off-grid energy products and services.
Africa Enterprise Challenge Fund– Renewable Energy and Adaptation to Climate Technologies (REACT).	2008	Alliance for Green Revolution in Africa AGRA) family. Governments of Australia, Canada, Denmark, The Netherlands, Sweden, and the United Kingdom), and international financial institutions.	Private sector businesses
Beyond the Grid Fund for Zambia.	2016	SIDA, Power Africa.	Industry actors (Independent energy service providers).
China-Zambia South Cooperation on Renewable Energy Technology Transfer.	2014	China, GRZ, and Denmark.	Government Regulatory bodies.
Electricity Service Access Project.	2017	World Bank	Government regulatory bodies and private sector
GET-FIT.	2013	KFW, DFID.	Energy Authorities, On-IPPs.
Grand Challenges for Development Initiative (GCDI).	2012	USAID, SIDA, BMZ, Duke Energy, OPIC.	Energy Enterprises.
Increased Access to Electricity Services Project.	2009	JICA, World Bank	ZESCO.

Funding opportunity	**Period from**	**Funded by**	**Fund available to,**
InfraCo Africa.	2004	Private Infrastructure Development Group (PIDG) Trust, European Government.	Project developers.
Nordic Climate Facility (NCF).	2009	Nordic Development Fund.	Companies that wish to test an innovative business concept that contributes to increased climate resilience and /or mitigates climate change.
Off-Grid Market Opportunity Tool.	2013	AfDB, Canada, DBSA, SE4All, EU, AFD, IDC, IRENA. Japan, NEPAD, Norway, Sweden, UK aid, World Bank, The USA, and private Sector.	Governments and donors.
Private Enterprise Programme Zambia (PEPZ).	2013	UKaid	Micro, small, and medium enterprises.
Rural Electricity Fund (REF).	1995	ZESCO	Private-driven rural electrification projects.
Scaling Solar.	2015	Denmark, Netherlands, Power Africa, DFID, IDCP.	Government and Utilities.
Scaling-up Renewable Energy in Low Income Countries Program (SREP).	2009	DFID, Norway, Netherlands, the USA, Sweden, Japan, Switzerland, Australia, Denmark, South Korea, Spain.	Governments.
Technology and Innovation in Developing Economies (TIDE) Fund.	2013	AFDB	Companies that use new technology to provide affordable services in the energy sector.

2.7 CASE STUDIES

Hydropower atlases have been developed and implemented for some African countries. These have been developed mainly for run-of-river types of hydropower. These existing atlases provide good examples of successfully developed hydropower atlases and therefore provide applicable information regarding hydropower potential and the data selection process. Furthermore, there are several existing hydropower installations on existing water infrastructure such as WWTWs, Weirs, Bulk Water Supply Systems, Canals, and Dams around the world. Most of these installations are not located in Zambia but serve as good examples regarding the fundamentals of evaluating hydropower potential on existing water infrastructure.

2.7.1 Case Study I: The Madagascar Hydropower Atlas

The assessment and mapping of the Madagascar hydropower atlas (Figure 2-38) were completed in 2017. The study delivered a spatial database that shows that the small hydro of Madagascar consists of more than 350 potential sites that have a power capacity in the range of 1-20 MW with a cumulative capacity of approximately 1,350 MW (World Bank, 2017b). Hydropower potential sites were identified from relevant literature and new sites were identified using SiteFinder, a spatial analysis tool that identifies river stretches featuring a high hydropower potential based on precipitation and topography data (a commercial-owned tool developed by SHER Ingénieurs-Conseils). The study showed that Madagascar has a great small-scale hydropower potential for both private and government investments. The selection criteria of the potential sites that were included in the Atlas were a result of complex spatial planning which was based on the considerations presented in Table 2-18.

Table 2-18: Multicriteria considerations in the selection process of potential hydropower sites added in the Hydropower Atlas of Madagascar (World Bank, 2017b)

Consideration	Description
Technical	This involved the assessment of the hydraulic, hydrological, geological risk, and topographic characteristics of the site to judge if the site was favourable or not.
Economic	The Levelized Cost of Energy (LCOE), including the costs related to the access and evacuation of the produced energy, was estimated in the process of determining the promising sites.
Environmental	Common ownership with protected areas, villages, military sites, and the presence of important sediment transport even in the dry season were determined in the selection of promising sites.
Adequacy	This involved the determination of the adequacy between energy supply and demand.

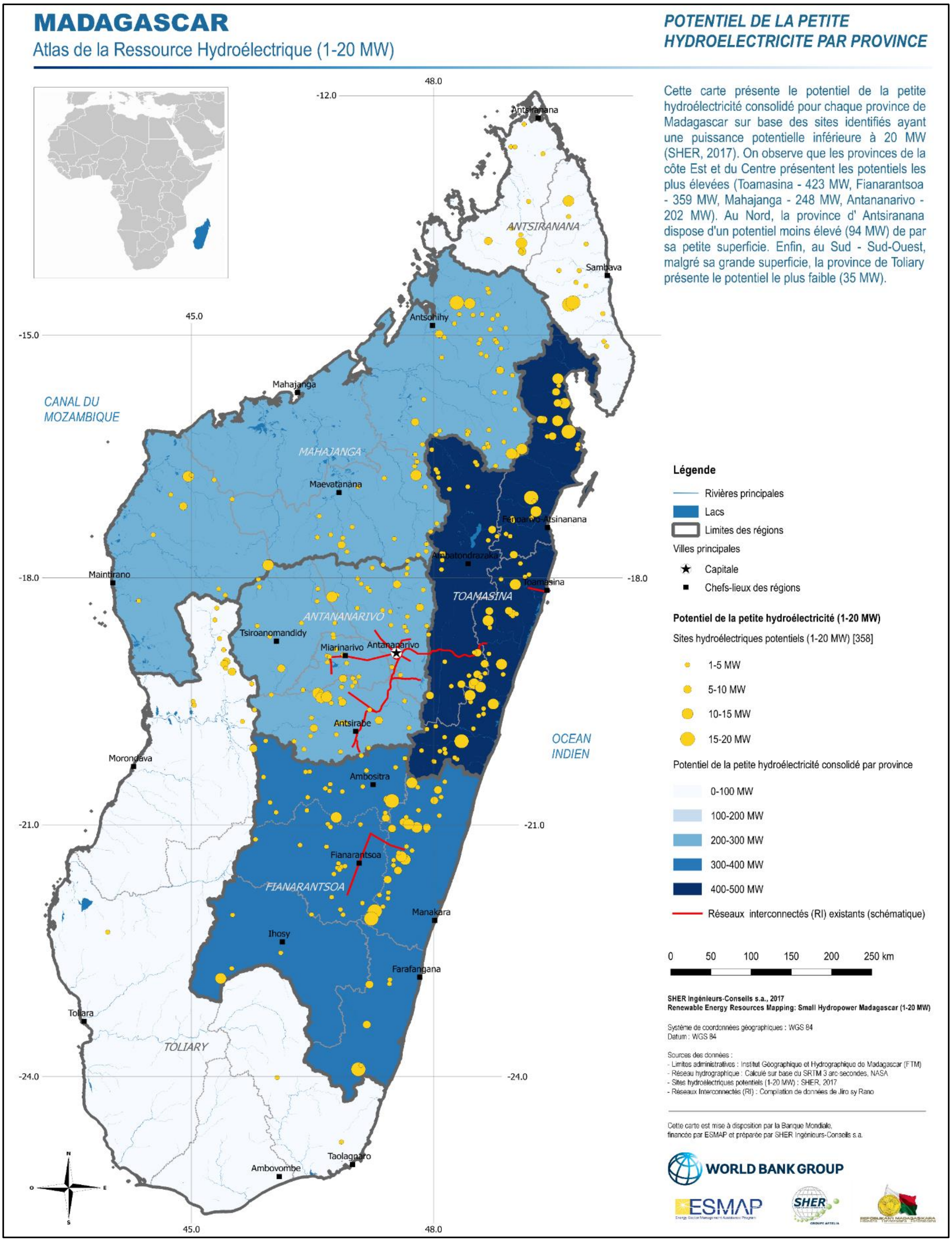


Figure 2-38: Madagascar Hydropower Atlas (1 – 20 MW) (World Bank, 2017b)

2.7.2 Case Study II: The Tanzania Hydropower Atlas

The Tanzanian Hydropower Atlas (Figure 2-39) focuses exclusively on potential sites in the range of capacities between 0.3 and 10 MW (World Bank, 2018b). All the information related to the hydropower sector in Tanzania having geographical coordinates were compiled into a Geographic Information System (GIS). The spatial database of potential hydropower sites is the result of the consolidation of information from various sources: it contains a total of 455 potential hydropower sites amongst which 278 came from relevant literature and 177 newly identified by SiteFinder (World Bank, 2018b). The selection criteria of the potential sites that were included in the Atlas were as a result of a multicriteria analysis which was based on the considerations described in Table 2-19. The study showed that Tanzania has good small-scale hydropower potential for private or government investments and the potential is still largely untapped.

Table 2-19: Multicriteria considerations in the selection process of potential hydropower sites added in the Tanzanian Hydropower Atlas (World Bank, 2018b)

Consideration	Description
Power Capacity	This was based on the project scope. Hydropower potential sites with capacities between 0.3 MW and 10 MW were added to the Atlas.
Technical	This involved the assessment of the hydraulic, hydrological, geological risk, and topographic characteristics of the site including sediment transport. Hydropower potential for new sites was determined based on rainfall and topography using the SiteFinder tool. The design flow used in the analysis was considered to correspond to the median flow of the river.
Economic	This involved the estimation of the Levelized Cost of Energy (LCOE), including the costs related to the access and transmission lines to select the promising sites.
Environmental	Hydropower potential sites with a lack of environmental constraints that may jeopardize the development of the project were considered.
Adequacy	The consideration of the adequacy between energy demand and supply from the potential site.

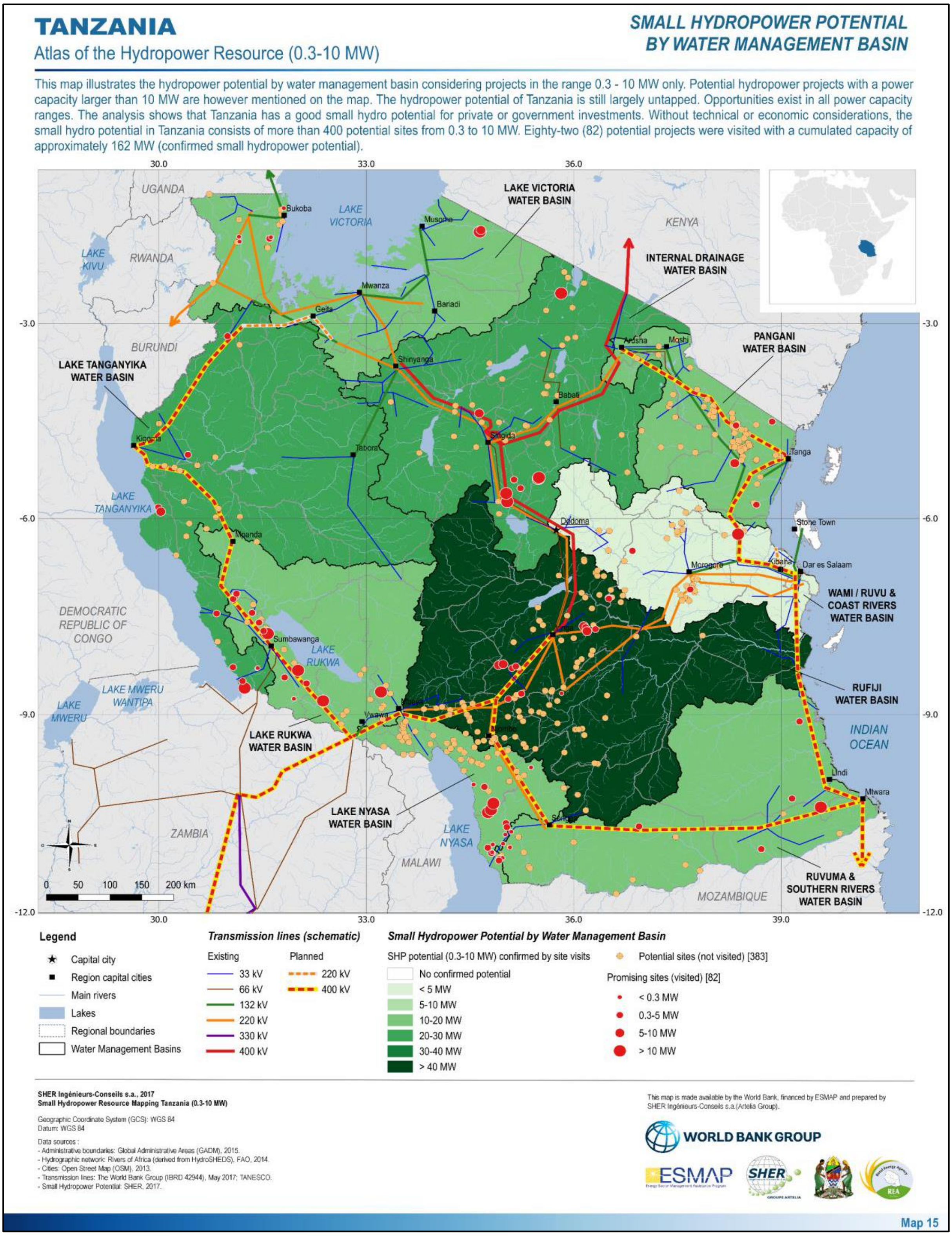


Figure 2-39: The Tanzanian Hydropower Atlas (World Bank, 2018b)

2.7.3 Case Study III: The Rwanda Hydropower Atlas

The mapping of the Rwanda Hydropower Atlas was completed in 2010 by the country's Ministry of Infrastructure (Kazungu, et al., 2016). The Atlas identified over 192 potential sites with power capacities of less than 50 kW and 333 potential sites with capacities ranging between 50 kW and 1 MW. The existing potential sites were identified both from literature and the SiteFinder tool. According to Gasore, et al., (2018), 28 of the potential sites have already been developed and feasibility studies for other sites are ongoing. This study enabled the government and private sector to be aware of the untapped small hydro potential in Rwanda of over 300 MW. Figure 2-40 shows the Rwanda Hydropower Atlas.

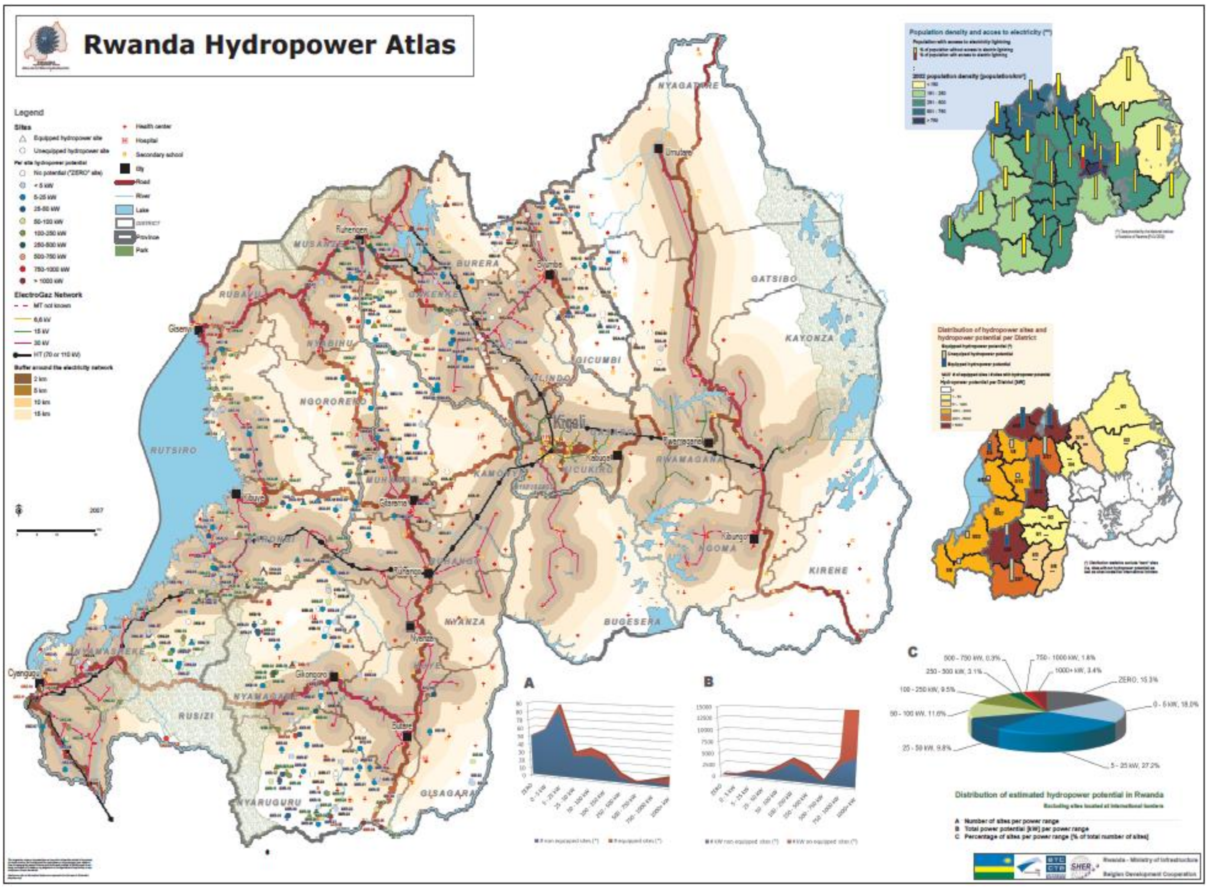


Figure 2-40: The Rwanda Hydropower Atlas (Rwanda Water Portal, 2019)

2.7.4 Case Study IV: The ECOWAS Hydro Map

The mapping of the small hydro potential in 14 Economic Community of West African States (ECOWAS), was done by Pöyry working in conjunction with the ECOWAS Observatory for Renewable Energy and Energy Efficiency (ECREEE). The ECOWAS Small-Scale Hydropower Map addressed the untapped potential of mini/micro (<1 MW capacity) and small hydropower (ranging from 1 MW – 30 MW) sector in West Africa (Pöyry & ECREEE, 2017). The potential sites were identified using GIS technology and hydrological conditions modelling for more than 500,000 river reaches in West Africa. Figure 41 shows the hydropower potential map of ECOWAS.

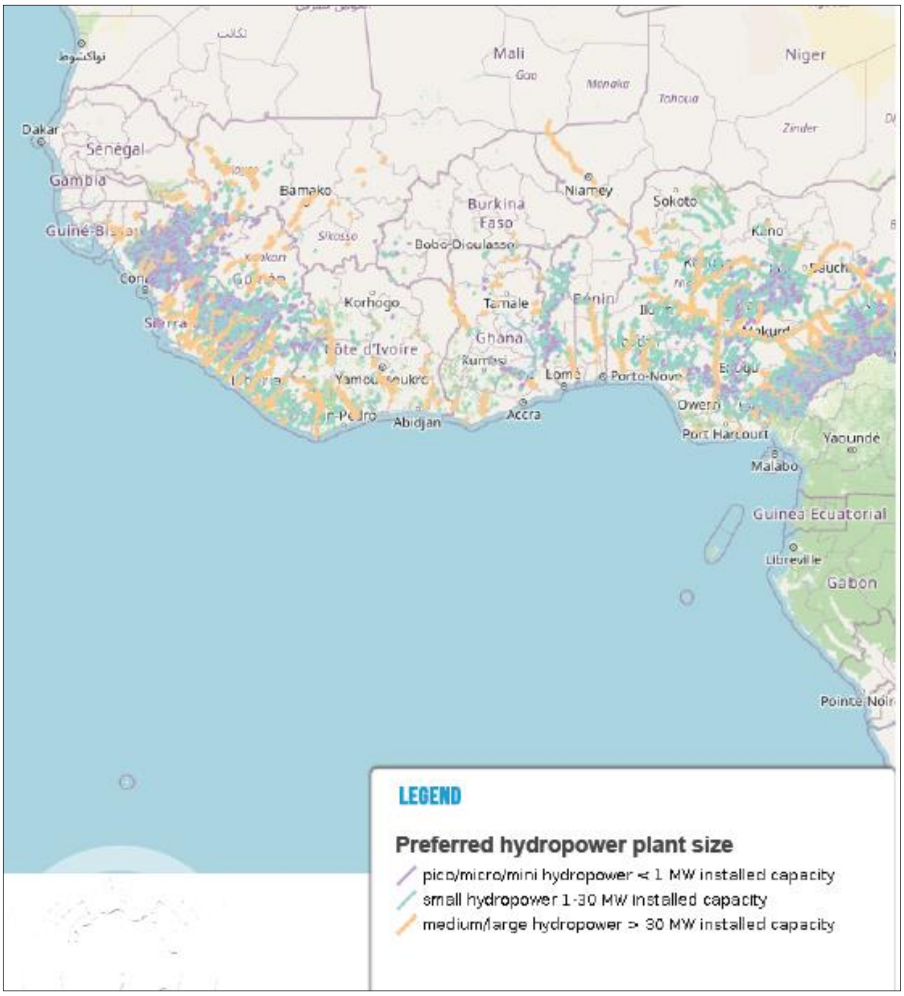


Figure 2-41: The ECOWAS Hydro-Resources Map (available at ECOREX Web Services*)

**http://www.ecowrex.org/mapView/index.php?lang=eng&mclayers=layerPlantSize&lat=1507621.6019522&lon=-2309999.6995641&zoom=7*

2.7.5 Selection Criteria for Hydropower Potential sites included in the existing atlases.

As already stated, the hydropower potential sites in the existing hydropower atlases were identified from relevant literature and spatial analysis using the SiteFinder tool. The hydropower potential sites were required to meet the selection criteria to be included in the atlas. The preliminary selection process and criteria used in the selection of the potential sites included in the Madagascar and Tanzania hydropower atlases are given in Figure 2-42 and Figure 2-43**,** respectively. There is little information available on the selection criteria used in the development of the Rwanda hydropower atlas. As an example, the selection process used in the development of the Madagascar hydropower atlas is explained as follows,

- Site Identification: 1,537 potential sites were identified from existing literature and 987 sites were identified using Site Finder.

- Initial selection: The 1,537 sites were checked if the coordinates for their locations were available and correct. Only those with available coordinates were considered. The 987 sites from SiteFinder were checked if they had a potential of 50kW and above. Only sites meeting this criterion were considered.
- The result was a total of 2,045 potential sites (1,470 from literature, 575 from SiteFinder). The sites from both sources were checked for duplicates. 163 sites from SiteFinder were already identified from the literature, therefore, SiteFinder added 412 sites to the database. The total number of sites after clearing the duplicates was 1,882.
- The 1,882 were checked if they were within the country's borders and if the information on the gross head, discharge, and capacity were available. Only sites meeting these criteria were considered.
- The result was a total of 1,301 potential sites. These were compiled to form the Gross Database of hydropower potential sites in Madagascar (World Bank, 2017a).
- Finally, sites not located in protected areas and having hydropower potential of 1-20 MW were selected and added to the hydropower atlas.

The studies on the existing hydropower atlases also developed a prioritization selection process and criteria for the selection of the most promising sites from the hydropower atlas. This process included hydropower sites conforming to certain technical and economic criteria. Site visits to the identified sites were also conducted. The Madagascar study identified 33 most promising sites and out of these 20 were identified to be more promising for short-term investments (World Bank, 2017a). The Tanzania study as well identified more than 70 promising sites of which 20 sites were considered to have more priority for short-term investments (World Bank, 2015).

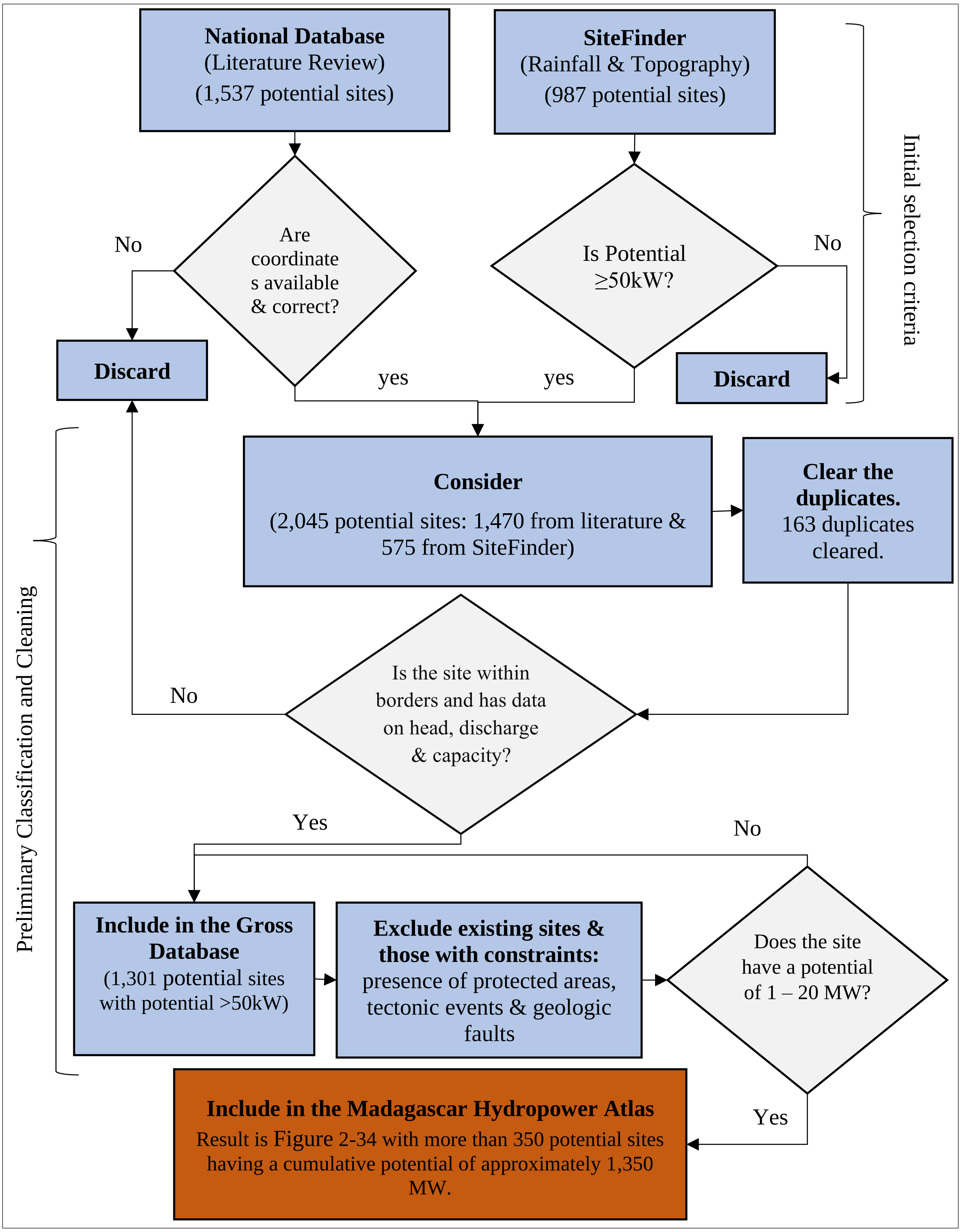


Figure 2-42: Selection process and criteria used in the selection of run-of-river hydropower potential sites included in the Madagascar Hydropower atlas. Adapted from (World Bank, 2017a)

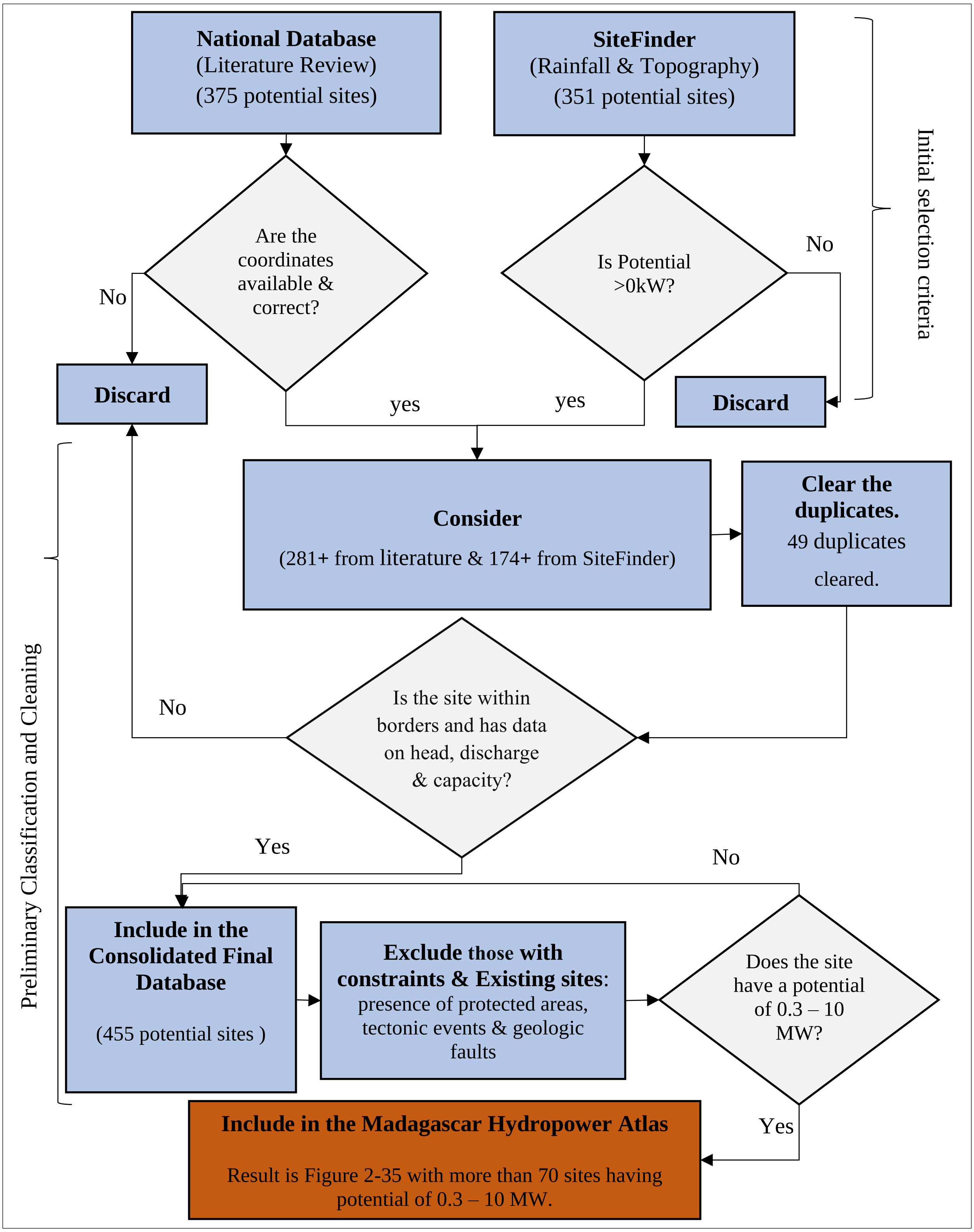


Figure 2-43: The Selection process and criteria used in the selection of run-of-river hydropower potential sites included in the Tanzania Hydropower Atlas. Adapted from (World Bank, 2015).

2.7.6 Data Selection Criteria for Evaluation of Hydropower Potential

As already stated, new sites were identified using the SiteFinder tool which uses rainfall and topography data while the other sites identified from the literature were required to have discharge, head, and capacity information. The evaluation criteria used in the data selection process for the calculations of the hydropower potential of the sites included in the existing atlases are presented in Table 2-20. The table also includes data criteria from other studies on the run-of-river hydropower potential evaluation. The evaluation criteria for other types of hydropower obtained from other studies that have been conducted around the world are presented in Table 2-21.

Table 2-20: Existing data selection criteria for the run-of-river hydropower potential evaluation

Data type	**Data selection criteria**	**Reference (s)**
Discharge (m^3/s)	- considered the mean flow at a gauged site to be equal to 0.0065 times the average annual rainfall in the watershed (m^3).	Tanzania Hydropower Atlas (World Bank, 2015)
	- considered the mean flow at an ungauged station (with a gauged station upstream or downstream having watershed ratios of 0.5 – 2) to be equal to the mean flow at the gauging station times the watershed area ratio (ungauged area / gauged area).	
	- considered the mean flow at an ungauged site (with a gauged station upstream or downstream having watershed ratios below 0.5 or above 2) to be equal to 0.0065 times the average annual rainfall in the watershed (m^3).	
	- selected gauged stations with less than 5% of missing data in the evaluation of the design flow.	
	- considered the design discharge to be equal to the median (Q_{50}) of the interannual mean flows.	Tanzania, Madagascar Atlas (World Bank, 2015; World Bank, 2017a)
	-sites with design flow (Q_{50}) <50m^3/s were considered.	
	- considered design flow to be equal to Q_{80} (80% days availability on the FDC) for mini-hydropower in Northern, North-western, Luapula and Western Provinces of Zambia.	(JICA, 2009)
	- considered design flow to be equal to Q_{50} and Q_{75} on the FDC for the run-of-river flow in South West England	(Vincenzo, et al., 2019)
	- considered design flow to be equal to Q_{30} on the FDC for the small and mini run-of-river hydropower in Thailand.	(Rojanamon, et al., 2009)
	- considered sites within the area of 113 – 2,099 km^2 of the gauged stations to successfully calculate the design flow at the ungauged sites in Thailand	

Data type	Data selection criteria	Reference (s)
	- assumed 100% river discharge was available for hydropower generation	ECOWAS Hydropower Map (Pöyry & ECREEE, 2017a)
Head	- sites with Gross head measured using a total station were considered.	(JICA, 2009)
	- considered sites with a Gross head of 3m and above.	
	- the effective head was set at 90% of the Gross head.	
	- the head was calculated at intervals of 100m using GIS for the selected sites	(Vincenzo, et al., 2019)
	- the head was assessed based on the elevation difference (derived from DEM) between the selected point and its closest upstream neighbour, which in this case was located at a distance of 1000m.	(Korkovelos, et al., 2018)
	- the maximum distance from the weir to the powerhouse was set at 5km (head was calculated within this range) in the study	(Kusre, et al., 2010)
	- the head was assessed at 400m intervals in the study	(Ballance, et al., 2000)
	- the effective head was assumed to be equal to 87% of the Gross Head	ECOWAS Hydropower Map (Pöyry & ECREEE, 2017a)
Riverbed slopes	- rivers with slopes of less than 5% were considered	(Vincenzo, et al., 2019)
	- sites with a minimum bed slope of 2% and more were selected.	(Kusre, et al., 2010)
	- slopes were calculated and analysed at intervals of 400m for the selected sites.	(Ballance, et al., 2000)
	- slopes for the river stretches were derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) GDEM v2 DEM data with a spatial resolution of 30m.	(World Bank, 2015)
	- slopes were calculated and analysed at intervals of 100m for the selected sites.	(Vincenzo, et al., 2019)
Distance between nearest sites	- sites selected were required to be at least 1,000m apart.	(Ballance, et al., 2000)
	- the distance between small hydropower plants maintained at 100m	(Garegnani, et al., 2018)

Data type	Data selection criteria	Reference (s)
	- the minimum distance for the consecutive sites selected was set at 500m.	(Kusre, et al., 2010)
River data	- rivers within the country's borders were considered.	(World Bank, 2015; World Bank, 2017a)
	- rivers with flow accumulation of 100,000 cells (50 x 50 m) were selected for hydropower potential evaluation	(Vincenzo, et al., 2019)
Topography	- sites appearing on the 1: 50,000 topo map were considered	(World Bank, 2015)

Table 2-21: Criteria in the data selection process for hydropower potential evaluation for other types of hydropower

Hydropower type	Data type	Data selection criteria	Reference (s)
Hydrokinetic in stream channels	effective potential	assumed 50% of the potential would interfere with fish concerns at the sites.	(National Research Council, 2013)
	minimum potential	assumed 3 kW as a minimum potential in rural electrification application	(Mvula, et al., 2019)
Hydrokinetic	Velocity	Hydrokinetic turbines usually require sites with velocities of around 2-3.5m/s	(Niebuhr, et al., 2019)
	Velocity	V = 0.0027 Q (m^3/s)	(Lalander, 2010)
	Water depth	Minimum depth was considered to be 2 m in streams	(Jacobson, 2012)
	Velocity	Minimum velocity was considered to be 0.5 m/s	
	Turbine efficiency Cp	Cp=0.30 was considered	
	Manning's number	n = 0.035 was considered	
Weir	distance between existing weir and	100m was considered for the selected site	(Marence, et al., 2016)

Hydropower type	Data type	Data selection criteria	Reference (s)
	fish channel upstream		
	design flow	considered design flow to be equal to Q_{75} (75 days availability) on the mean FDC.	
Conduit hydropower in pressurized water supply pipelines	head	initially, it was assumed that half of the available static head can provide power	(Loots, et al., 2014)
	energy generation	initially, it was assumed that power can be generated for 6hrs only per day.	
Dammed	Minimum height	dams with a height of 15m and above were selected.	(Bakıs, 2005)
Dammed	Minimum height	dams with height 1.52 m (5ft) and above were selected	(U.S Department of Energy, 2012)
Dammed	Gross head	was assumed to equal to the hydraulic height of the dam if available otherwise it was assumed to equal to 0.7*Structural height of the dam	
Dammed	Discharge	dams with at least 10 years of discharge data records were considered	(Reclamation, 2011)
Dammed	Hydraulic Head	was assumed to equal to the elevation difference between the headwater and the tailwater elevations	
Dammed	Minimum Hydraulic Head	dams with a net hydraulic head of 0.91 m (3ft) and above were considered	

Hydropower type	Data type	Data selection criteria	Reference (s)
Dammed	Design flow	considered design flow to be equal to Q_{30} on the mean FDC	

2.8 SUMMARY OF LITERATURE REVIEW

As can be concluded from this literature study, hydropower atlases play an important role in making the government and private investors aware of the untapped hydropower potential. For example, the Madagascar hydropower atlas identified 350 run-of-river sites with a cumulative untapped potential of more than 1,350 MW suitable for both government and private investments. The hydropower atlas database also provided information on the 20 most promising and priority sites which were suitable for short-term investment.

The hydropower potential sites included in the existing hydropower atlases were required to conform to the established selection criteria such as the capacity, presence of coordinates, and presence of protected areas. The evaluation of the hydropower potential for the sites was limited to data availability. For example, the discharge was calculated from the precipitation data due to the limited flow data at gauging stations in the Tanzania study. The study on the existing hydropower atlases, however, did not provide enough information regarding the data selection criteria followed in the evaluation of other data types such as slopes and heads. Due to this, further literature was conducted on other studies related to the evaluation of hydropower potential, and information on the data selection criteria was obtained, but mainly for the run-of-river hydropower.

Zambia has in total 17 utilities and private schemes which provide bulk water supply and distribution services to 103 municipalities around the country. The country also has small dams, weirs, and irrigation canals which have been developed by local communities, government agencies, NGOs, and private sectors. As can be seen from the existing installations and studies conducted in other countries, within these infrastructures lies untapped hydropower potential which has not yet been identified and evaluated in Zambia. The hydropower generated at such infrastructure as seen with the case of South Africa and other countries could be used to supply peak demands at utility offices, meet terrain power demand for reservoirs within the systems, street lighting, communication systems, alarms, etc. The power could also be sold back to the electricity suppliers.

Various institutions in charge of water resources and water infrastructure in Zambia have been identified and mentioned in the literature study. These include the Department of Water Resources Development (DWRD), Water Resources Management Authority (WARMA), Zambezi River Authority (ZRA), Ministry of Agriculture (MoA), ZESCO, Water Supply and

Sanitation Service providers, and private owners of existing water infrastructure. Different data types (discharge data, river data, reservoir storage, dam storage, bulk pipeline pressure, flow data, WTWs and WWTWs data, canal types, canal dimensions, slopes, etc.) required for hydropower potential evaluation were collected from these sources. Other web-based data such as the Digital Elevation Model (DEM) (for analysis of topology and slopes) were obtained from the NASA Shuttle Radar Topographic Mission (SRTM). Based on the data that were available and collected, the selection criteria for the evaluation of hydropower potential were developed. The detailed process that was followed in the collection of data and development of the selection criteria builds the next chapter of this dissertation.

3 DATA COLLECTION AND SELECTION OF A GIS PLATFORM

3.1 INTRODUCTION

This chapter outlines the process followed and tools used in obtaining the data required in the evaluation of hydropower potential and the development of the selection criteria for the six types of hydropower outlined in the scope of this study. The sources of the data are also mentioned in this chapter. Finally, the chapter outlines the selection of a suitable Geographical Information System (GIS) platform to host the web-based Zambian Hydropower Atlas.

3.2 DATA COLLECTION FRAMEWORK

The framework followed in the process of obtaining data for all the different types of hydropower considered in this study is shown in Figure 3-1. The process starts with conducting a detailed literature review to identify the data sets and the sources of the data. The data is then collected using various data collection tools described in the section below.

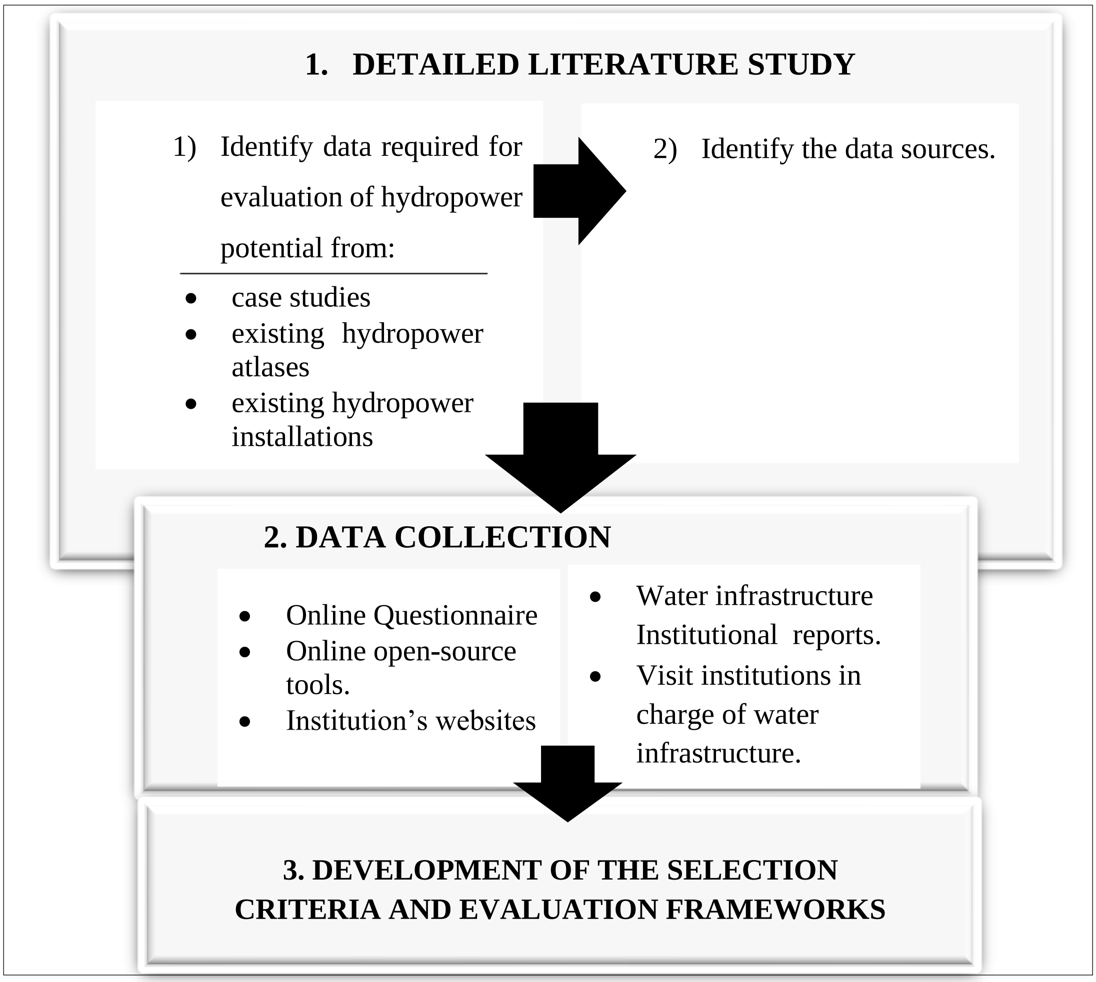


Figure 3-1: Framework for collection of data required for criteria development

3.2.1 Run-of-river hydropower data.

Data parameters required in the evaluation of the hydropower potential for the run-of-river type of hydropower identified according to the above framework are shown in Table 3-1.

Table 3-1: Run-of-river data parameters and data sources

<table>
<tr><th>Data parameters</th><th>Application</th><th>Data Source (s)</th></tr>
<tr><td>River network data</td><td>Location</td><td>• World Wide Fund (WWF)
• HydroATLAS of Zambia (HAZ)
• Google Earth Pro</td></tr>
<tr><td>Riverbed slopes</td><td>Head evaluation</td><td>• Google Earth Pro
• USGS Earth Pro
• HAZ</td></tr>
<tr><td>Discharge data</td><td>Flow evaluation</td><td>• WWF-Zambia
• Rural Electrification Authority (REA) reports, ZESCO ltd
• Zambezi River Authority (ZRA)
• GresP/BGR- Zambia reports</td></tr>
<tr><td>Precipitation data</td><td>Flow evaluation</td><td>• Zambian Meteorological Department (ZMD)
• SASSCAL WeatherNet</td></tr>
<tr><td>Distance between inlet and powerhouse</td><td>Head evaluation</td><td rowspan="3">• REA reports
• JICA master plan reports
• Energy Regulation Board (ERB)
• ZESCO website</td></tr>
<tr><td>Power Capacity</td><td>Minimum Capacity</td></tr>
<tr><td>Turbine type</td><td>Power capacity calculation</td></tr>
</table>

3.2.1.1 Existing run-of-river hydropower plants in Zambia

Zambia has seven existing run-of-river hydropower plants with capacities ranging from 750kW to 108 MW (Figure 3-2) and a cumulative capacity of 152.25 MW. The technical information regarding these plants including their coordinates were collected from the ZESCO and ERB websites. The available data parameters on existing run-of-river hydropower plants in Zambia which could be useful in criteria development include:

- ✓ Location of plant
- ✓ The capacity of the plant (MW)

- ✓ Name of river
- ✓ Design discharge (m^3/s)
- ✓ Gross head (m)
- ✓ Effective head (m)
- ✓ Turbine type
- ✓ Length of penstock (m)

3.2.1.2 Zambia's River Network Data

Zambia's river network was generated from a 30 m spatial resolution STRM DEM using QGIS. STRM data can be downloaded for free on the USGS earth explorer for any part of the world. The river network generated from STRM data can be validated using Google Earth Pro to confirm the location and layout. Google Earth Pro enables the visualization of the features on the earth's surface as they are in real-time. The generated river network together with the 30m spatial resolution STRM DEM for Zambia is shown in Figure 3-2.

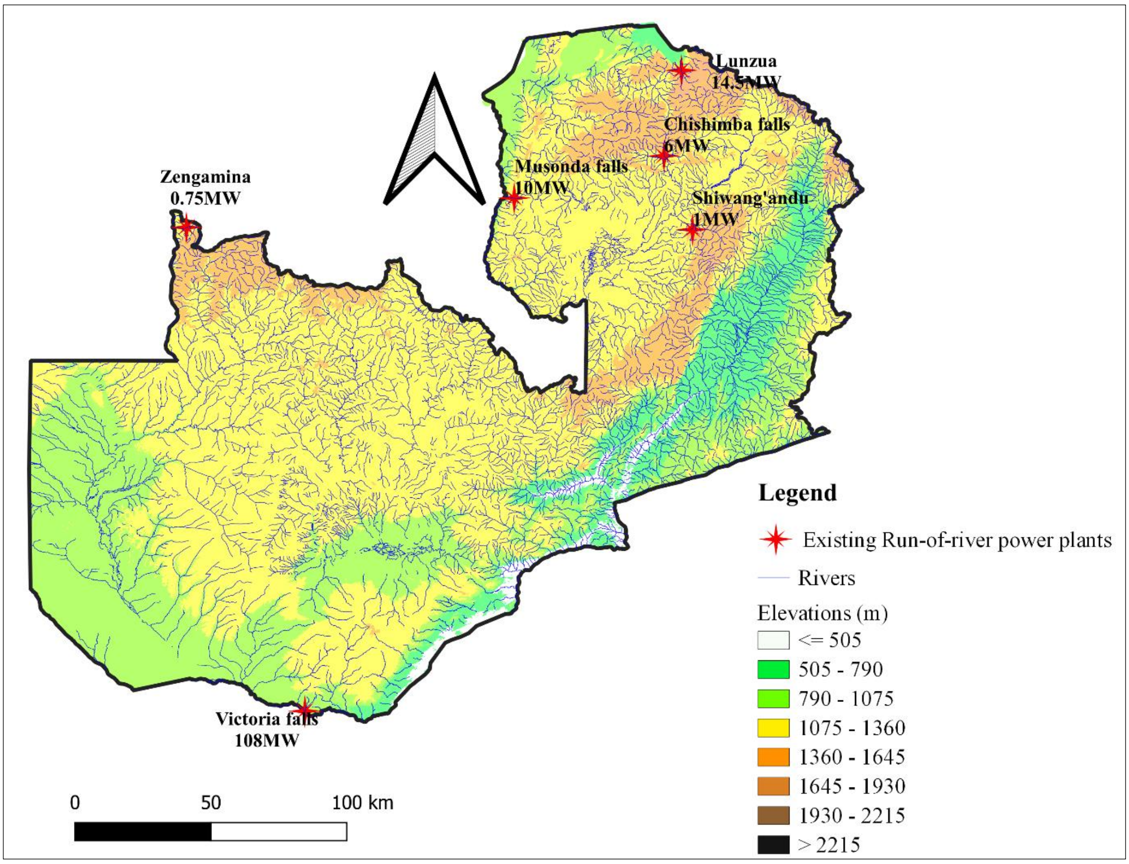


Figure 3-2: Zambia's River network, existing run-of-river power plants, and elevation data (m) obtained from the 30 m STRM DEM

3.2.1.3 Zambia's waterfalls

Opportunities for run-of-river hydropower development exist at naturally occurring waterfalls due to the availability of a height difference. The database of existing waterfalls on Zambian rivers was compiled by WWF Zambia and is available for download on the WWF website. The database contains data such as average discharge (m^3/s), coordinates, and the name of the river. Furthermore, JICA (2011) master plan provides the available auto-level measured gross head at 29 of the waterfalls. This could be useful in the evaluation of hydropower potential. Figure 3-3 shows the location of waterfalls across Zambia.

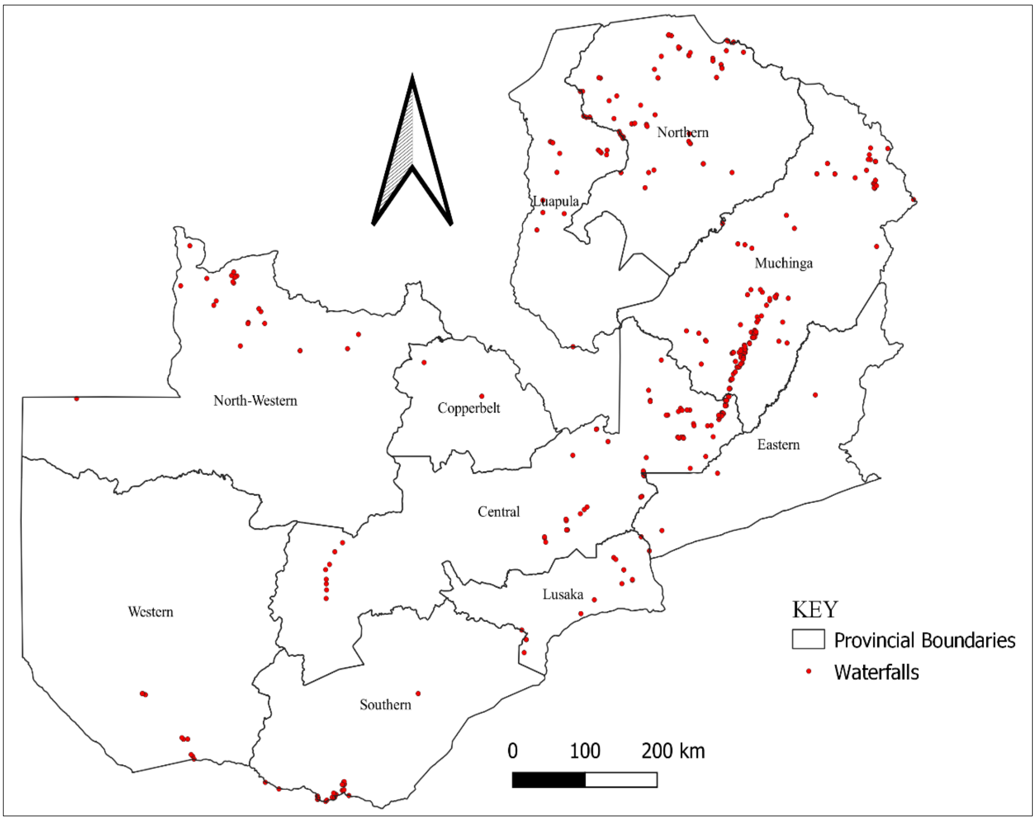


Figure 3-3: Zambia's waterfalls (WWF, 2019a)

3.2.1.4 Terrain Characteristics

The slopes in Zambia generated from the 30m STRM DEM using QGIS are presented in Figure 3-4. Google Earth Pro was used to display the elevation profiles of rivers at sections where existing run-of-river hydropower plants are located to obtain the riverbed slopes. The riverbed slopes were verified using the slope map shown in Figure 3-4.

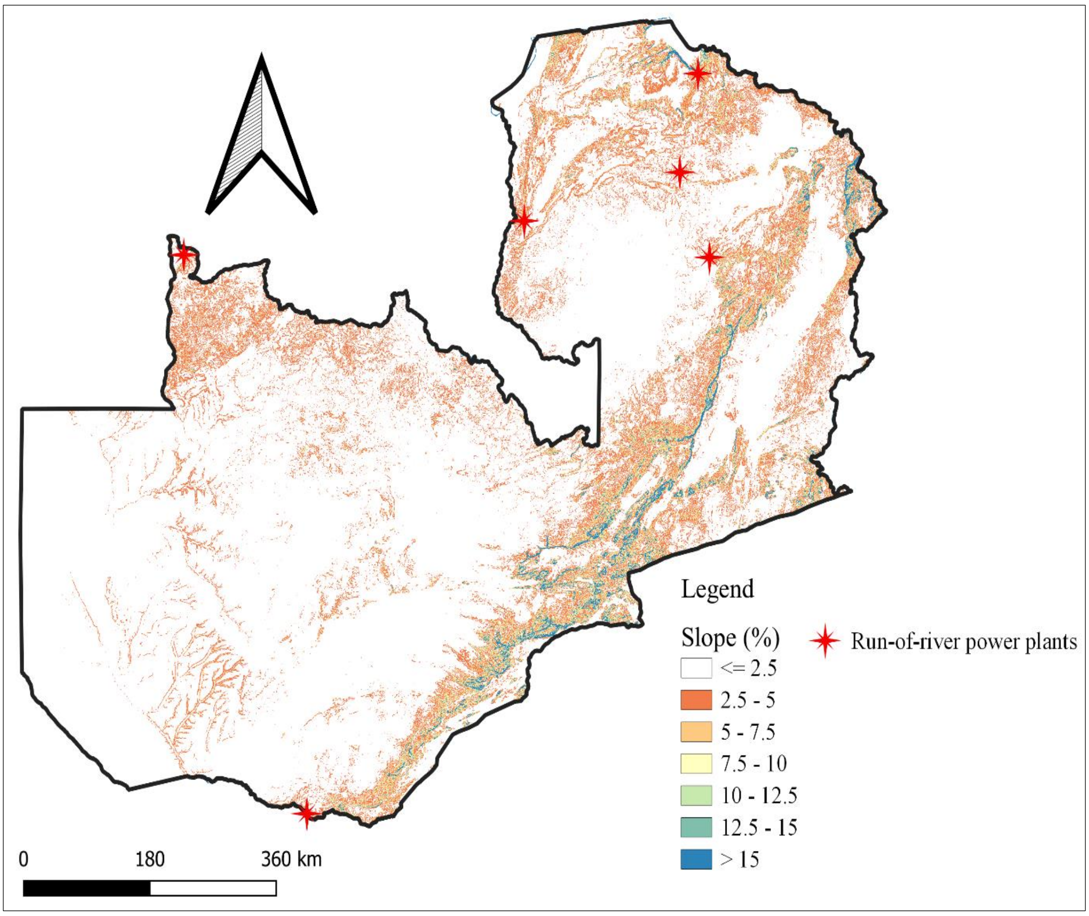


Figure 3-4: Zambia's slopes in percentage (derived from 30m STRM DEM)

3.2.1.5 Discharge data

Discharge-related data at existing run-of-river hydropower plants were obtained from REA reports. The data is available in m^3/s. Measured discharge data can further be obtained from institutions in charge of river infrastructures such as dam owners and operators. Examples of these include local councils, mines, and private companies. Other institutions were identified from the online questionnaire as potential sources of discharge data required for the further development of the Zambian hydropower atlas due to the presence of water infrastructure at the institutions.

3.2.1.6 Precipitation data

Data related to Precipitation is provided by the Zambia Meteorological Department (ZMD). The ZMD data is available for manual rain gauge stations for over 50 years period. The rainfall data records for the automated weather stations are available at the SASSCAL Weather.net website from the year 2013 to date. The data from these stations can be used in the further development of the Zambian hydropower atlas. Figure 3-5 shows the locations of both automated and manual rain gauging stations in Zambia.

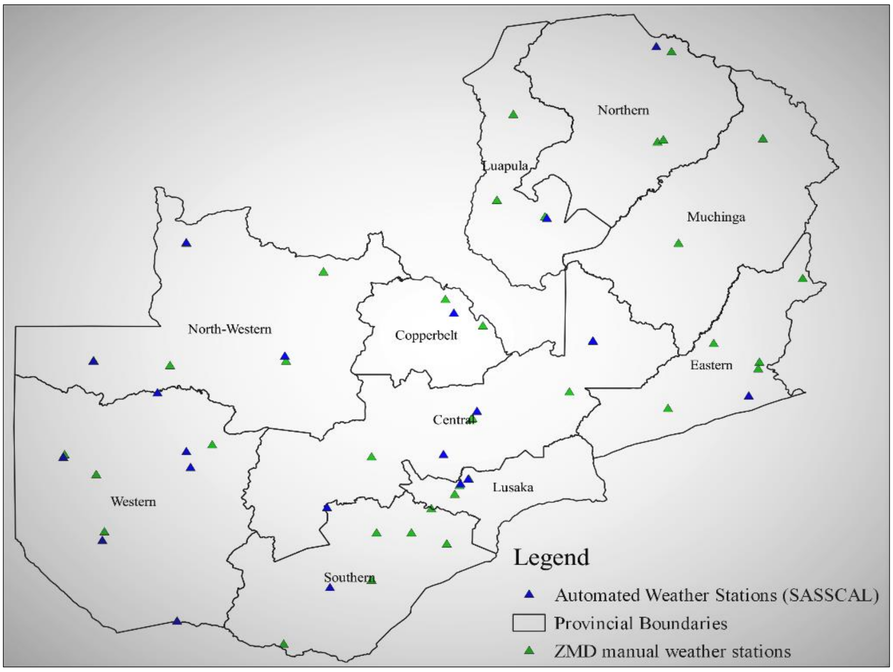


Figure 3-5: Weather stations of Zambia

3.2.2 The HAZ

The HAZ developed by WWF-Zambia is an important tool in the collection of run-of-river hydropower evaluation data because it contains the hydrological data for Zambian river systems. The HAZ can easily be accessed on the WWF – Zambia website and is provided for free to the public. The HAZ provides a set of geospatial data layers ready to be used in any GIS software (WWF-Zambia, 2020). The provided data layers in the HAZ contain hydro-environmental sub-catchment series and river reach characteristics at high spatial resolution for the entire extent of Zambia. Data provided in the HAZ which could be used in the further evaluation of hydropower potential include:

- ✓ Surface runoff (m^3/s)
- ✓ Natural river discharge (m^3/s)
- ✓ Lengths of rivers (km)
- ✓ Elevations (m)
- ✓ Slopes (degrees)
- ✓ Precipitation distribution (mm)
- ✓ Land cover
- ✓ Protected areas.

A demonstration of the available data on the HAZ in the case of annual average river discharge distribution across Zambia is shown in Figure 3-6.

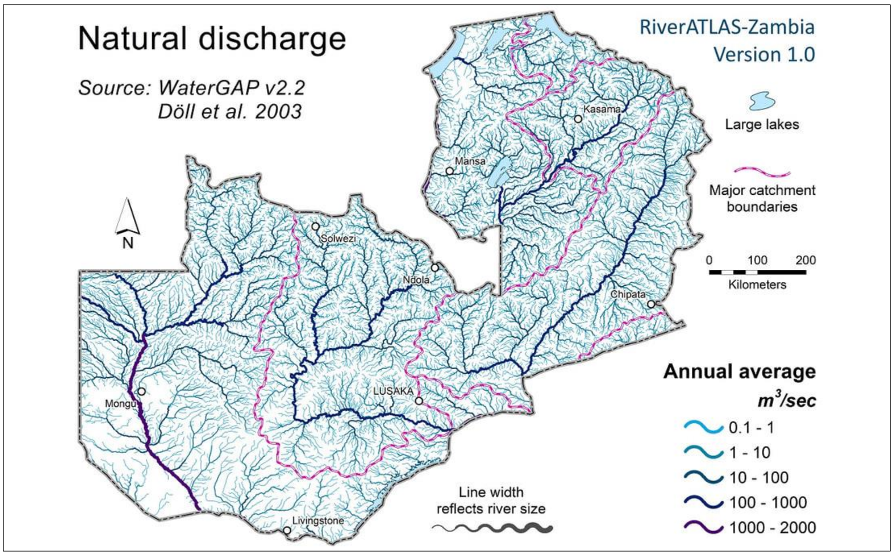


Figure 3-6: Annual average discharge of Zambian rivers as displayed in the HAZ datasets (WWF, 2019b)

3.2.3 Google Forms online questionnaire tool

An online questionnaire using the Google Forms tool has been developed to assist with the collection and identification of water infrastructure data sources. The questionnaire can be sent out to institutions in charge of water-related infrastructure in Zambia. The questionnaire can also be updated anytime. During this study, 15 responses were received from respondents from various institutions in charge of water infrastructure in Zambia. Figure 3-7 shows the responses from the 14 respondents who selected the available water infrastructure at their institutions. Some of the respondents were able to send some reports on the existing infrastructure via email while others suggested the means of obtaining data from their institution. The complete Google Forms questionnaire is shown in appendix B. The institutions with water infrastructure data obtained from the questionnaire responses are also included in Appendix B.

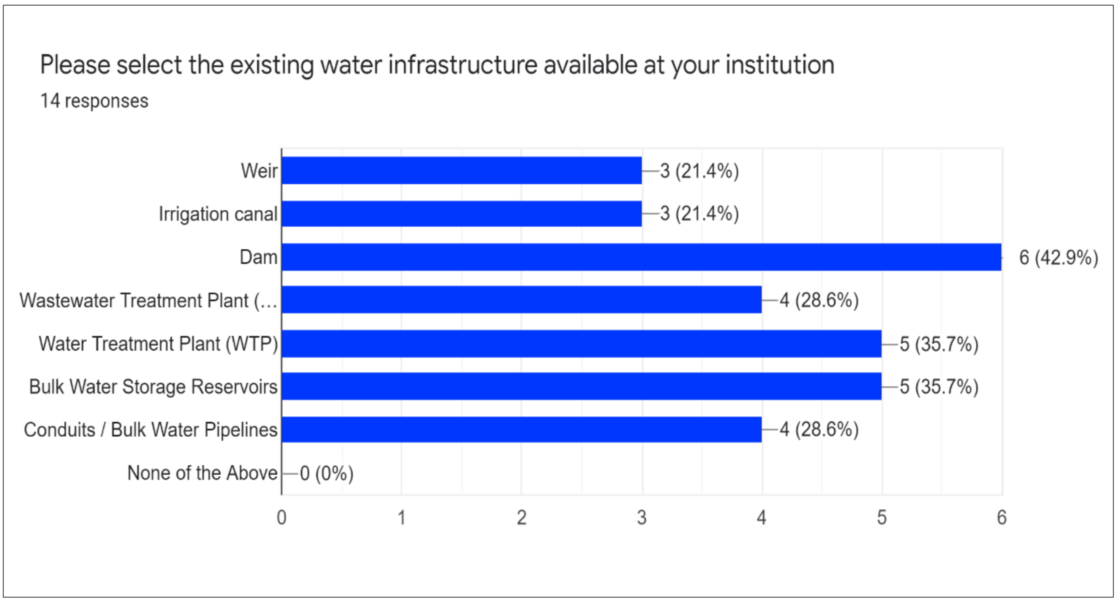


Figure 3-7: Summary of responses on available water infrastructure at the respondent's institution (extracted from Google Forms online questionnaire)

3.2.4 Water supply and sanitation data

The water supply and sanitation utilities in Zambia manage WTWs, water storage reservoirs, bulk water pipelines, and WWTWs. Some useful data related to the evaluation of hydropower potential on these water infrastructures are available in the reports provided by the utilities. Some measured data are directly provided by the utility company engineers. The available data from these utility institutions which could be useful in the evaluation of hydropower potential include:

- ✓ Location of WWTWs,
- ✓ The design capacity of WWTWs (m^3)
- ✓ Dimensions of WWTWs ponds (L x b in metres)
- ✓ Discharge from WWTWs (m^3/s)
- ✓ Location of WTWs
- ✓ The design capacity of WTWs (m^3/day)
- ✓ Treated water production at WTWs (m^3)
- ✓ Size of the bulk pipeline (diameter-mm)
- ✓ Location of water storage reservoirs
- ✓ Capacities of storage reservoirs (m^3)
- ✓ Type of reservoir (elevated or ground)

3.2.5 Weir structures data

The data relating to weir structures in Zambia were found in the hydrological yearbook provided by Federal Institute for Geosciences and Natural Resources (BGR)/Groundwater Resources Management Program(GReSP): Zambia and irrigation reports in Zambia. The available data which could be useful in the evaluation of hydropower generated at weir structures from these sources include:

- ✓ location of the weir,
- ✓ height (m),
- ✓ width (m),
- ✓ discharge (m^3/s)
- ✓ Rating curve
- ✓ purpose of the weir.

3.2.6 Irrigation canal data

Data relating to irrigation schemes and canals can be obtained from various irrigation and agricultural reports in Zambia. The following are some reports which were reviewed:

- The Master Plan for Promotion of Irrigated Agriculture for Smallholders in the Peri-Urban Area in the Republic of Zambia Final Report (JICA, 2011b).
- Report of the Committee on Agriculture, Lands and Natural Resources on the Report of the Auditor-General on the Management of Irrigation Systems in Zambia for the Period 2015 to 2019 for the Fifth Session of the Twelfth National Assembly (National Assembly of Zambia, 2021)
- Evaluation of the Small-Scale Irrigation Project (SIP) Zambia (Swennenhuis, 2015).
- Zambia Agriculture Status Report 2020 (Mulenga, et al., 2020).
- The Study on the Capacity Building and Development for Smallholder Irrigation Scheme in Northern and Luapula Provinces: Technical Manuals (JICA, 2011a)
- Environmental and Social Impact Assessment Final Report Volume I for the Proposed Irrigation Scheme in Mwomboshi in Chisamba District (SOFRECO, 2015)
- Technical Feasibility Report: Strengthening Climate Resilience of Agricultural Livelihoods in Agro-ecological Regions I and II in Zambia (MoA, 2016).
- Impacts of Climate Change on Water Availability in Zambia: Implications for Irrigation Development (Hamududu & Ngoma, 2019).
- Trends and Outlook: Agricultural Water Management in Southern Africa: Country Report Zambia (Akayombokwa, et al., 2015).

Some data are provided directly by the respondents of the Google Forms questionnaire. The data that could be useful in the evaluation of hydropower potential available from these sources include:

- ✓ Location of irrigation canals and schemes,
- ✓ Users of the irrigation canals (ha),
- ✓ Canal construction material,
- ✓ Canal dimensions (depth, widths),
- ✓ Drawings of irrigation canals,
- ✓ Water level (m)

3.2.7 Dams

Zambia has six large hydropower generating dams. Data related to these dammed hydropower plants is available on ZESCO and ZRA websites. Furthermore, data related to dams can be obtained from a dam inventory of Zambia compiled by the World-Wide Fund (WWF). The available dam data from these sources which could be useful in the evaluation of hydropower potential at existing dams include:

- ✓ Location of dam
- ✓ Dam ownership
- ✓ Purpose of dam
- ✓ Dam type
- ✓ Dam height
- ✓ Dam width
- ✓ Storage capacity
- ✓ Catchment area (km^2)
- ✓ Withdraws for Irrigation (Mm^3)
- ✓ Head (m)
- ✓ Turbine type
- ✓ Design discharge (m^3/s)
- ✓ Hydropower plant capacity (MW)
- ✓ Hydropower energy generation (KWh)
- ✓ Gauging station flow records

3.2.8 Google Earth Pro tool

With the location data of various water infrastructures such as WWTWs, canals, rivers, and dams available, visualization in Google Earth Pro can be done. Height differences between two points of interest can be obtained using Google Earth Pro. For example, WWTWs were visualized in Google Earth Pro to obtain the height difference between the outlet of the WWTW and the discharge point into the receiving water body. The height difference was considered as the available gross head at the WWTW. The available gross head was therefore calculated using equation 3.1 shown below:

$\Delta h = h_{outlet} - h_{dp}$ (Equation 3.1)

Where:

Δh = the available gross head at the WWTW (m)

h_{outlet} = altitude of the WWTW outlet point (m)

h_{dp} = altitude of the WWTW discharge point (m)

A typical demonstration of these head parameters at WWTWs in Google Earth Pro is shown for the Kaunda Square WWTW in Lusaka, Zambia. Figure 3-8 demonstrates the WWTW outlet point and the WWTW discharge point into a receiving water body.

Figure 3-8: Demonstration of the WWTW outlet point and Discharge point into a receiving water body at Kaunda Square WWTW

Further on examples, the google earth view of an irrigation canal at Nakambala sugar estates in Mazabuka, Zambia is shown in Figure 3-9. With the use of the add path tool in Google Earth Pro, an elevation profile of a canal, stream, or river section can be visualized. Figure 3-10 shows the demonstration of this at a section of the Lunzua diversion canal on the Lunzua river in Zambia. Useful data in the evaluation of hydropower potential which could be obtained from this tool include:

- ✓ the height gain or loss between two points (m)
- ✓ channel slope at a given point (%)
- ✓ the overall average slope for the channel section (%)
- ✓ the horizontal distance (m)

- ✓ the altitude at any given point (m)

Figure 3-9: Google earth view of the Nakambala irrigation canal in Mazabuka, Zambia

Figure 3-10: Google earth generated elevation profile of the Lunzua diversion canal section

3.3 TURBINE SELECTION AND EFFICIENCY

As already stated in the previous chapter, a turbine converts the potential energy in the falling water into mechanical or shaft power. Therefore, selecting a suitable turbine is essential in the development of the hydropower plant. According to Van Vuuren, et al.,(2011), the design of a turbine is carried out by the manufacturer and does not fall within the engineer's scope of work on a hydropower project. Therefore, the selection of the turbines requires the consideration of factors specified by the manufacturer such as the net available head across the turbine and the range of flow values that the turbine must be able to handle (Van Vuuren, et al., 2011). The manufacturer also specifies the operational efficiency of the type of turbine selected. Table 3-2 shows a summary of factors considered in the selection of turbines and the efficiencies of each type of turbine.

Table 3-2: Operational ranges of different turbines (Van Vuuren, et al., 2011)

Type of turbine	Head range (m)	Maximum efficiency	Head variation	Flow variation
Kaplan/ Propeller	2-40	91-93	Low	Low/medium
Francis	25-350	94	Low	Medium
Pelton	50-300	90	High	High
Crossflow	2-200	86	High	High
Turgo	50-250	85	Low	High

3.4 SELECTION OF THE GIS PLATFORM

NASA (2020) defines a geographic information system (GIS) as a computer-based system for capturing, storing, managing, analysing and visualizing all types of geographical data on the earth's surface. Data from multiple sources such as satellite imagery, global positioning system (GPS) recordings, coordinates, and textual attributes associated with a certain area can be integrated and evaluated using GIS. This helps individuals and organizations to well comprehend spatial patterns and relationships (National Geographic, n.d.). Reviewing recent years' renewable energy developments, GIS can be seen as an important tool in the mapping of renewable energy sources. As shown in Figure 3-11, GIS enables the compilation of a database of information that can be visualized in an interactive way with a click of a mouse. With the available query and analysis tools, the GIS database can be updated, new information can be added, or old information can be deleted and replaced.

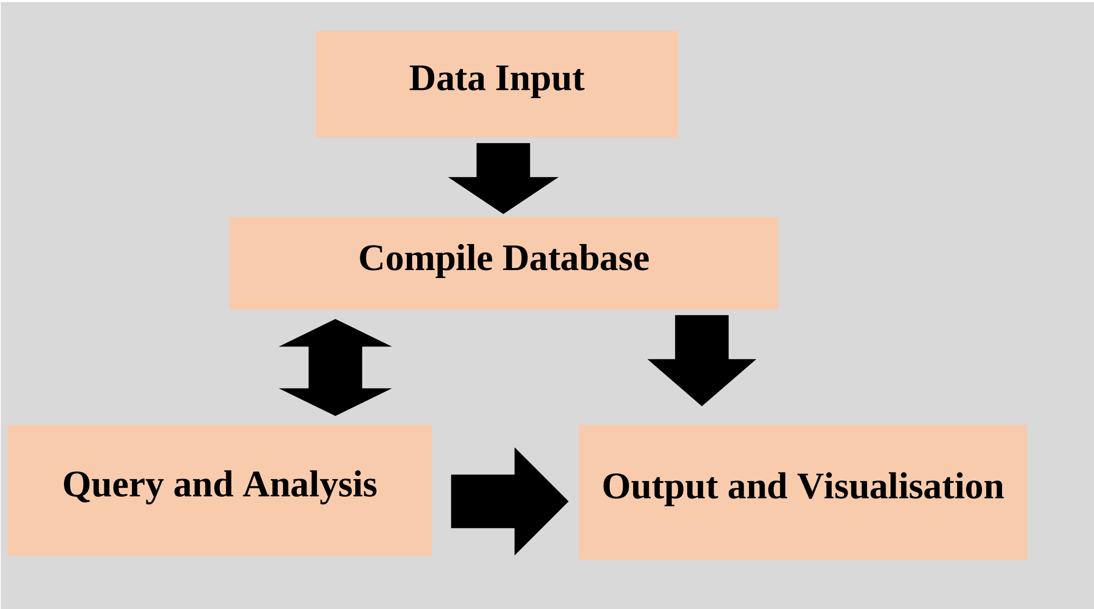


Figure 3-11: Architecture of Geographical Information System (GIS)

According to Mapline (2017), GIS plays a significant role in establishing where to focus renewable energy efforts and how best to manage them. Furthermore, GIS can be used to highlight the potential for sustainable energy resources and show the important data related to that particular energy source in question, land topography, and potential sites where renewable energy power plants can be designed and developed (Mapline, 2017). In the case of a hydropower atlas, a suitable GIS platform is required to display the selected hydropower potential sites including the attribute data related to developing the sites. The suitable GIS platform that can host the Zambian Hydropower Atlas was selected based on the criteria described in Table 3-3.

Table 3-3: Selection criteria for a GIS platform to host the Zambian Hydropower Atlas

Criteria	Description of Criteria	Suitable GIS Platforms
Ease of use	A GIS platform that is does not require too much work and time to set up is more preferred. This includes fewer programming and coding requirements.	✓ QGIS Cloud ✓ ArcGIS Online ✓ CARTO ✓ Mango ✓ Google Earth
Ordinary platform	A GIS platform that is commonly used in Zambia is more preferred. This makes it easy for most Zambian institutions to understand the atlas and new users can be easily trained.	✓ QGIS Cloud ✓ ArcGIS Online ✓ Google Earth
Features	A GIS platform with more features that allow the hosting of the hydropower atlas is preferred.	✓ QGIS Cloud ✓ ArcGIS Online ✓ CARTO ✓ Mango ✓ Google Earth ✓ GeoDjango ✓ GeoMoose ✓ GvSIG Online ✓ Leaflets.js ✓ Mapbox GL JS ✓ MapGuide Open Source ✓ OpenLayers
Reliability	A more reliable GIS platform is preferred. This includes the availability of updates,	✓ QGIS Cloud ✓ ArcGIS Online ✓ Mango

Criteria	Description of Criteria	Suitable GIS Platforms
	and maintenance to avoid crashing of the software.	✓ CARTO
Security	A GIS platform with the provision of data and user security is preferred. This enables users to feel safe when using the hydropower atlas.	✓ QGIS Cloud ✓ ArcGIS Online ✓ Mango ✓ CARTO
Accessibility	Preference is given to a more accessible GIS platform satisfying the other criteria.	✓ QGIS Cloud ✓ ArcGIS Online

From the criteria outlined in Table 3-2, it can be seen that the most suitable GIS platforms to host the Zambian hydropower atlas are QGIS Cloud and ArcGIS Online. QGIS Cloud is a free and open-source software (FOSS). It is a powerful Web-GIS platform for publishing maps, data, and services on the internet. It is also easy to use. As QGIS Cloud (n.d.) puts it, "if you know QGIS Desktop, then you know QGIS Cloud". Furthermore, with only a few short mouse clicks one can share work with the public through the QGIS cloud. In terms of security, the data is stored in the cloud in PostgreSQL databases. Access to the databases is protected with a password and accessed through the Secure Shell Protocol (SSH). QGIS Cloud also allows access to the services to be limited only to a restricted group of people (QGIS Cloud, n.d.). QGIS is also updated regularly, and a user is provided with a notification whenever a new update is available. ArcGIS Online on the other hand has all the necessary described features as QGIS cloud. It is also widely used and understood in Zambia. The web-based Zambia Data Hub (available at https://zambia-open-data-nsdi-mlnr.hub.arcgis.com/) has been hosted using ArcGIS online. The hub enables the exploring of available data resources such as population, health facilities, and settlements in an interactive way. Despite ArcGIS Online being proprietary software, it has been reported to be the most secure, reliable, and right-hand platform to host web-based maps and resources (Esri, n.d.). Because of this and its proven application in Zambia, ArcGIS online has been selected as the best suitable platform to host the web-based Zambian Hydropower Atlas. It should be noted, however, that this is a first-order assessment of the selection of the suitable GIS platform. A more detailed methodological approach and information can be found in the study conducted by van Dijk (2021) in the development of the South African Hydropower Atlas (SAHA).

4 CRITERIA DEVELOPMENT

4.1 INTRODUCTION

The main objective of this research was to develop the data selection criteria to be used in the evaluation of hydropower potential to select sites with potential which may be included in the Zambian Hydropower Atlas. This chapter discusses the development process of the data selection criteria to be followed in the evaluation of hydropower potential at rivers, dams, WWTWs, weirs, bulk water supply systems, and canals. The outcome of this Chapter forms the basis for the development of the evaluation frameworks presented in chapter 5 of this report.

4.2 RUN-OF-RIVER HYDROPOWER

The hydropower potential at a run-of-river hydropower potential site can be computed using equation 2.1. Therefore, the evaluation of the potential depends on the data availability associated with the parameters in the equation. The selection criteria for datasets associated with each variable of the parameters in equation 2.1 were developed as discussed below. It should be noted that this largely depended on the data availability associated with existing run-of-river hydropower setups, terrain, and hydrological data in Zambia.

4.2.1 Head evaluation

According to the existing criteria presented in chapter 2, the effective head at a run-of-river hydropower potential site depends on the riverbed slope, available gross head, and hydraulic head loss. These datasets related to the head and their selection criteria process are presented below.

4.2.1.1 River slope criterion

The existing slope selection criterion from the hydropower potential studies conducted by Vincenzo, et al. (2019) and Kusre, et al. (2010), entails selecting hydropower potential sites with a minimum slope of 5% and 2% respectively. Applying Vincenzo, et al (2019)'s slope criterion to the 6-existing run-of-river hydropower plants in Zambia with slopes shown in Table 4-1, would imply that only 1 site (Victoria falls) would be considered. The criterion discards the 5 sites with significant hydropower potential ranging from 0.75 MW to 14 MW. Similarly, applying Kusre, et al. (2010)'s criterion discards the Zengamina hydropower plant which has a significant capacity of 750kW with a slope of 1.2%. Therefore, there is no clear relationship between the river's slope and hydropower potential in Zambia. As can be seen in Table 4-1, some sites with steeper slopes have lower hydropower potential than some sites with lesser steeper slopes. For these reasons, slope criterion was not considered in the selection of hydropower potential sites to be included in the Zambian Hydropower Atlas. This was seen as a way of reducing the probability of leaving out sites with significant potential. It should, however, be noted that steeper riverbed slopes still indicate the presence of a head and therefore should be considered when identifying the location of hydropower potential sites, especially when using GIS-based methods (Kusre, et al., 2010).

Table 4-1: Slopes at existing run-of-river hydropower plants

Name of Plant	Capacity MW	Slope(%)
Victoria falls*	108	41.4
Lunzua	14.5	2.1
Chishimba falls	6	4.6
Musonda falls	10	2.2
Shiwang'andu	1	3.5
Zengamina	0.75	1.2

**Assumed to represent the combined Zambezi River slope of Victoria falls sites A, B, and C*

4.2.1.2 Gross head criterion

The power output of a hydropower potential site depends on the available head and discharge. According to CETC (2004), there is a minimum head below which there may be no economic advantage for undertaking the hydropower project. This is quite difficult to specify because the desired minimum power output can be obtained by a combination of high values of the head with low values of the discharge and vice versa. The micro hydropower systems buyer’s guide by the CANMET Energy Technology Centre (2004) recommends a minimum head of 1m. In the Zambian case, the existing information from the study for the development of the rural electrification master plan in Zambia by JICA (2009) entails considering run-of-river hydropower potential sites with a minimum gross head of 3m. This criterion was adopted in this study. It is recommended that the economic advantage of run-of-river hydropower potential sites having a gross head of below 3 m should be assessed in future research in Zambia.

4.2.1.3 Effective head criterion

The effective head is used to compute the power output of a hydropower plant taking into account the head loss due to friction and additional components in the penstock and channel system. The actual effective head is only known after these system components have been designed. Therefore, a reasonable estimate of the effective head has to be made when estimating the hydropower potential. The criterion used in the study for the development of the rural electrification master plan in Zambia by JICA (2008) assumed the effective head to be equal to 90% of the available gross head at the site. To validate this criterion, the effective head was computed as a percentage of the gross head at the existing run-of-river hydropower plants in Zambia for which head data was available. As shown in the data presented in Table 4-2, the existing criterion underestimated the effective head by less than 5% at 4 sites and overestimated the effective head by less than 10% at 1 site (Victoria falls Station A). Therefore, this criterion was adopted in this study because it gives a reasonable estimate of the effective head at existing run-of-river hydropower plants in Zambia. Mathematically, the effective head at a river scheme can be calculated using equation 4.1.

$H_n = 0.9H$ (Equation 4.1)

Where:

H_n = the effective head (m)

H = the available gross head (m)

Table 4-2: Effective head as a percentage of the gross head at 5 existing run-of-river hydropower plants in Zambia

Name of site	**Zengamina**	**Shiwang'andu**	**Victoria Falls at stations**		
			A	B	C
Capacity (MW)*	0.750	1	8	60	40
Design discharge* (m^3/s)	8.0	11	10.5	64	43
Gross head (m)*	18.0	12.0	105.77	112.77	112.77
Effective head (m)*	17.0	10.9	86.30	106.18	105.36
Effective/gross head (x100%)	94.4%	90.8	81.6%	94.2%	93.4%
% deviation from 90% criterion	4.89%	0.09%	-9.33%	4.67%	3.78%

* *Technical data adopted from MEWD (2011)*

4.2.2 Discharge evaluation

The success in the estimation of the hydropower capacity of a potential site depends on the availability of discharge data. The output of a run-of-river hydropower plant depends on the derived FDC of the river discharge at the site. The FDC integrates the combined impacts of climate, geology, geomorphology, land use, soil, and vegetation. Therefore, it differs from place to place. The FDC allows the estimation of the percentage of time that a specified discharge is equalled or exceeded. Therefore, the time step under which the FDC is developed is important in the accuracy of the output of hydropower plants. The use of a daily time step in the derivation of an FDC for small-scale hydropower plants gives a higher accuracy (Reichl & Hack, 2017). Therefore, a daily time step FDC was adopted in this study. It was assumed that the design discharge should be obtained at 80% days availability (Q_{80} on the FDC) considering the design discharge used at the existing run-of-river hydropower plants in Zambia. Typical Zambian flow duration curves are shown in Figure 4-1 and 4-2 from the South-West and North-East regions of Zambia. On average the FDCs throughout the country are similar and Q_{80} is considered to be more reliable.

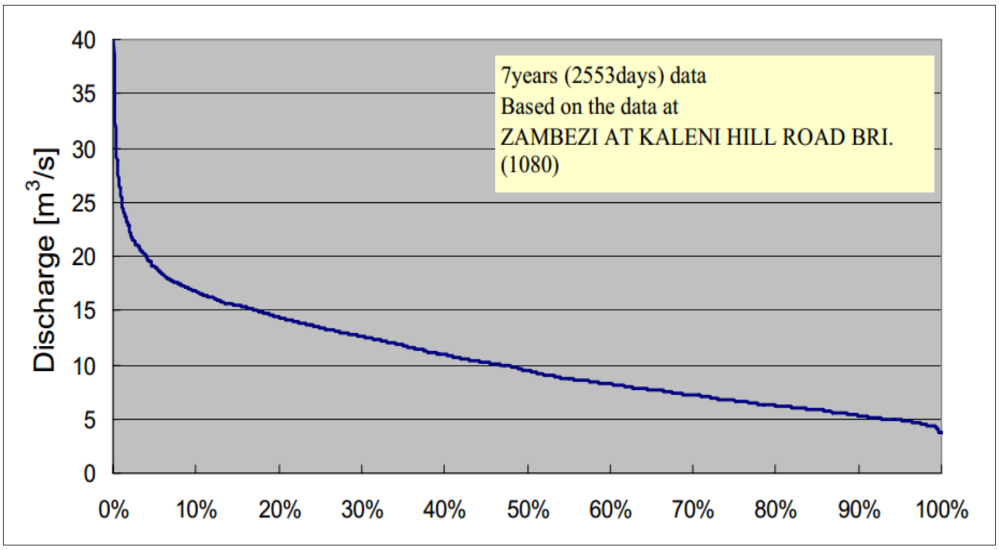


Figure 4-1: An FDC at Kalene Hill Road Bridge Gauging Station (JICA, 2009)

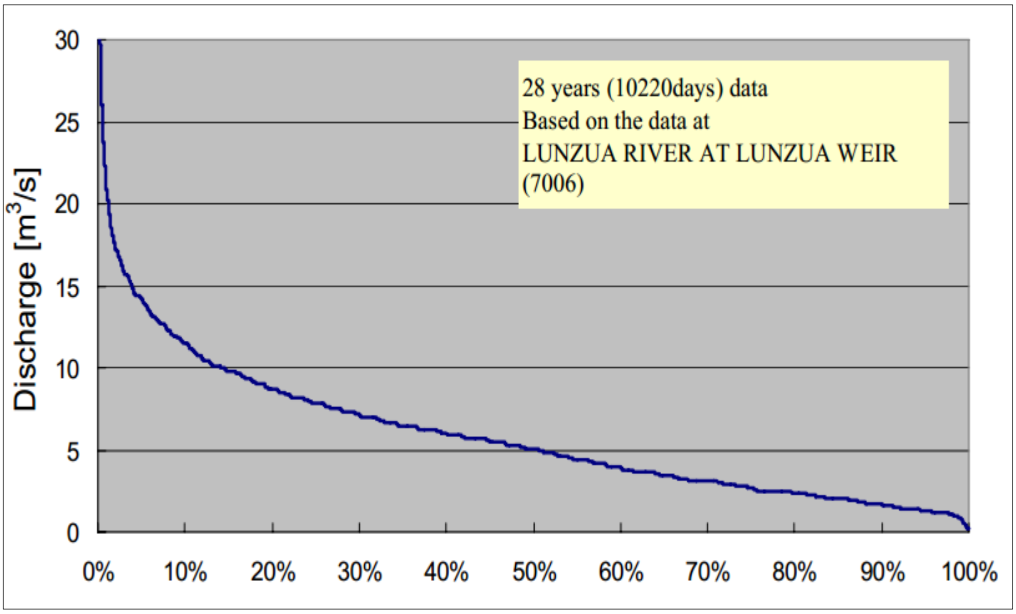


Figure 4-2: An FDC at Lunzua Weir on Lunzua River (JICA, 2009)

The following two scenarios were considered in the evaluation of discharge data in this study based on the available datasets:

4.2.2.1 Gauged sites

The Water Resources Management Authority (WARMA), and the Zambezi River Authority (ZRA) have river gauging stations across Zambia to monitor the daily river water levels. A site in this study is assumed to be gauged if it is located within the catchment area of a river gauging station. There are various factors that affect the degree of completeness of hydrological data. In this study, two factors were considered: 1) length of dataset time series and ii) presence of missing data. The former involved the minimum number of years of gauging station data to accept in giving a reliable estimate of discharge. The study for the development of the rural electrification master plan in Zambia by JICA (2009) considered gauging stations with discharge data records of 10 years and above, otherwise, a different method was used to compute the discharge. This criterion was adopted in this study because some hydropower plants that were identified during the study have been implemented and some are in the implementation phase (Gauri, et al., 2013).

Regarding the latter factor, some gauging stations may happen to contain missing data. The existing criterion from the development of the Tanzania Hydropower Atlas study entails using gauging stations with no more than 5% of missing data (World Bank, 2015). This is because having more than 5% of missing data affects the statistical analysis of hydrological data. This is also supported by Osman, et al. (2018). This criterion was adopted to apply to the selection of the river gauging station data to consider in Zambia. It is however recommended that methods of filling in missing data in the flow datasets having more than 5% missing data such as the one presented by Osman, et al. (2018) should be explored in future studies.

4.2.2.2 Ungauged sites or sites with incomplete hydrological data

When the potential site is situated in an ungauged location, it was assumed that the discharge should be estimated using the annual average discharge dataset available in the HAZ. As previously mentioned, the HAZ provides hydrological data of Zambian rivers categorized based on the annual average discharge with the following categories.

a) 0.1 – 1 m^3/s
b) 1 – 10 m^3/s
c) 10 - 100 m^3/s
d) 100 - 1000 m^3/s
e) 1000 – 2000 m^3/s

These represent the average annual discharge of the whole river, however, in run-of-river hydropower setups, usually, only a portion of the river flow is diverted to generate hydropower. It is recommended to provide environmental flows to secure the aquatic life, livelihoods, and the requirements of the downriver communities and industries. Ndebele-Murisa, et al. (2020) in their study on the environmental flow analysis of the Zambezi River Basin in Zambia, recommended providing 30-60% of the average annual flow of a river as environmental flows in the wet seasons. To account for this, it was assumed that 30% of the average annual discharge of a river presented in the HAZ is available for hydropower generation and therefore can be diverted to a powerhouse. It was further assumed that the mean discharge of each river discharge category should be considered as the annual discharge of the river as shown in Table 4-3.

Table 4-3: Criteria for available discharge at ungauged stations based on the HAZ data

River discharge category (m^3/s)	Mean discharge: Qm(m^3/s)*	Discharge available for hydropower generation (m^3/s)**
0.1 - 1	0.55	0.165
1 - 10	5.5	1.65
10- 100	55	16.5
100 -1000	550	166.5
1000-2000	1500	450

**Calculated as an average of upper limit and lower limit of the range*
***calculated as 30% of the mean discharge*

To validate the mentioned criteria, the discharge was compared with the known design discharge values at 3 existing run-of-river hydropower plants in Zambia shown in Table 4-4. As can be seen in Table 4-4, the criteria estimated the available discharge for hydropower generation to be 33.33%, 51.52 %, and 29.43% higher than the design discharge at the existing Shiwanga'ndu, Zengamina and Victoria falls hydropower plants respectively. This could reasonably imply that the river discharge at these existing sites has not been fully utilized. Therefore, the criteria were adopted in this study.

It should be noted that these criteria were been developed based on hydrological model results presented by WWF (2019) which could possibly contain some uncertainties. Therefore, these criteria should be considered as a first-order estimation of the available discharge at ungauged sites. It is recommended that future research should consider other methodologies in the estimation of discharge at ungauged stations in Zambia such as the use of the rainfall-runoff method, and neighbouring gauged stations, and compare with these criteria.

Table 4-4: Comparison of the existing design discharge with the proposed criteria-based

Name of site	River Name	Discharge category (m^3/s)	Discharge available for hydropower generation (m^3/s)	Existing design discharge (m^3/s)	%Deviation
Shiwang'andu	Manshya	10-100	16.5	11	33.33
Zengamina	Zambezi	10-100	16.5	8	51.52
Victoria falls	Zambezi	100-1000	166.5*	117.5	29.43

**Calculated as the sum of discharge at Victoria falls sites A, B, and C*

4.2.3 Hydropower capacity criterion

The existing criterion from the development of the Madagascar Hydropower Atlas study entails selecting run-of-river hydropower potential sites with capacities of 50kW and above (World Bank, 2017a). In the Zambian case, the study for the development of the rural electrification master plan for Zambia by JICA (2009) considered hydropower potential sites with capacities of 30kW and above to be suitable for non-electrified rural areas in Zambia. Therefore, this was adopted in this study to give a first-order selection of sites to be included in the Zambian Hydropower Atlas. It is recommended that future studies should investigate the economic benefits of including run-of-river sites with capacities of no more than 30 kW.

4.2.4 National Regulation Restrictions

It was assumed that run-of-river potential sites that are located within Zambia's protected areas should not be included in the Zambian Hydropower Atlas. As already stated in the literature review, the protected areas in Zambia are heavily managed by various national regulations, and siting of projects such as hydropower projects in these areas is discouraged.

4.3 DAMMED HYDROPOWER

Similarly, to run-of-river hydropower, the hydropower potential at a dammed hydropower potential site can be computed using equation 2.1. Therefore, the evaluation of the potential at a dam site depends on the data availability associated with the parameters in equation 2.1. The data selection criteria to enable the computation of hydropower potential at dams in Zambia were developed based on the available datasets. The datasets and criteria development are discussed below.

4.3.1 Head evaluation

The parameters of interest were the gross head and the effective head.

4.3.1.1 Gross head criteria

The existing criterion in the study conducted by the U.S Department of Energy (2012) entails considering the gross head at a dam to be equal to 70% of the dam height. The gross head criterion in Reclamation (2011), entails considering the gross head to be equal to the elevation difference between the headwater and the tailwater at a dam. In addition, Bakis (2005) considered the gross head to be equal to the dam height. In the case of Zambia, the dam database contains dam heights. The headwater and tailwater elevation data are unavailable. Therefore, the gross head was assumed to be a function of dam height in this situation based on the criteria used in the studies conducted by U.S Department of Energy (2012) and Bakis (2005).

To check the application of these criteria in the Zambian case, the gross head in terms of dam height at Zambia's existing hydropower generating dams was assessed as shown in Table 4-5. From the table, the gross head criterion (gross head = 70% of dam height) by the U.S Department of Energy (2012) estimated the gross head nearer to the gross head at Kariba North, Itezhitezhi, and Kariba North Extension than the criterion (gross head = dam height) by Bakis (2005) did. Therefore, the criterion by the U.S Department of Energy (2012) was adopted to apply in the Zambian situation to provide a first-order estimate of gross head available at a dam. Mathematically, the gross head at a dam can be computed using equation 4.2.

$H = 0.7\ H_d$ (Equation 4.2)

Where:

H = the available gross head (m) at a dam

H_d = the dam height (m)

This criterion assumed that the powerhouse is located at the dam site. However, it should be noted that the criterion largely underestimates the gross head at dams where there are opportunities of positioning the powerhouse at a distance further from the dam to increase the head by use of underground tunnels as in the case of the Kafue Gorge Upper, Kafue Gorge Lower, Lunsenfwa and Lusiwasi hydropower stations which have a high head as compared to the dam height. Therefore, it is recommended that a detailed field assessment should always be conducted to determine the actual gross head measurements and to assess site conditions for such opportunities.

Table 4-5: Ratio of Gross head to dam height at existing dammed hydropower plants in Zambia.

Station	Dam Name	Dam height (m)	Gross head (m)	System head (m)	*Ratio of Gross head to dam height
Kariba North	Kariba dam	128	92	85	0.71
Itezhi-tezhi	Itezhi-tezhi dam	65	51	40	0.78
Kariba North Extension	Kariba dam	128	-	87	0.68
Kafue Gorge upper	Kafue gorge dam	50	400	390	7.8
Kafue Gorge Lower	Kafue gorge lower dam	140	200	186 (appr.)	1.43
Mulungushi	Mulungushi dam	46	-	-	-
Lunsemfwa	Mita hills dam	49	-	330.5	6.74
Lusiwasi	Lusiwasi dam	7	522.6	500	71.42

**where the gross head was unavailable, the system head was used to calculate the ratio.*

Technical data sourced from MEWD (2011), Klunne (2013), Klunne (2013a), Klunne (2013b) & Klunne (2014)

4.3.1.2 Effective head

The effective head at a dam site is used to compute the potential of a hydropower plant taking into account the head loss due to friction and additional components in the penstock. The run-of-river effective head criterion developed in section 4.2.1.3 of this report, entails that the effective head can be assumed to be equal to 90% of the available gross head at a run-of-river scheme. However, since it was assumed that there is no canal from the dam site to the powerhouse, water losses encountered in the canal may be eliminated. The water losses may be due to evaporation and seepage in the canal. Assuming that these account for 5% of the 10% head loss at a run-of-river scheme, implies that the head loss at a dam site equals 5% being encountered in the penstock only. Therefore, the effective head at a dam site was assumed to equal 95% of the available gross head. In mathematical terms, the effective head at a dam site can be calculated using equation 4.3 below.

$$H_n = 0.95H \qquad \text{(Equation 4.3)}$$

Where:

H_n = the effective head (m)

H = the available gross head (m) at a dam

Combining Equation 4.2 and Equation 4.3 gives the effective head in terms of dam height as shown in Eq. 4.4 which was assumed as a final equation for computing the available effective head at a dam site.

$$H_n = 0.63H_d \qquad \text{(Equation 4.4)}$$

Where:

H_n = the effective head (m)

H_d = is the dam height (m)

4.3.2 Minimum dam height criterion

The existing dam height selection criterion used in the study conducted by the U.S Department of Energy (2012) entails selecting dams with heights of 5 ft (1.52 m) and above. The criterion used in the study conducted by Bakis (2005) entails selecting dams with heights of 15 m and above. Applying the later criterion in Zambia would eliminate the Lusiwasi dam which has a height of 7 m and generates 12 MW of power. Zambia has over 3,000 small dams with heights ranging from 0.5 m to 15 m. Therefore, applying the U.S Department of Energy (2012) criterion (1.52 m) would allow the consideration of many dams in Zambia for hydropower generation opportunities. However, small dams in Zambia are mainly used for irrigation purposes and conflicts exist between upstream and downstream farmers due to these impoundments. In most cases, downstream farmers complain of their dams not getting enough inflow (Chisola & Kuráž, 2016). Therefore, considering dams with low heights may not provide enough water for hydropower generation. To take this into account, it was assumed that dams with a height of 3 m and above can be reasonably considered for hydropower generation to provide sufficient head in Zambia.

4.3.3 Discharge Evaluation

The following two scenarios were considered in this study based on the available dam datasets in the evaluation of discharge at a dam hydropower site.

4.3.3.1 Dam with flow measurement

It was assumed that a dam with flow measurement should be considered the same as a gauged run-of-river site. Therefore, the completeness of the hydrological data should be checked to give a better estimate of the design discharge. As already explained in section 4.2.2.1 under run-of-river hydropower, sites with at least 10 years of discharge records and no more than 5% of missing data should be considered in the computation of the design discharge. The design discharge should be obtained at 80% days availability (Q_{80} on the FDC). For more details, refer to section 4.2.2.1 under run-of-river criteria development.

4.3.3.2 Dam without flow measurement or with incomplete hydrological data

If the dam has no flow measuring instrument or it has incomplete hydrological data, it was assumed that the design discharge should be obtained from the dam inventory database compiled by WWF-Zambia. The dam inventory contains the average annual discharge for some Zambian dams captured in the inventory. Since dams are more reliable than run-of-rivers in terms of flow, it was initially assumed that the design discharge should be considered to be 50% of the average annual discharge at the dam site to allow for other dam purposes. To evaluate this criterion, the estimated discharges were compared with the design discharges at the 4 existing hydropower generating dams in Zambia as shown in Table 4-6. As can be seen from the table, the criterion under-estimates the discharge at 4 sites and over-estimates it at 1 site. On average, the criterion estimates the discharge within deviations of ±8% to ±21% at 4 sites. However, these deviations were observed to be quite high. Therefore, the criterion was adjusted to consider the discharge to equal to 55% of the annual discharge which resulted in better estimations (Table 4-6) at 4 sites (±0.4% to ±16%).

Table 4-6: Comparison of criterion-based discharge with the design discharge at the existing hydropower generating dams in Zambia.

Station	Dam Name	Average annual discharge from Dam inventory: Q (m^3/s)	50% of Average annual discharge (m^3/s)	55% of the Average annual discharge (m^3/s)	Existing design discharge (m^3/s)	Error due to 50% criterion	Error due to 55% criterion
Kariba North	Kariba dam	1,313.6	656.8	722.5	747.2	-12.1%	-3.4%

Station	Dam Name	Average annual discharge from Dam inventory: Q (m^3/s)	50% of Average annual discharge (m^3/s)	55% of the Average annual discharge (m^3/s)	Existing design discharge (m^3/s)	Error due to 50% criterion	Error due to 55% criterion
Itezhitezhi	Itezhitezhi dam	554.1	277.1	304.9	306.0	-9.4%	-0.4%
Kariba North Extension	Kariba dam	1,313.6	656.8	722.5	455.2	+30.7%	37.0%
Kafue Gorge upper	Kafue gorge dam	485.0	242.5	266.8	264.0	-8.1%	1.0%
Mulungushi	Mulungushi dam	20.4	10.2	11.2	13.0	-21.4%	-16.1%

Technical data sourced from MEWD (2011), Klunne (2013), Klunne (2013a), Klunne (2014) & WWF (2019a)

4.3.4 Hydropower capacity criterion

The smallest dammed hydropower plant (Lusiwasi) in Zambia generates 12MW of hydropower. This is connected to the national grid and supplies the eastern part of the country. As stated previously, opportunities for hydropower generation exist at small dams as well. The generated electricity could be used remotely in a rural setting including farms for lighting, cooking, etc. Solar power plants have been installed in Zambia with capacities as low as 30kW to supply electricity to farm blocks. Hydropower operations at an already existing dam could be comparable in cost. Therefore, it was assumed that dams with at least 30kW capacity should be included in the Zambian Hydropower Atlas.

4.4 HYDROPOWER GENERATED AT WWTW

The hydropower potential at a WWTW hydropower potential site can be computed using equation 2.1. Therefore, the evaluation of the potential at a WWTW site depends on the data availability associated with the parameters in equation 2.1. The data selection criteria to facilitate the calculation of hydropower potential at WWTWs in Zambia were developed based on the available datasets. The datasets and criteria development are discussed below.

4.4.1 Head evaluation

Opportunities for hydropower generation at a WWTW potential site can exist due to the presence of an elevation difference between the outlet of the WWTW and the discharge point into the receiving water body. The head evaluation parameters considered in this study were the gross head and the effective head.

4.4.1.1 Gross head evaluation

As stated in chapter 3, it was assumed that the gross head was equal to the elevation difference between the outlet of the WWTW and the discharge point into the receiving water body according to equation 3.1 ($\Delta h = h_{outlet} - h_{dp}$). As already mentioned, there is a minimum head beyond which there is no economic value of undertaking the hydropower project of course taking into account the corresponding available discharge. The micro hydropower systems buyer's guide by the CANMET Energy Technology Centre (2004) recommended a minimum head of 1 m for micro hydropower plants. It was therefore assumed that only WWTWs with a gross head of at least 1 m should be considered in the evaluation of hydropower at WWTWs. Applying this criterion to the WWTWs located in the city of Lusaka would imply that all the 6 WWTWs shown in Table 4-7 would be considered for hydropower evaluation. Lusaka is generally the flattest land in Zambia which can make it a benchmark to give the lowest elevation differences in the country. It is important to realise that Google Earth Pro has limitations in providing the gross head nicely WWTWs which is normally a few meters only as can be seen in Table 4-7. To avoid such inaccuracies in the estimation of the gross head, a generic figure of 3 m (average of the 6 WWTWs in Table 4-7) was adopted to be considered as the gross head at any WWTW which has a Google Earth Pro measured gross head of at least 1 m.

Table 4-7: Available gross head at 5 WWTWs in the city of Lusaka (Extracted from Google Earth Pro)

Name of WWTW	The altitude of WWTW Outlet: h_{outlet} (m)	The altitude of discharge point: h_{dp} (m)	Gross head: Δh (m)
Manchinchi WWTP	1254	1252	2
Kaunda Square WWTP	1209	1205	4
Chunga WWTP	1193	1192	1
Chelstone ponds	1211	1206	5
Matero ponds	1210	1206	4
Ngwerere ponds	1240	1238	2
		Average (m)	3

4.4.1.2 Effective head

There is currently no existing WWTW hydropower plant in Zambia to refer to for effective head criterion development. Because of this, it was assumed that the effective head should be treated as in the case of run-of-river evaluation. Thus, the effective head was considered to be equal to 90% of the available gross head at a WWTW as shown in equation 4.5.

$h_n = 0.9\Delta h$ (Equation 4.5)

Where:

h_n= the effective head (m)

Δh = the available gross head at the WWTW (m)

4.4.2 Discharge evaluation

The following two scenarios were considered in this study based on the available WWTW datasets in the evaluation of discharge data.

4.4.2.1 Gauged WWTWs

Usually treated wastewater flow is measured at WWTWs to monitor the flow and compare it with the design flow of the plant. Assessment of the wastewater flow at 4 WWTWs in Lusaka showed that the monthly daily average flow is generally constant with small variations (See Figure 4-3, Figure 4-4, Figure 4-5, and Figure 4-6 showing the flow variation at the 4 WWTWs located in Lusaka). It was assumed that the design discharge for hydropower generation at a WWTW should be obtained at 50% availability on the monthly daily average FDC (Q_{50} on the FDC).

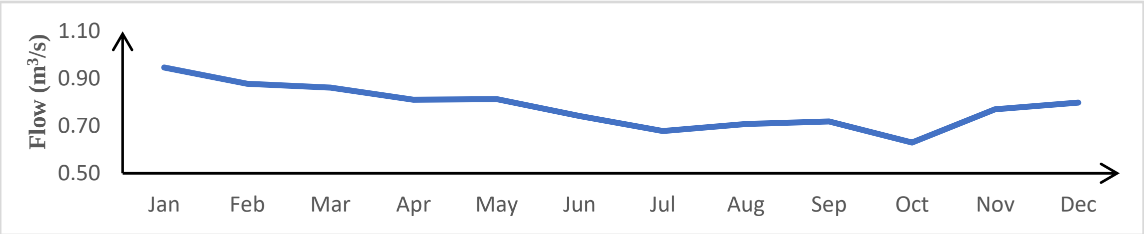


Figure 4-3: Variation of the monthly daily average flow of Wastewater discharge at Chelstone WWTW for the period 2011-2018 (LWSC, 2018)

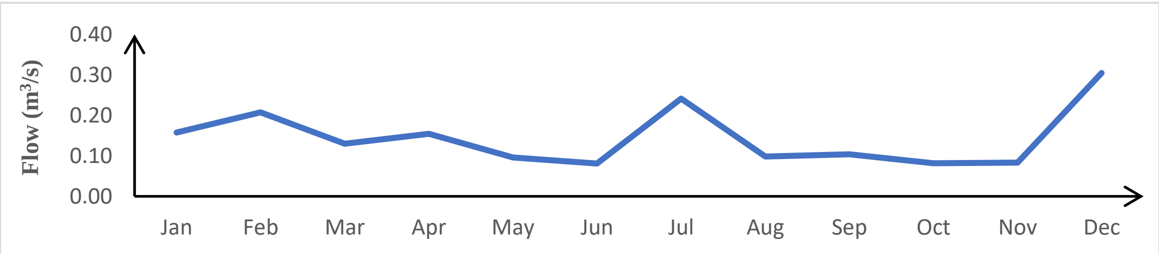


Figure 4-4: Variation of the monthly daily average flow of Wastewater discharge at Ngwerere WWTW for the period 2011-2018 (LWSC, 2018)

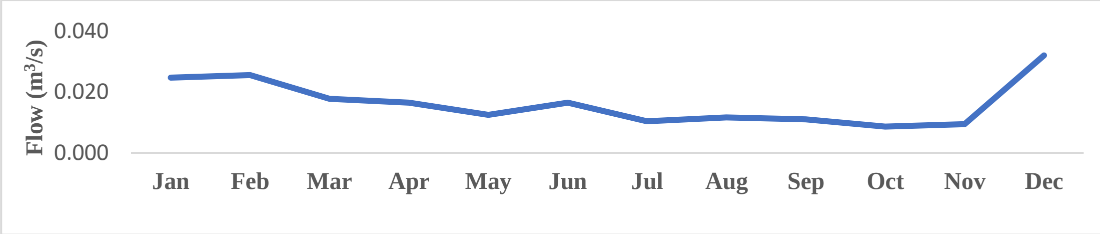


Figure 4-5: Monthly daily average flow of Wastewater discharge at Kaunda Square WWTW for the period 2011-2017 (LWSC, 2018)

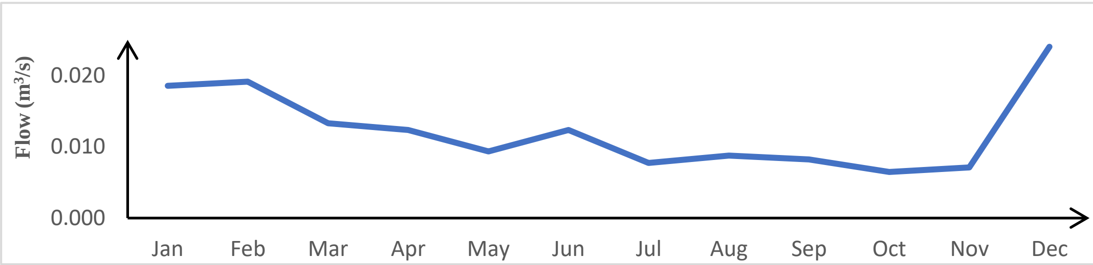


Figure 4-6: Monthly daily average flow of Wastewater discharge at Chelstone WWTW (2011-2017). Source: LWSC

In terms of the completeness of the discharge data, it was assumed that the data should be at least 1 year period and should contain no more than 10% of missing data. This was reasonably selected because the monthly daily average flow of treated wastewater does not vary significantly throughout the year and the statistical influence of missing data is expected to be lesser than in the case of a run-of-river system. It is recommended that future research should carry out a comprehensive assessment of missing data and its statistical influence on wastewater discharge results.

4.4.2.2 Ungauged WWTWs or WWTWs with incomplete discharge data

In a situation where the WWTW is ungauged or contains discharge data with less than 1-year records and more than 10% of missing data, it was assumed that the design discharge of the WWTW should be considered to be the available design discharge for hydropower generation. This assumption is reasonably valid because most WWTWs in Zambia operate at more than their design flow capacity. This is for instance depicted in Figure 4-7 and Figure 4-8 which show the comparison of actual monthly daily average flow with the design discharge at Manchinchi and Chunga WWTPs in Zambia in the year 2017. As can be seen from the Figures, the design discharge of the WWTW underestimates the actual available discharge, therefore, it should be considered as a first-order estimate.

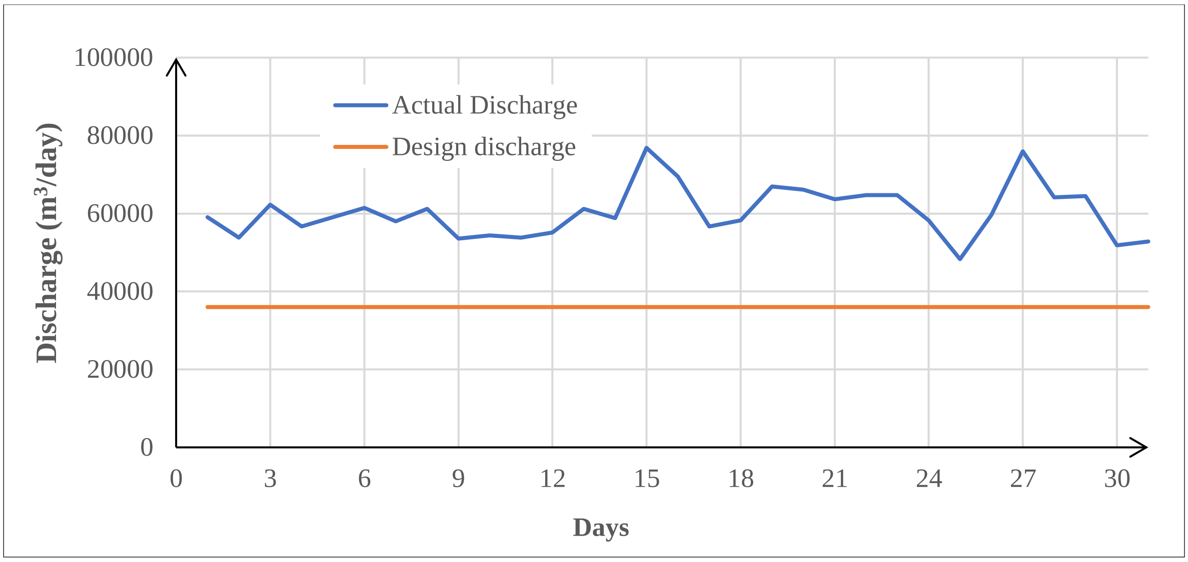


Figure 4-7: Actual and design average daily wastewater discharge at Manchinchi WWTP in Lusaka (LWSC Wastewater Department Report, 2017)

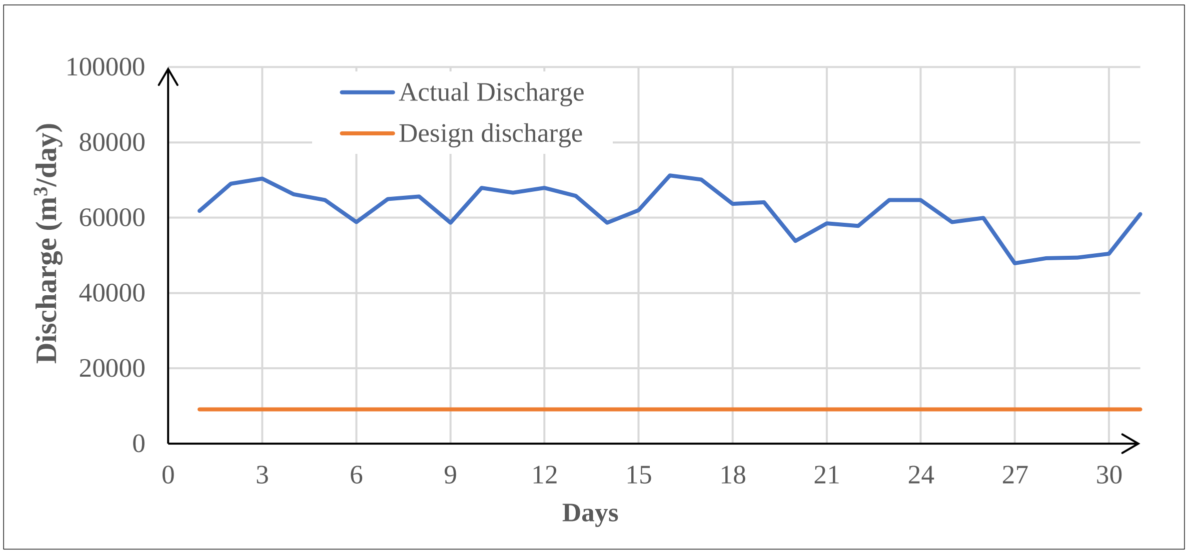


Figure 4-8: Actual and design average daily wastewater discharge at Chunga WWTP in Lusaka (LWSC Wastewater Department Report, 2017)

4.4.3 Hydropower capacity criterion

It was assumed that only WWTWs with hydropower potential of at least 3kW should be included in the Zambezi Hydropower Atlas. This was reasonably assumed because, by observation, most of the WWTWs in Zambia are located in cities close to residential settlements. The 3 kW power could be used for domestic, street lighting, etc, or could be used in the WWTW.

4.5 WEIR HYDROPOWER

The evaluation of hydropower potential at a weir site also depends on the data availability associated with the variable parameters of equation 2.1 such as the effective head and discharge. The data selection criteria to facilitate the calculation of hydropower potential at weirs in Zambia were developed based on the available datasets as discussed below.

4.5.1 Weir type and height criteria

It was assumed that a weir should have a height of 1.5 m and above to be considered in the evaluation of hydropower potential in Zambia. Weirs of this height are likely to be concrete wall type as provided in the weir construction guidelines developed by the Ministry of Agriculture and JICA (2011a) for smallholder farmers in Zambia. The technical guidelines recommend that any weir having a height of 1.5 and above should be of concrete wall type. Therefore, this criterion assumes that only concrete wall type weirs should be included in the Zambian Hydropower Atlas. Selecting concrete wall type weirs for hydropower generation has several advantages which include minimized concrete works required, minimized influence on existing neighbouring plant infrastructures, little or no earthworks, and reduced environmental impact (Marence, et al., 2016).

4.5.2 Head Evaluation

The head-related parameters of interest were the gross head and the effective head.

4.5.2.1 Gross head criteria

It was assumed that the available gross head at a weir should be equal to the height difference between the headwater and tailwater. This method was also used in the study conducted by Marence, et al. (2016). Mathematically, the gross head can be calculated using equation 4.6.

$$\Delta H = H_{hw} - H_{tw} \qquad \text{(Equation 4.6)}$$

Where:

ΔH = the available gross head at a weir (m)

H_{hw} = height of headwater at a weir (m)

H_{tw} = height of tailwater (m)

In a situation where the parameters of equation 4.6 are not available, it was assumed that the gross head should be considered to be equal to the height of the weir.

4.5.2.2 Effective head criterion

There is currently no existing weir hydropower plant in Zambia to refer to in the effective head criterion development. Because of this, it was assumed that the effective head should be considered as in the case of run-of-river effective head evaluation. Thus, the effective head was considered to be equal to 90% of the available gross head at a weir as shown in equation 4.7.

$$H_n = 0.9\Delta H \quad \text{(Equation 4.7)}$$

Where:

H_n= the effective head (m)

ΔH = the available gross head at a weir site (m)

4.5.3 Discharge evaluation

The following two scenarios were considered in this study based on the available weir discharge-related datasets.

4.5.3.1 Weir with flow records

It was assumed that a weir with flow measurement should be considered the same as a gauged run-of-river site with the difference being in the completeness of the hydrological data. It was assumed that sites with at least 1 year of discharge records and no more than 5% of missing data should be considered in the computation of the design discharge. The design discharge should be obtained at 80% days availability (Q_{80} on the FDC). For more details, refer to section 4.2.2.1 under run-of-river criteria development.

4.5.3.2 Weir with no flow records or with incomplete hydrological data

It was assumed that if no flow records exist or if flow records are less than 1 year at a weir site, the flow should be estimated using the short-crested weir equation as shown in equation 4.8 (Munson, et al., 2009). This equation was selected because the weirs in Zambia are largely short-crested (JICA, 2011a).

$$Q = \frac{2}{3} C_d b \sqrt{2g} h^{3/2} \quad \text{(Equation 4.8)}$$

Where:

Q = weir flowrate (m^3/s)

b = the weir width (m)

g = the acceleration due to gravity (9.81 m/s^2)

h = elevation head at the weir (m)

C_d = is the weir coefficient which is usually determined from experiments

The following assumptions were made with regard to the use of equation 4.8 in the estimation of the discharge at a weir.

- The elevation head should be considered to be equal to the effective head (H_n) at the weir
- C_d = 0.33: assuming the minimum conservative low value of C_d for a short-crested weir (Chen, et al., 2018)

Equation 4.8 was applied on the existing weir with the properties shown in Table 4-8. As can be seen from the Table, the criteria overestimated the design discharge by 3.4 m^3/s (29.8%). This criterion was adopted in this study to give a first-order estimate of the design discharge at a weir provided the parameters in Equation 4.8 are available.

Table 4-8: Discharge evaluation at the Zengamina weir in Zambia

Name of Weir	Zengamina
Measured discharge (m^3/s)*	8.0
Height of weir (m)*	1.5
Width of weir (m)*	7.5
Discharge (m^3/s) as per equation 4.8	11.4

**Technical data obtained from ERB (2015) and MEWD (2011)*

4.5.4 Hydropower capacity criterion

It was assumed that only weirs with hydropower potential of at least 3kW should be included in the Zambezi Hydropower Atlas. This was reasonably assumed because most of the weirs are located in smallholder farms where power could be used for domestic, pumping water, irrigation, etc. (JICA, 2011a).

4.6 CANAL HYDROPOWER

As already mentioned in Chapter 2, the potential for the development of small-scale hydropower schemes exists within canals where electricity can be captured from the flows either by i) the use of diversion channels or ii) by installing hydrokinetic turbines within the canal itself. The former methodology is mostly used on run-of-river systems. This study only considered the criteria development where electricity is captured in irrigation canals through the use of hydrokinetic turbines. Therefore, the evaluation of hydropower potential depends on the data availability related to the parameters of equation 2.2 mentioned in chapter 2 under hydrokinetic turbines. These datasets and the criteria development are explained below.

4.6.1 Hydrokinetic turbine parameters

The two parameters in equation 2.2 that depend on the turbine are the turbine swept area and the power coefficient (C_p).

4.6.1.1 Turbine swept area

It was assumed that the hydrokinetic turbine with a circular rotor configuration should be used in the computation of hydropower potential in a canal. As mentioned in chapter 2, the turbine swept area can be computed using equation 4.9.

$$A_t = \frac{\pi D^2}{4} \qquad \text{(Equation 4.9)}$$

Where:

A_t= the swept area of the turbine (m^2)

D = the diameter of the turbine (m).

In using equation 4.9, it was assumed that the diameter of the turbine should be considered to be equal to one-third of the irrigation canal depth. There was no existing hydrokinetic turbine installation in an irrigation canal in Zambia at the time of the assessment to validate this assumption. However, the assumption was made to provide enough space for submerging the turbine rotor.

4.6.1.2 Power coefficient (C_P)

As already mentioned in the literature review, the values of C_P are usually specified by the manufacturers of the hydrokinetic turbine and may vary with its size. It was assumed that the value C_P should be equal to 0.4. This was used in the Zambian context in the study conducted by Mvula, et al. (2019) entitled “Design of Circular Arc Blade Hydrokinetic Turbine-A Case of Rural Electrification in Zambia”. In the mentioned study, the designed circular turbine was successfully tested in Zambia and good results were obtained. Therefore, the assumption can be considered to give reasonable estimations in the evaluation of hydrokinetic hydropower potential in Zambia.

4.6.2 Velocity evaluation

The velocity in equation 2.2 depends on the discharge and the channel properties of the canal. Two methods of computing velocity were explored in this study. They are explained below.

4.6.2.1 Using available discharge records

During the assessment, no measured velocity records were available for any irrigation canal in Zambia. Therefore, it was assumed that velocity should be calculated using equation 4.10 below when the canal has a flow gauging station.

$$V = \frac{Q}{A} \qquad \text{(Equation 4.10)}$$

Where:

Q = the discharge in the canal (m^3/s)

A = the cross-sectional flow area of the channel (m^2)

Table 4-9 shows the assumptions made in using equation 4.10.

Table 4-9: Discharge criteria for a gauged irrigation canal

Parameter	Criteria	Comment
Length of flow records	Consider gauging stations with flow records of at least 1-year	• Irrigation canals tap water from the rivers and dams, however, the flow in the canals does not fluctuate so much as compared to rivers per annum
Missing data	Consider gauging stations with flow records having no more than 5% of missing data	• See section 4.2.2 under run-of-river discharge evaluation
Velocity	Consider the velocity to be uniform in the canal	• It was assumed that the velocity is constant throughout the irrigation canal regardless of the distance from the gauging station

4.6.2.2 Using Manning's equation

If the irrigation canal has no flow gauging station, it was assumed that the velocity of the water in the channel should be estimated using manning's equation (equation 2.6) mentioned in chapter 2 and rewritten below.

$$V=\frac{1}{n}\, R_h^{2/3}(S_0^{1/2}), \qquad \text{(Equation 2.6)}$$

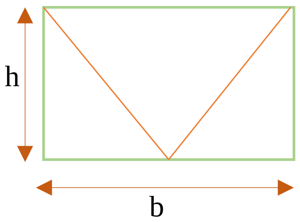
Additionally, Table 4-10 shows the assumptions made in using equation 2.6.

Table 4-10: Assumptions in the use of equation 2.6

Parameter	Criteria	Comment
Manning's number (n)	Assume n = 0.019	• Most irrigation canals in Zambia are masonry or concrete-lined (JICA, 2011a). The criteria assumed the average manning's number of these two materials (USACE, 2010).
The slope of the channel (S_0)	If the channel slope is unknown, assume S_0= 0.005 (0.5%)	• Canal construction guidelines in Zambia recommend 1% as the ideal longitudinal slope (JICA, 2011a). To take into account irregularities and uncertainties in achieving the ideal slopes, it was assumed that the slope should be equal to 0.5% which is 50% of the ideal slope (1%).
Hydraulic radius (R_h)	Assume R_h= 0.5 h where h is the depth of the channel	• This assumes the shape of the channel to be V-shaped. This overestimates the hydraulic radius of the rectangular

		channel with the same depth and width by 33% determined as shown in Table 4-11 • This criterion is expected to estimate the trapezoidal hydraulic radius by less than 33% since the trapezium has a smaller cross-sectional area than a corresponding rectangle • This assumption is often made in other studies to simplify the geometric shape-related calculations yet give reasonable estimates of the parameters (Jacobson, 2012)

Table 4-11: Hydraulic radius comparison: triangular vs rectangular shape

Schematic	Triangular (criterion)	Rectangular	%Deviation
	R_h=0.5 h assuming h = 1 m R_h= 0.5 m	$R_h=\frac{h^2}{(h+2h)}$ assuming h=b=1 m R_h=0.33 m	+33%

4.6.2.3 Cross Section Properties

The existing criterion in the study conducted by Jacobson (2012) assumed considering natural river channels having a water depth of at least 2 m during low flow periods. Since this study considered masonry and concrete-lined channels, it was assumed that the minimum depth of the water during low flows in the channel should be 1 m. This was selected because, in the lined canals, lesser plant growths are expected as compared to the natural stream or river channels. Similarly, it was assumed that the canal should have a minimum top width of 1 m to provide sufficient space for the installation of the hydrokinetic turbine.

4.6.3 Hydropower capacity criterion

Hydrokinetic turbines can be easily installed in the canal without the need for constructing powerhouse infrastructure as compared to other types of hydropower, therefore, they can be installed to power simple household energy requirements such as phone charging, lighting, refrigeration, etc. For these reasons, it was assumed that irrigation canals having at least 500 W hydropower potential should be included in the Zambian Hydropower Atlas.

4.7 BULK WATER SUPPLY SYSTEMS HYDROPOWER

Opportunities for hydropower generation exists in bulk water supply systems at different locations due to the presence of high-pressure head and flow in the conduits. As already stated in chapter 2, the presence of high pressure is due to the elevation difference between the water source and the discharge points or points of delivery. While these opportunities exist at different locations within the bulk water supply system, the evaluation of the hydropower potential depends on the data availability of the parameters at the respective stations. In this study, hydropower potential that could be tapped in conduits between the WTWs and inlets to service reservoirs was considered. In this case, the evaluation of hydropower potential depends on the availability of data related to the effective pressure head and flow. The datasets and criteria development related to these parameters are explained below.

4.7.1 Flow criterion

In accordance with equation 2.1, the hydropower potential in the conduit as well depends on the available flow. Flow measurement data in the bulk water supply conduits were not available during the assessment. Flow-related data that were readily available are the design capacity of WTWs, the daily flow of treated water at WTWs, and the design volume of service reservoirs. The main pipelines from the WTWs distribute into smaller pipelines that supply water to service reservoirs in different localities. Therefore, using the design and daily flow of treated water at WTWs would not give a good estimation of the flow at individual service reservoirs. Because of this, the flow criterion was based on the service reservoir design capacities.

The flowing two assumptions were made in the flow evaluation,

1. 80% of the reservoir capacity is available: this assumption was based on providing 20% of the service reservoir capacity for daily emergency purposes such as firefighting.
2. Electricity could be generated in 8 hours of water supply during the day: According to NWASCO (2020) sector report, the average hours of supply by commercial utilities in Zambia is 18 hours. However, the peak hours range from 8 hours to 12 hours for different utilities. 8hours which is the lower limit was therefore selected.

Based on these assumptions, the available flow can be calculated using equation 4.11 below to give a first-order estimation of the available flow at the inlet of a service reservoir.

$$Q = \frac{0.8\ V_r}{8 \times 3600} \qquad \text{(Equation 4.11)}$$

Where:

Q = the average available flow (m^3/s)

V_r = the capacity of service reservoir (m^3)

4.7.2 Effective Pressure Head

Ideally, the effective pressure is equal to the difference between the upstream distribution reservoir pressure and the downstream service reservoirs pressure. During the assessment of the data availability, pressure records were not available. Therefore, it was assumed that the effective pressure head should be calculated using the static head which is the elevation difference between the upstream reservoir and the downstream reservoir (Figure 4-9).

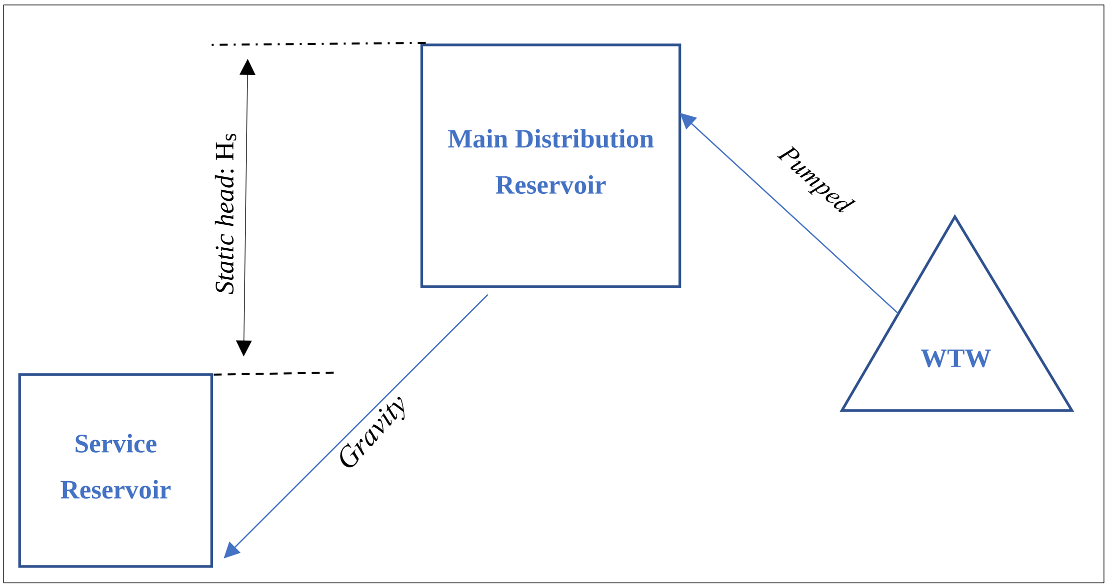


Figure 4-9: Schematic of a bulk water supply system with service reservoirs

The head loss can be estimated using equation 2.4 explained in chapter 2. The velocity can be calculated from the discharge using equation 4.12 given below.

$$v = \frac{4Q}{\pi D^2} \qquad \text{(Equation 4.12)}$$

Where:

v = the average velocity in the pipe (m/s)

Q = the average available flow (m^3/s)

D = the diameter of the pipe (m)

Equation 4.12 was validated by estimating the velocities at the inlet of 25 service reservoirs in the Mulonga bulk water supply system located in the Copperbelt Province of Zambia. As can be seen from Appendix C, the velocities were realistic and are within the allowable velocities in bulk water supply pipelines. Therefore, equation 4.12 was adopted in this study.

Finally, it was assumed that the pipes are considered to be straight, therefore the minor head losses are negligible. With these assumptions, the effective pressure head can be computed using equation 4.13 give.

$$H_n = H_s - \left[f \frac{L}{D} \cdot \frac{V^2}{2g} \right] \qquad \text{(Equation 4.13)}$$

Where:

H_n = the effective pressure head (m)

H_s = the static elevation head (m)

L = the length of the pipeline (m)

D = diameter of the pipe in meters (m)

g = the acceleration due to gravity (9.81 m/s^2)

f = the frictional factor which can be obtained from the moody diagram

The use of equation 4.13 however, requires that the diameter and length of the pipe should be known. In the situation where these are unknown, it was assumed that the effective pressure head should be computed based on the existing criterion from the study conducted by Loots, et al. (2014) in the South African context. The criterion entails considering the effective pressure head available for hydropower generation to be equal to half of the available static head. Hence the effective head can be calculated using equation 4.14.

$$H_n = 0.5\, H_s \qquad \text{(Equation 4.14)}$$

Where:

H_n = the effective pressure head (m)

H_s = the static elevation head (m)

4.7.3 Hydropower Capacity

It was assumed that bulk water supply systems with hydropower potential of at least 3 kW should be included in the Zambezi Hydropower Atlas. This was reasonably assumed because service reservoirs in Zambia are located close to residential areas. The 3 kW power could be used for indoor light, telemetry, street lighting, and data logging onsite.

5 EVALUATION FRAMEWORKS FOR SITE SELECTION

5.1 INTRODUCTION

This chapter presents the selection process of hydropower potential sites to be included in the Zambian Hydropower Atlas through the use of evaluation frameworks. The evaluation frameworks are based on the criteria developed in Chapter 4 of this report. The chapter also presents some important tools and sources of data specific to the application of the evaluation frameworks. The evaluation frameworks presented in this chapter form the basis of chapter 6 which presents the case studies to show the application and verification of the frameworks.

5.2 RUN-OF-RIVER EVALUATION FRAMEWORK

The run-of-river data selection criteria presented in chapter 4 were summarized to formulate the evaluation framework to show the inclusion or exclusion of a potential site in the Zambian Hydropower Atlas. The developed evaluation framework for run-of-river hydropower is shown in Figure 5-1. The framework starts with providing guidance on the rivers to be considered. Zambia has 6 main river catchments which serve as administrative units for the Water Resources Management Agency (WARMA) and the Zambezi River Authority (ZRA). The river discharge data at gauged stations can be obtained at administrative offices (Table 5-1) of these institutions. For ungauged stations, the framework suggests using the average annual discharge data (Figure 3-6) available in the HAZ. It should be noted that this framework only provides a first-order or preliminary selection of potential sites.

Table 5-1: Zambia's River Catchment Administrative offices where river discharge data could be obtained.

Administrative office	Province	River Catchment
WARMA-Headquarters	Lusaka	All river catchments
WARMA-Ridgeway office	Lusaka	Lower Kafue
WARMA- Kabwe office	Central	Luangwa and Kafue
WARMA- Livingstone office	Southern	Zambezi
WARMA-Ndola office	Copperbelt	Upper Kafue
WARMA-Kasama office	Northern	Chambeshi, Tanganyika and Luapula
WARMA-Mkushi office	Central	Luangwa
WARMA-Mazabuka office	Southern	Lower Kafue
WARMA-Mongu office	Western	Zambezi
ZRA-Kariba house, Lusaka	Lusaka	Zambezi

Table 5-2 shows the relevant abbreviations used in the run-of-river evaluation framework for reference.

Table 5-2: Abbreviations/Symbols used in the evaluation framework

Abbreviation	Meaning
ΔH	The available gross head at the run-of-river site (m)
H_n	Effective head (m)
FDC	Flow Duration Curve
Q_{80}	80% days availability on the FDC (m^3/s)
Qm	Mean discharge of the river (m^3/s)-see Table 4-3
Q	Design discharge for hydropower generation (m^3/s)
P	Hydropower potential (W)
ρ	The density of water (1,000 kg/m^3)
g	The gravitational due to gravity (9.81 m/s^2)
η	The efficiency of the turbine (%)

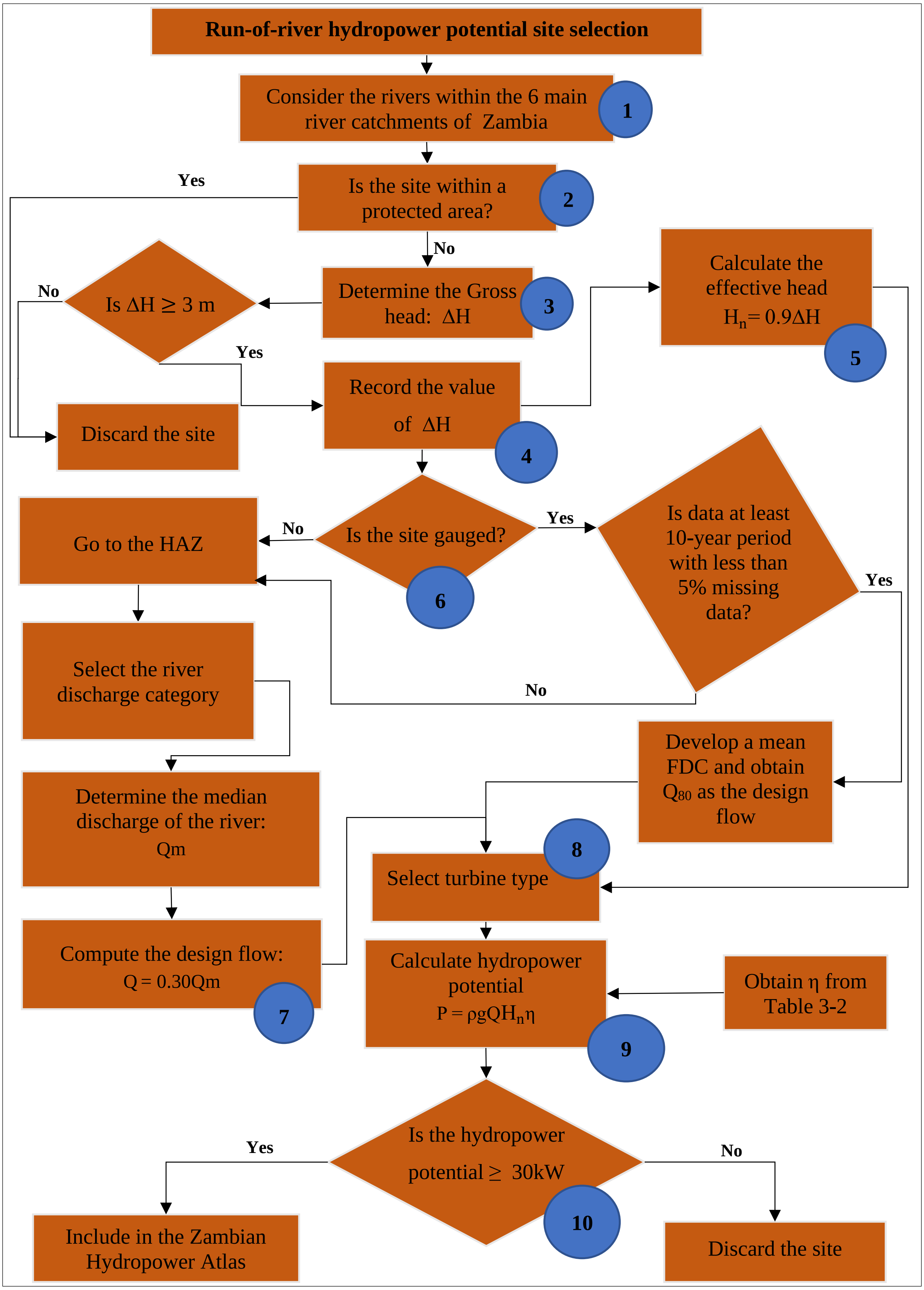


Figure 5-1: Evaluation framework for the selection of run-of-river hydropower potential sites to be included in the Zambian Hydropower Atlas

5.3 DAMMED HYDROPOWER EVALUATION FRAMEWORK

The evaluation framework for the selection of Zambian dam sites having hydropower potential to be included in the Zambian Hydropower Atlas is shown in Figure 5-2. The framework starts with guiding on the dams to be considered and to obtain the dam heights. As already mentioned in chapter 3 and chapter 4 dam height data can be obtained from the WWF dam inventory for Zambia. The dam heights can also be obtained from the dam owners and the reports done on Zambian dams. The online Google Forms questionnaire explained in chapter 3 and shown in Appendix A can also play an important role in obtaining this information for the further development of the Zambian Hydropower Atlas. The discharge data can be obtained from the sources listed in Table 5-1 under the run-of-river evaluation framework.

It should be noted that this evaluation framework provides only a preliminary selection process of the dams with hydropower potential as it is based on reasonably made assumptions and without the consideration of other factors that affect dam site characteristics such as the level of sediment settlement in Zambian dams. Other factors not considered include the effect of the current purpose of each dam such as irrigation and water supply.

The relevant abbreviations used in the evaluation framework for the selection of dams are shown in Table 5-3 for reference.

Table 5-3: Abbreviations/Symbols used in the evaluation framework

Abbreviation	Meaning
H_d	The height of the dam (m)
Q_a	The average annual discharge at the dam site (m^3/s)
h_n	Effective head (m)
FDC	Flow Duration Curve
Q_{80}	80 days availability on the FDC (m^3/s)
Q	Design discharge for hydropower generation (m^3/s)
P	Hydropower potential (W)
ρ	The density of water (1,000 kg/m^3)
g	The gravitational due to gravity (9.81 m/s^2)
η	The efficiency of the turbine (%)

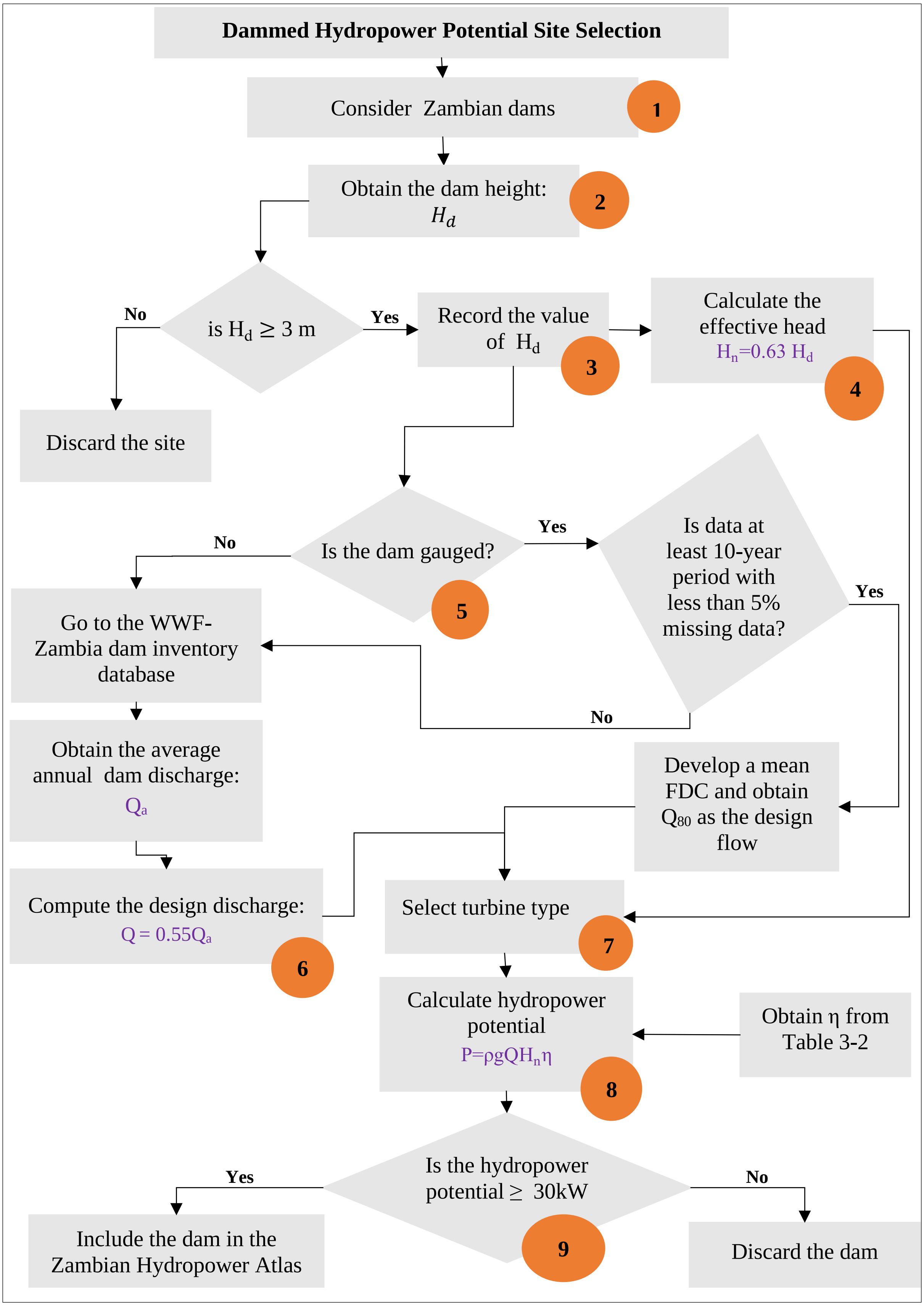


Figure 5-2: Evaluation framework for the selection of dams with hydropower potential to be included in the Zambian Hydropower Atlas

5.4 EVALUATION FRAMEWORK FOR WWTW HYDROPOWER

The evaluation framework for the selection of Zambian WWTWs having hydropower potential to be included in the Zambian Hydropower Atlas is shown in Figure 5-3. As already stated in chapter 3, a first-order estimate of the gross head can be obtained using Google Earth Pro by observing the altitude of the outlet point to the WWTW and the discharge point of the treated wastewater into the receiving water body. It should be noted that the google earth elevations are inaccurate and the users must be aware of its limitations. Therefore, it is recommended that accurate field measurement methods such as levelling and global position system (GPS) surveying should be carried out to evaluate the gross head obtained by using Google Earth Pro.

The discharge data can be obtained from the water supply and sanitation utilities listed in Table 2-8 of chapter 2. The online Google Forms questionnaire respondents who indicate the presence of WWTWs at their institutions are also potential sources of discharge data. Therefore, the online Google Forms questionnaire will play a vital role in the further development of the Zambian Hydropower Atlas.

The relevant symbols and abbreviations used in the evaluation framework are shown in Table 5-4.

Table 5-4: Symbols and Abbreviations used in the evaluation framework

Abbreviation	Meaning
Δh	The available gross head at the WWTW (m)
h_{outlet}	The altitude of the WWTW outlet point (m)
h_{dp}	The altitude of the WWTW discharge point (m)
h_n	Effective head (m)
FDC	Flow Duration Curve
Q_{50}	50 days availability on the FDC (m^3/s)
Q_{WD}	Design flow of treated wastewater at WWTW (m^3/s)
Q	Design discharge for hydropower generation (m^3/s)
P	Hydropower potential (W)
ρ	The density of water (1,000 kg/m^3)
g	The gravitational due to gravity (9.81 m/s^2)
η	The efficiency of the turbine (%)

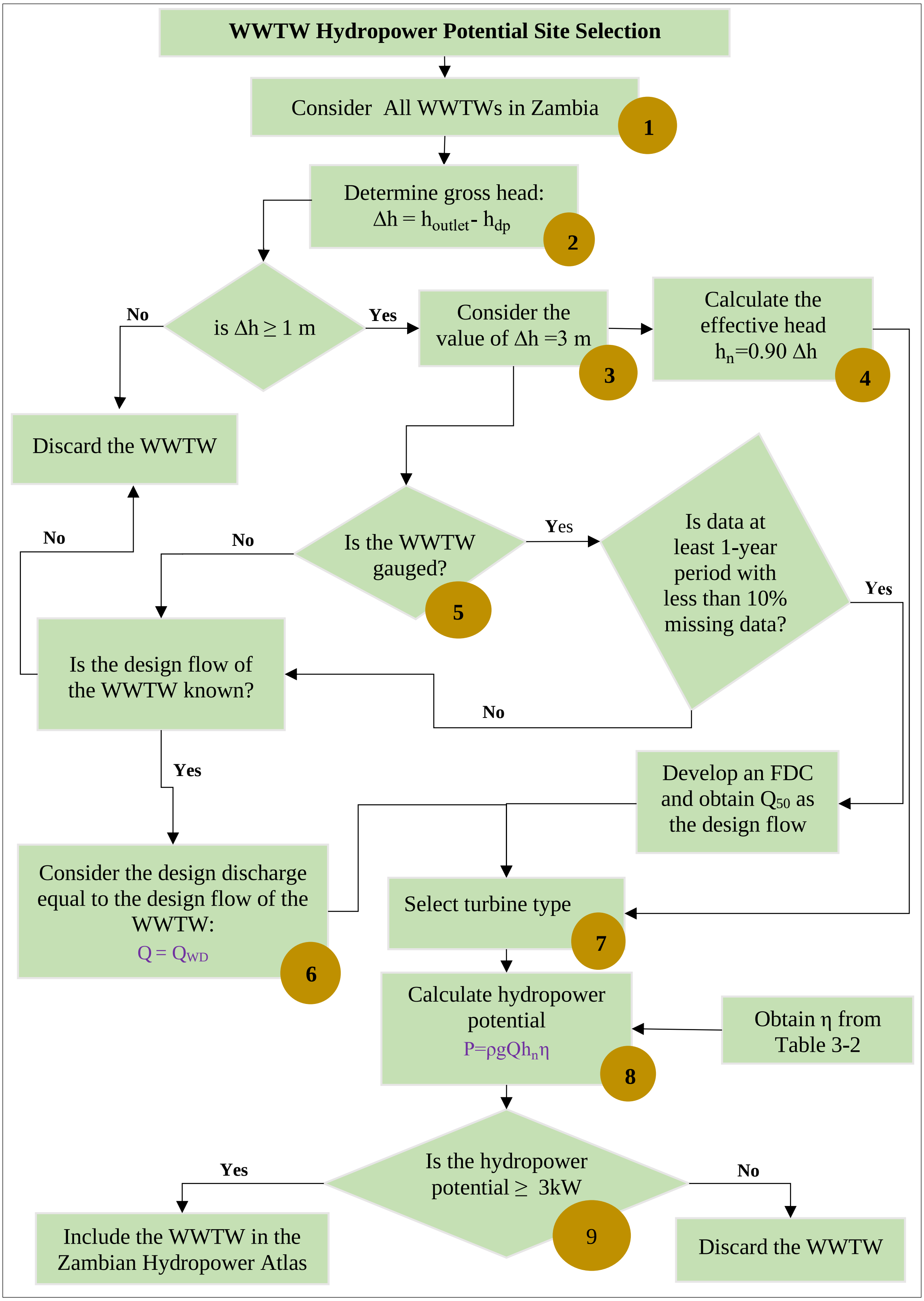


Figure 5-3: Evaluation framework for the selection of WWTWs with hydropower potential to be included in the Zambian Hydropower Atlas

5.5 EVALUATION FRAMEWORK FOR WEIR HYDROPOWER

The evaluation framework for the selection of Zambian weirs having sufficient hydropower potential to be included in the Zambian Hydropower Atlas is shown in Figure 5-4. The framework starts with guiding on the weirs to be considered and to obtain the weir heights. As mentioned in chapter 3 and chapter 4 weir technical data such as heights and widths can be obtained from the hydrological yearbook provided by Federal Institute for Geosciences and Natural Resources (BGR)/Groundwater Resources Management Program(GReSP)/Zambia and irrigation reports in Zambia. The weir headwater and tailwater levels can be obtained from the weir owners and the reports done on Zambian weirs. The online Google Forms questionnaire explained in chapter 3 and shown in Appendix A can also play an important role in obtaining this information for the further development of the Zambian Hydropower Atlas. The discharge data can also be obtained from the sources listed in Table 5-1 under the run-of-river evaluation framework.

It should be noted that this evaluation framework provides only a first-order selection process of the weirs with hydropower potential as it is based on reasonably made assumptions and without the consideration of other factors that affect weir site characteristics such as the weir type. Other factors not considered include the effect of the current purpose of each weir such as water level regulation, fish passage control, and water supply.

The relevant abbreviations used in the evaluation framework for the selection of weirs are shown in Table 5-5 for reference.

Table 5-5: Abbreviations/Symbols used in the evaluation framework

Abbreviation	Meaning
h_w	The height of the weir (m)
b	Weir width (m)
H_{hw}	Elevation of headwater at a weir (m)
H_{tw}	Elevation of tailwater at a weir (m)
ΔH	Height difference between the headwater and tailwater (m)
H_n	Effective head (m)
C_d	Weir coefficient
FDC	Flow Duration Curve
Q_{80}	80 days availability on the FDC (m^3/s)
Q	Design discharge for hydropower generation (m^3/s)
P	Hydropower potential (W)
ρ	The density of water (1,000 kg/m^3)
g	The gravitational due to gravity (9.81 m/s^2)
η	The efficiency of the turbine (%)

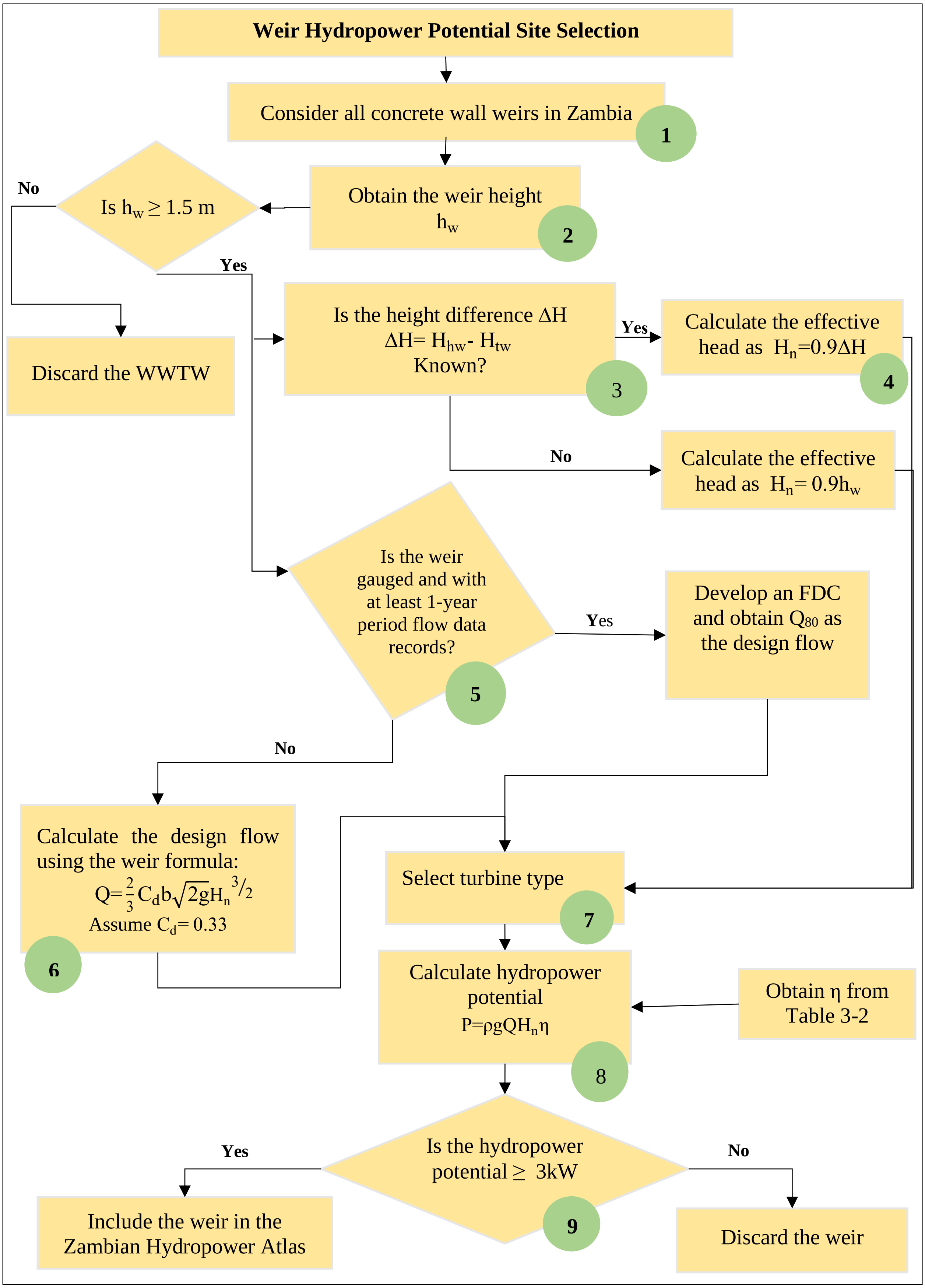


Figure 5-4: Evaluation framework for the selection of weirs with hydropower potential to be included in the Zambian Hydropower Atlas

5.6 EVALUATION FRAMEWORK FOR CANAL HYDROPOWER

The evaluation framework for the selection of canals having hydropower potential to be included in the Zambian Hydropower Atlas is shown in Figure 5-5. The framework firstly guides with the type of irrigation canals to be considered. The input data required in the framework such as the cross-section properties (depths, slopes, and widths) and discharge data for gauged canals can be obtained from the ministry of agriculture and irrigation reports done in Zambia. For irrigation canals located in the Zambezi River Basin, the Zambezi River Authority could also provide the data. Furthermore, the online Google Forms questionnaire shown in Appendix A can also play an important role in obtaining this information for the further development of the Zambian Hydropower Atlas. With this questionnaire, the data required in the framework could be from the individual owners or operators of the canals and thus hydropower could be estimated.

The relevant abbreviations used in the evaluation framework for the selection of irrigation canals are shown in Table 5-6 for reference.

Table 5-6: Abbreviations/Symbols used in the evaluation framework

Abbreviation	Meaning
h	The depth of the canal (m)
b	The width of the canal (m)
A	The cross-sectional flow area of the channel (m^2)
R_h	The hydraulic radius (m)
V	The velocity of water in the canal (m/s)
S_0	The slope of the channel (m/m)
n	The manning's roughness number ($s/m^{1/3}$)
A_t	The swept area of the turbine blade (m^2)
D	The diameter of the turbine (m)
FDC	Flow Duration Curve
Q_{80}	80 days availability on the FDC (m^3/s)
P	Hydropower potential (W)
ρ	The density of water (1,000 kg/m^3)
C_P	The power coefficient of the hydrokinetic turbine

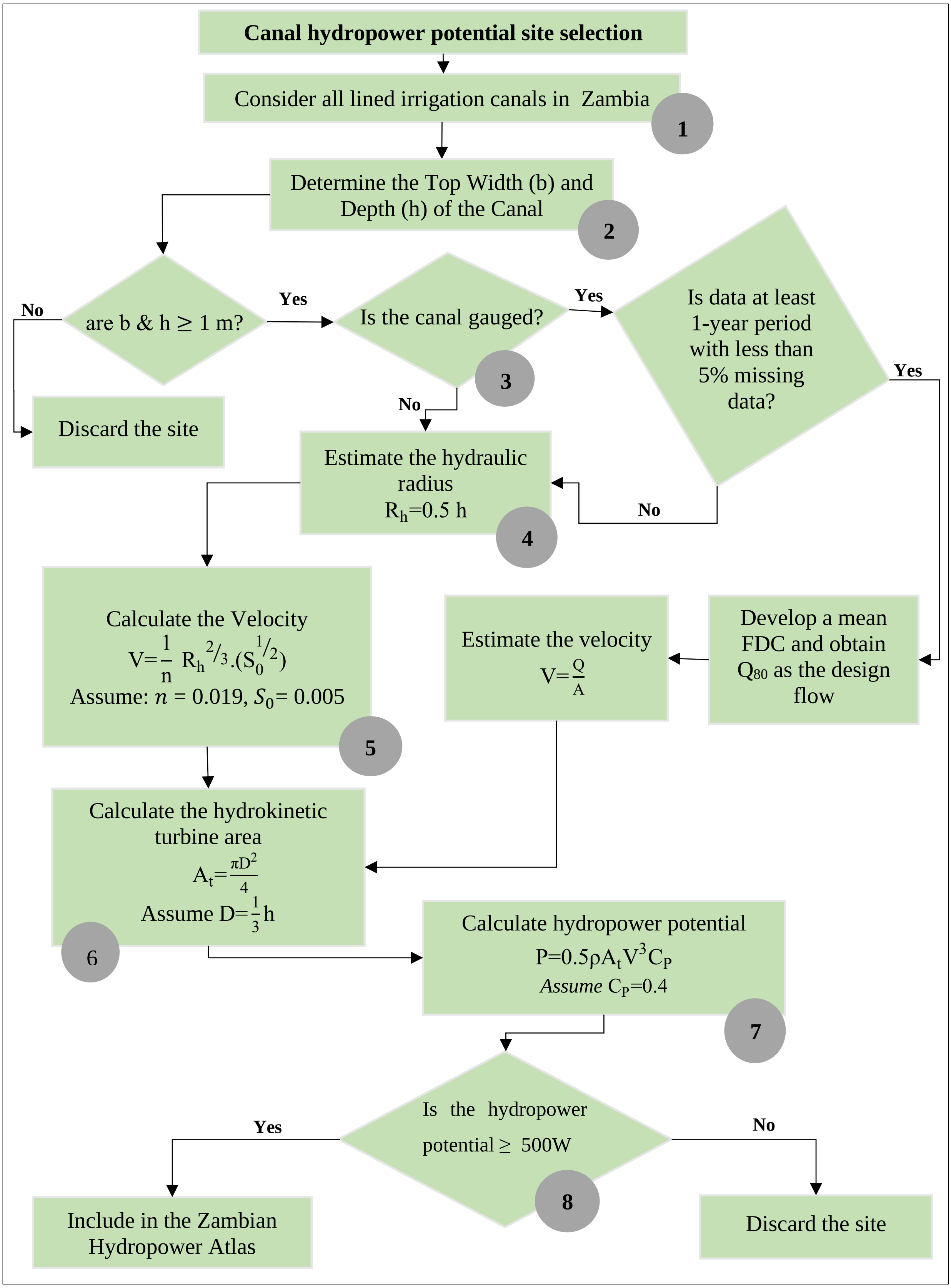


Figure 5-5: Evaluation framework for the selection of Irrigation canals with hydropower potential to be included in the Zambian Hydropower Atlas

5.7 EVALUATION FRAMEWORK FOR BULK PIPELINE HYDROPOWER

The evaluation framework for the selection of bulk water supply systems having hydropower potential to be included in the Zambian Hydropower Atlas is shown in Figure 5-6. This evaluation framework provides the steps to follow when estimating the hydropower potential available in the bulk water systems of Zambia. As explained in chapter 4, the data selection and inclusion or exclusion criteria used in the framework were based on the datasets available in Zambia. This framework, therefore, provides only a first-order evaluation of the hydropower potential in the bulk water supply systems of Zambia. The bulk water pipeline and reservoir data such as design volume, diameter, elevations, location, and elevations can be obtained from the water supply and sanitation utility companies listed in Table 2-8 of chapter 2. The online Google Forms questionnaire respondents who indicate the presence of bulk water pipelines (conduits) at their institutions are also potential sources of this data.

As with other frameworks presented already, the relevant symbols and abbreviations used in this evaluation framework are shown in Table 5-7.

Table 5-7: Abbreviations/Symbols used in the evaluation framework

Abbreviation	Meaning
H_s	Static head (m)
V_r	the capacity of service reservoir (m^3)
H_n	Effective head (m)
Q	Design discharge for hydropower generation (m^3/s)
f	The frictional factor
L	The length of the pipeline (m)
D	The diameter of the pipe in meters (m),
P	Hydropower potential (W)
ρ	The density of water (1,000 kg/m^3)
g	The gravitational due to gravity (9.81 m/s^2)
η	The efficiency of the turbine (%)

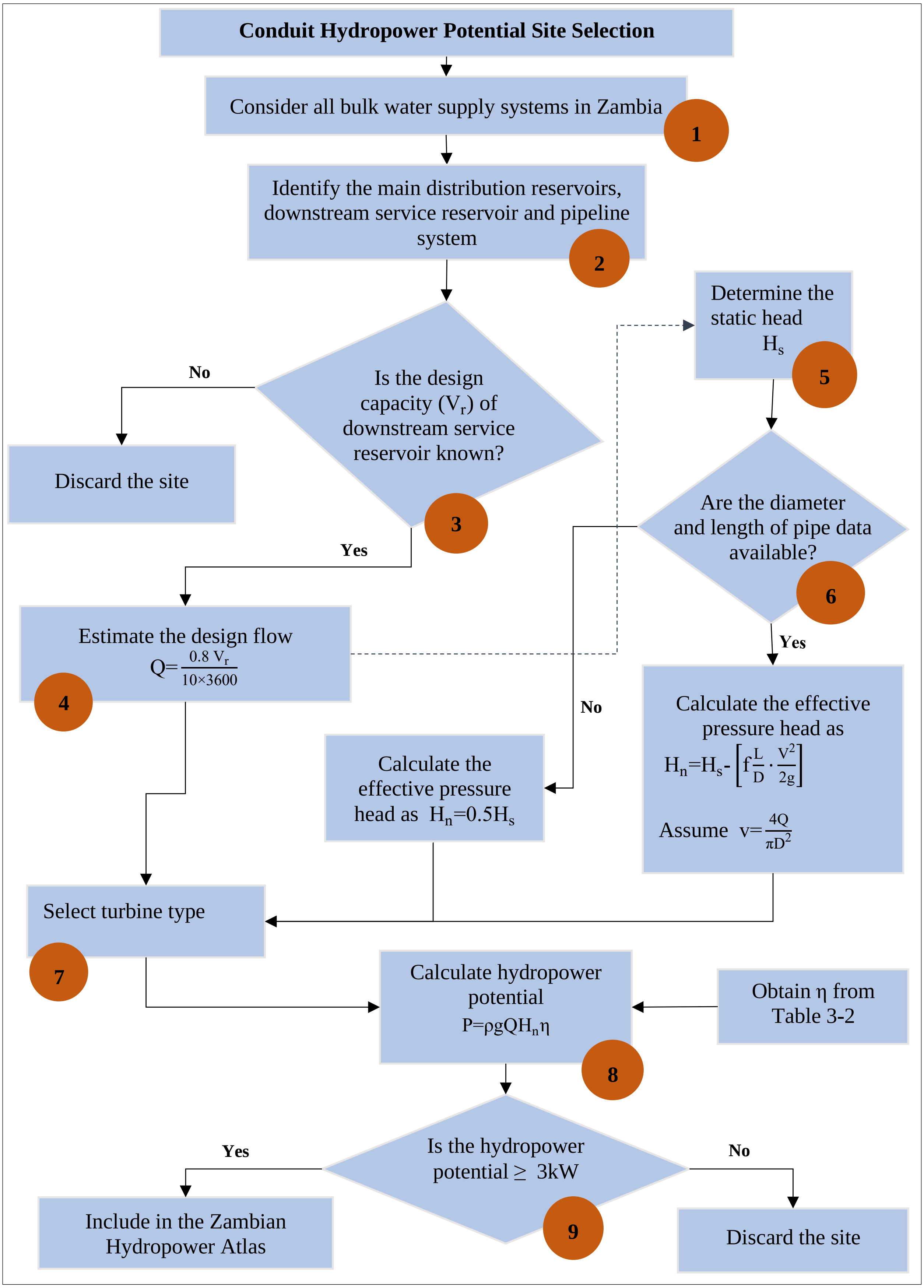


Figure 5-6: Evaluation framework for the selection of bulk water supply pipelines with hydropower potential to be included in the Zambian Hydropower Atlas

5.8 SUMMARY OF EVALUATION FRAMEWORKS

Data availability is critical when it comes to the development of data selection criteria and evaluation frameworks. The datasets were reviewed and assessed as presented in chapter 4 and evaluation frameworks were developed. A summary of the evaluation criteria for the six types of hydropower developed to be followed in the evaluation frameworks is given in Table 5-8. The evaluation frameworks contain the criteria and the step-by-step process of assessing a hydropower potential site to be included in the Zambian hydropower atlas. A total of six evaluation frameworks presented in chapter 5 were developed in this study to be used in the Zambian context. These evaluation frameworks were applied to selected case studies presented in chapter 6 of this dissertation.

Table 5-8: Summary of the developed evaluation criteria for six types of hydropower

SN	Parameter	Run-of-river	Dam	WWTW	Weir	Canal	Conduit
1	Head	• Minimum head = 3m • Effective head = 90 % of the gross head	• Minimum head = 3m • Effective head = 63% of the dam height	• Minimum head = 1m • Gross head = 3m • Effective head = 90 % of the gross head	• Minimum head = 1.5 m • Gross head = weir height • Effective head = 90% of gross head	-	• Effective pressure head = 50% of the static pressure head
2	Discharge	• Q_{80} on the FDC to be considered the design discharge when flow data is available • Design discharge = 30% of median river discharge on the HAZ	• Q_{80} on FDC to be considered the design discharge when flow data is available • Design discharge = 55% of the annual river discharge on the HAZ	• Q_{50} on FDC to be considered the design discharge when flow data is available • Design discharge of WWTW is available for power generation	• Q_{80} on FDC to be considered the design discharge when flow data is available • Weir coefficient (Cd) = 0.33 in the weir equation	• Q_{80} on FDC to be considered the design discharge when flow data is available • Manning's number = 0.019 • Slope of channel = 0.005 (0.5%) • Hydraulic radius = 50% of the channel depth	• 80% of the reservoir capacity can generate power • Power can be generated for 8 hours a day
3	Power Coefficient	-	-	-	-	0.4	-
4	Minimum Potential	30 kW	30 kW	3 kW	3 kW	500 W	3 kW

6 APPLICATION OF THE EVALUATION FRAMEWORKS

6.1 INTRODUCTION

This chapter contains the application of the developed evaluation frameworks presented in chapter 5. The frameworks were applied on the selected sites for each type of hydropower to show a step-by-step selection process of hydropower potential sites that could be included in the Zambian Hydropower Atlas. The weaknesses of the evaluation frameworks are also discussed in this chapter. The run-of-river evaluation framework was applied to a site with known hydropower potential to compare with the results of the framework. For the other five evaluation frameworks, the lack of known hydropower potential sites was a drawback as there were no comparisons to be made. However, the frameworks provided the initial first-order estimation of the hydropower potential and selection process which could be updated anytime in future studies when more detailed information becomes available.

6.2 RUN-OF-RIVER FRAMEWORK EVALUATION

6.2.1 Case Study: The Zengamina Hydropower site

The Zengamina hydropower plant (Figure 6-1) is a run-of-river off-grid micro-hydropower plant based in the Ikelengi district of North-Western Province of Zambia. It has a hydropower potential of 1400 kW of which 750 kW has been installed (ERB, 2015). The plant supplies power to the Kalene mission hospital and surrounding farms, businesses, and residential areas. The plant is privately owned by the North West Zambia Development Trust (NWZDT). It was commissioned on 14th July 2007.

Figure 6-1: View of the Zengamina Hydropower Site (Source: Google Earth Pro)

Application of the evaluation framework

The developed run-of-river evaluation framework was applied to the Zengamina site. This application process together with the data parameters is shown in Table 6-1. The step number in the table corresponds to the number indicated on the evaluation framework. The Zengamina site was selected as a case study because of its uniqueness in terms of capacity (smallest run-of-river plant in Zambia), location (isolated), and purpose (rural electrification). Therefore, the success of the framework in evaluating hydropower potential at this site implies that the framework could be used to also evaluate similar sites.

Table 6-1: Application of the run-of-river evaluation framework to the Zengamina site in Zambia

Name of site: Zengamina		**Coordinates:** Latitude: 11°07'26" S Longitude: 24°11'32" E	
Step No.	**Framework Step**	**Explanation**	**Result**
1	Consider the rivers within the 6 main river catchments of Zambia	The Zengamina site is located on the Upper Zambezi River	The river is within the Zambezi River Catchment of Zambia
2	Is the site within a protected area?	No. The site is not within the protected areas of Zambia shown in Figure 2-37	Consider the site in the evaluation
	Head Evaluation		
3	Determine the Gross head: ΔH	From Google Earth Pro – the estimated gross head is 13 m (i.e., 1222 m -1209 m) over a horizontal distance of approximately 500 m	$\Delta H = 13$ m
	Is $\Delta H \geq 3$ m?	Yes. The gross head is 13 m	Can proceed to compute the effective head
4	Record the value of ΔH		$\Delta H = 13$ m
5	Calculate the effective head $H_n = 0.9\Delta H$	Effective head: $H_n = 0.9 \times 13$	$H_n = 11.7$ m
	Discharge Evaluation		
6	Is the site gauged?	No discharge data records were available	Consider the site to be ungauged
	Go to the HAZ	The HAZ contains the hydrological data for Zambian Rivers	The upper Zambezi river discharge data is considered
	Select the river discharge category	The Upper Zambezi River in the Ikelengi district falls in the river category of 10 m^3/s to 100 m^3/s	Discharge category = 10 - 100 m^3/s
	Determine the median discharge of the river: Q_m	$Q_m = \frac{10+100}{2}$	$Q_m = 55$ m^3/s

7	Compute the design flow: $Q = 0.30\ Q_m$	Q=0.30 × 55	Q = 16.5 m^3/s
	Turbine Selection and Efficiency		
8	Select turbine type	With H_n= 11.7 m & Q=16.5 m^3/s. A cross-flow turbine is selected	From Table 3-2, η = 86%
	Calculation of Hydropower Potential		
9	Calculate Hydropower potential $P = \rho g Q H_n \eta$	P = 1000 ×9.81×16.5×11.7×0.86	P = 1629 kW
	Inclusion in the Zambian Hydropower Atlas		
10	Is the hydropower potential ≥ 30 kW?	Yes. The hydropower potential is 1629 kW	Include the site in the Zambian Hydropower Atlas

As can be seen in Table 6-1, the application of the framework at the Zengamina site estimated the hydropower potential at the site to be 1629 kW and entails that the site could be included in the Zambian Hydropower Atlas since the potential is greater than 30 kW. However, from the feasibility studies conducted during the development of the project, the site is said to have a potential of 1400 kW.

The framework, therefore, overestimates the hydropower potential by 14%. In terms of discharge, the framework estimated the discharge to be 16.5 m^3/s, while the available discharge at the existing site was estimated to be 14.9 m^3/s from the feasibility studies (ERB, 2015). This shows that the framework overestimates this discharge by 9.6%. This could be due to the use of the discharge data from the hydrological modelling results from the HAZ. This data could contain some uncertainties which were not evaluated in this study. Furthermore, in terms of head, there is an underestimation of 5 m. With this framework, the gross head is found to be 13 m while the estimated head from the feasibility study is 18 m (ERB, 2015). This could be attributed to the use of Google Earth Pro in estimating the gross head which is not accurate due to its resolution and therefore the user must be aware of its limitations. The evaluation framework however provides a reasonable first-order evaluation of run-of-river hydropower potential to be included in the Zambian Hydropower Atlas because, with its application, the ungauged sites can be easily evaluated without conducting detailed feasibility studies. The framework also includes the selection of the turbine which makes it possible to take the turbine efficiency into account when evaluating the hydropower potential.

6.3 DAMMED HYDROPOWER FRAMEWORK EVALUATION

6.3.1 Case Study: The Itezhi-tezhi dam

The Itezhi-tezhi hydropower plant (Figure 6-2) is a storage hydropower plant located on the Kafue River in the Itezhi-tezhi district of Southern Province in Zambia. The plant has an installed capacity of 120 MW with an effective head of 40 m and a design discharge of 306.2 m^3/s (MEWD, 2011). The dam was primarily built to regulate the flooding in the Kafue flats and to control the feeding of water into the Kafue Gorge Dam located downstream. The Itezhi-tezhi power plant supplies power to the national grid and is operated by ZESCO. It was commissioned in February 2016.

Figure 6-2: View of the Itezhi-tezhi Dam Site (Source: Google Earth Pro)

Application of the evaluation framework

The developed dammed evaluation framework was applied to the existing Itezhi-tezhi hydropower plant. The application process together with the data parameters is shown in Table 6-2. The step number in the table corresponds to the number indicated on the evaluation framework. The Itezhi-tezhi dam was selected as a case study because it was initially a non-hydropower generating dam and later converted to a hydropower generating dam. Therefore, the success of the framework in evaluating hydropower potential at this site implies that the framework could be used to evaluate other non-hydropower generating dams in Zambia and therefore estimate the untapped potential at these sites.

Table 6-2: Application of the dammed hydropower evaluation framework to the Itezhi-tezhi dam site in Zambia

Name of site: Itezhi-tezhi dam site		**Coordinates:** Latitude: 15°45’55” S Longitude: 26°01’05” E	
Step No.	**Framework Step**	**Explanation**	**Result**
1	Consider Zambian Dams	The Itezhi-tezhi dam in Southern Zambia is considered	-
2	Obtain the dam height: H_d	The existing dam height is obtained (MEWD, 2011)	Dam height: H_d = 65 m
	Is $H_d \geq 3$ m?	Yes. The dam height is 65 m	Can proceed to step 3
	Head Evaluation		
3	Record the value of H_d	H_d = 65 m	
4	Calculate the effective head $H_n = 0.63H_d$	Effective head: H_n=0.63×65 m	H_n = 40.95 m
	Discharge Evaluation		
5	Is the dam site gauged?	No discharge data records were available	Consider the dam site to be ungauged
	Go to the HAZ	The HAZ contains the hydrological data for the Zambian Dam inventory	*Itezhi-tezhi dam annual discharge Q_a= 554.079 m^3/s
6	Compute the design discharge $Q = 0.55Q_a$	Q = 0.55 ×554.079	Q = 304.7 m^3/s
	Turbine Selection and Efficiency		
7	Select turbine type	With H_n = 40.95 m & Q = 304.7 m^3/s. A Kaplan turbine is selected	From Table 3-2, η = 93%
	Calculation of Hydropower Potential		
8	Calculate Hydropower potential $P = \rho g Q H_n \eta$	P = 1000 ×9.81×304.7×40.95×0.93	P = 113.8 MW
	Inclusion in the Zambian Hydropower Atlas		
9	Is the hydropower potential ≥ 30 kW?	Yes. The hydropower potential is 113.8 MW	Include the dam site in the Zambian Hydropower Atlas

**See Appendix D for sample data from the dam database inventory*

As can be seen in Table 6-2, the application of the framework at the Itezhi-tezhi dam site estimated the hydropower potential at the site to be 113.8 MW and it entails that the site could be included in the Zambian Hydropower Atlas since the potential is greater than 30 kW. The site, however, has an installed potential of 120 MW (MEWD, 2011). This shows an underestimation of 5%.

In terms of the potential parameters, the framework overestimated the head only by 2% and under-estimates the discharge by 4%. Similar to the weakness of the run-of-river framework, the use of the discharge data from the hydrological modelling results from the HAZ could contain some uncertainties which were not evaluated in this study. The uncertainties in the hydrological data could have contributed to the underestimation of the hydropower potential.

The process demonstrated in Table 6-2 shows that dammed hydropower evaluation framework can be used to provide a first-order evaluation of hydropower potential at dam sites in Zambia. The frameworks ease the evaluation of hydropower potential at ungauged dam sites without conducting detailed feasibility studies. The framework also takes into account the turbine efficiency when evaluating the hydropower potential. Furthermore, the framework can be used to evaluate hydropower potential at non-hydropower generation dams including small farm dams which can be useful to small-holder farmers in Zambia who farm near these dams.

6.4 WWTW FRAMEWORK EVALUATION

6.4.1 Case Study: Kaunda Square WWTW

The Kaunda square wastewater treatment plant (Figure 6-3) is a non-conventional wastewater treatment plant located in the city of Lusaka in Zambia. Kaunda Square WWTW has a design flow capacity of 3,600 m^3/day. The treated wastewater from the Kaunda Square WWTW is discharged into freshwater bodies of the Ngwerere stream which is a tributary of the Chongwe River. The WWTW is operated by the Lusaka Water and Sewerage Company (LWSC) and regulated by NWASCO.

Figure 6-3: View of the Kaunda Square WWTW Site (Source: Google Earth Pro)

Application of the evaluation framework

The developed WWTW evaluation framework was applied to the Kaunda Square WWTW site. The application process together with the data parameters is shown in Table 6-3. The Kaunda Square WWTW is currently non-hydropower generating, however, it was selected as a case study due to the availability of measured data at the site for comparison with the framework. The application process could be followed at other WWTW in Zambia.

Table 6-3: Application of the WWTW hydropower evaluation framework to the Kaunda Square WWTW site in Zambia

Name of site: Kaunda Square WWTW		**Coordinates:** Latitude: 15°21'32" S Longitude: 28°21'05" E	
Step No.	**Framework Step**	**Explanation**	**Result**
1	Consider All WWTWs in Zambia	The Kaunda Square WWTW in Lusaka Province was considered	-
2	Determine the gross head: $\Delta h = h_{outlet} - h_{dp}$	From Google Earth Pro, h_{outlet}= 1209 m h_{dp} = 1205 m	Gross head: $\Delta h = 4$ m
	Is $\Delta h \geq 1$ m?	Yes. Gross head $\Delta h = 3$ m	Can proceed to step 3
	Head Evaluation		
3	Record the value of Δh	$\Delta h = 3$ m	
4	Calculate the effective head $h_n = 0.90\ \Delta h$	Effective head: $h_n = 0.90 \times 3$	h_n= 2.7 m
	Discharge Evaluation		
5	is the WWTW gauged?	Assume the WWTW is ungauged	
	Is the design flow of the WWTW known?	Yes, the design WWTW discharge: Q_{WD}= 3,600 m^3/day	Q_{WD}= 0.042 m^3/s
6	Consider the design discharge equal to the design flow of the WWTW	$Q = Q_{WD} = 0.042 m^3/s$	$Q = 0.042\ m^3/s$
	Turbine Selection and Efficiency		
7	Select turbine type	With H_n= 2.7 m & Q = 0.042 m^3/s. A cross-flow turbine is selected	From Table 3-2, $\eta = 86\%$
	Calculation of Hydropower Potential		
8	Calculate Hydropower potential $P = \rho g Q H_n \eta$	P =1000×9.81×0.042×2.7×0.86	P = 0.95 kW
	Inclusion in the Zambian Hydropower Atlas		
9	Is the hydropower potential ≥ 3 kW?	No. The hydropower potential is 0.95 kW	Do not include the WWTW site in the Zambian Hydropower Atlas

As can be seen in Table 6-3, the application of the framework at the Kaunda Square WWTW dam site estimated the hydropower potential at the site to be 0.95 kW and it entails that the site should not be included in the Zambian Hydropower Atlas since the potential is less than 3 kW. Using the actual measured flow data, the FDC for the Kaunda Square WWTW (shown in Figure 6-4) was generated. From the FDC, Q_{50} is approximately equal to 0.012 m^3/s. This shows that the framework overestimated the actual discharge by 72%. Using the field measured data, the hydropower potential can be estimated as follows:

$$P = 1000 \times 9.81 \times 0.012 \times 2.7 \times 0.86 = 0.27 \text{ kW}$$

This shows an overestimation of 72%. Using the field measured data, the site can still not be included in the Zambian Hydropower Atlas since the potential is less than 3 kW. Due to this overestimation, the framework should be considered to give only a first-order estimation of hydropower potential at WWTW in Zambia. Detailed feasibility studies should be conducted to determine the actual potential.

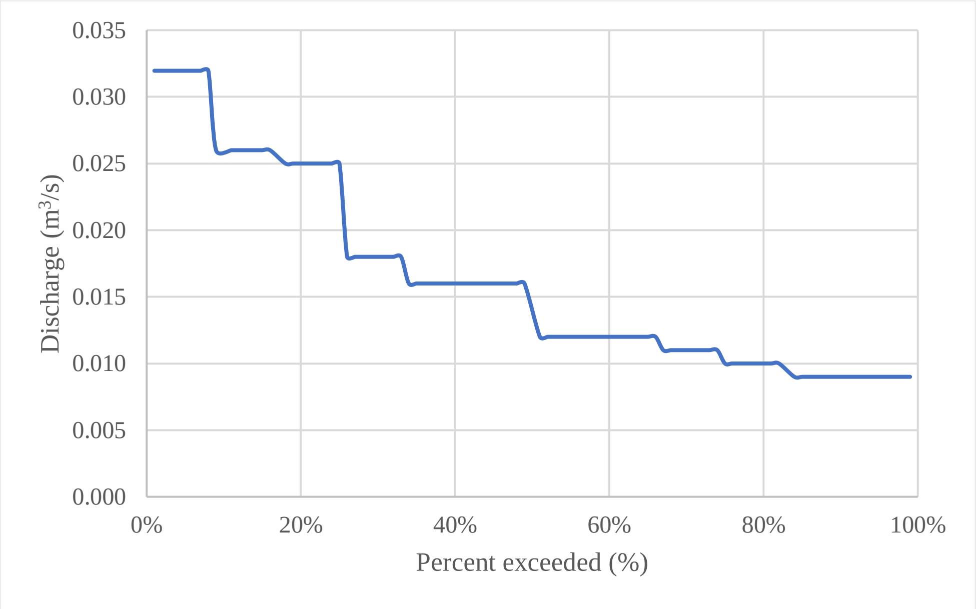


Figure 6-4: Kaunda Square WWTW Flow Duration Curve for 2017 (LWSC,2018)

The main advantage of the framework is that it provides a simplified approach to estimating hydropower potential at WWTWs in Zambia without requiring the WWTW to be a gauged site. The WWTWs can be visualized in Google Earth Pro to obtain the gross head. This however requires a strong internet connection to accurate elevations and resolutions. Finally, applying the framework to the Manchinchi WWTW which is also located in Lusaka but with a design capacity of 36,000 m^3/day and Google Earth Pro gross head of 2 m, the framework estimates the hydropower potential at the site to be 11.1 kW. This entails that the Manchinchi WWTW could be included in the Zambian Hydropower Atlas.

6.5 WEIR FRAMEWORK EVALUATION

6.5.1 Case Study: Zengamina Weir

The Zengamina site (Figure 6-5) is located in the North-Western Province of Zambia across the canal that diverts the water to the Zengamina hydropower plant described earlier. The weir is used to regulate water flowing towards the powerhouse of the Zengamina hydropower plant. It has a height of 1.5 m and a width of 7.5 m. The weir has a measured average discharge of 8.0 m^3/s (ERB, 2015).

Figure 6-5: View of the Zengamina Weir Site (Source: Google Earth Pro)

Application of the evaluation framework

The developed weir evaluation framework was applied to the Zengamina weir site. The application process together with the data parameters is shown in Table 6-4. The Zengamina weir is currently non-hydropower generating, however, this site was selected as a case study due to data availability required in the application of the weir evaluation framework. The application process could be followed at any other weir in Zambia.

The process demonstrated in Table 6-4, shows that the application of the framework at the Zengamina weir site in Zambia estimated the hydropower potential at the site to be 130 kW and this entails that the site should be included in the Zambian Hydropower Atlas since the potential is greater than 3 kW. With this process, several weirs could be assessed in Zambia and those that meet the criteria can be included in the Zambian Hydropower Atlas.

In terms of hydropower parameters, it should be noted that the framework overestimates the discharge by 3.46 m^3/s compared to the reported 8.0 m^3/s by ERB (2015). Assuming the effective head to be 1.35 m as determined in Table 6-4, the hydropower potential with the discharge equal to 8.0 m^3/s can be calculated as follow:

$P = 1000 \times 9.81 \times 8.0 \times 1.35 \times 0.86 = 101.2$ kW

This shows an overestimation of 29.3 kW in terms of hydropower potential. With the availability of more data such as an existing weir hydropower plant, this framework could be updated and improved. As can be seen in Table 6-4, the framework can be used to provide a first-order estimation of hydropower potential at the weir site in Zambia without requiring a detailed assessment and field measurements.

Table 6-4: Application of the weir hydropower evaluation framework to the Zengamina weir site in Zambia

Name of site: Zengamina Weir		**Coordinates:** Latitude: 11°07'26" S Longitude: 24°11'32" E	
Step No.	**Framework Step**	**Explanation**	**Result**
1	Consider all concrete wall weirs in Zambia	The Zengamina weir is a concrete wall weir and is located in the Northern Province of Zambia	-
2	Obtain the weir height h_w	The height of the Zengamina weir $h_w = 1.5$ m	Weir height $h_w = 1.5$ m
	is $h_w \geq 1.5$ m?	Yes. $h_w = 1.5$ m	Can proceed to step 3
	Head Evaluation		
3	Is the height difference $\Delta H = H_{hw} - H_{tw}$ Known?	No, tailwater and headwater elevations were not available	
4	Calculate the effective head as $H_n = 0.9\, h_w$	Effective head: $h_n = 0.90 \times 1.5$	$h_n = 1.35$ m
	Discharge Evaluation		
5	Is the weir gauged and with at least 1-year period flow data records?	The gauging station data were not available.	Consider the weir to be ungauged
6	Calculate the design flow using the weir formula: $Q = \frac{2}{3} C_d b \sqrt{2g} H_n^{3/2}$ Assume $C_d = 0.33$	Discharge: $Q = \frac{2}{3} \times 0.33 \times 7.5 \times \sqrt{2 \times 9.81} \times 1.35^{3/2}$	$Q = 11.46$ m³/s
	Turbine Selection and Efficiency		
7	Select turbine type	With $h_n = 1.35$ m & $Q = 11.46\ m^3/s$, A cross-flow turbine is selected	From Table 3-2, $\eta = 86\%$
	Calculation of Hydropower Potential		
8	Calculate Hydropower potential	$P = 1000 \times 9.81 \times 11.46 \times 1.35 \times 0.86$	$P = 130.5$ kW

	P=ρgQH_nη		
	Inclusion in the Zambian Hydropower Atlas		
9	Is the hydropower potential ≥ 3 kW?	Yes. The hydropower potential is 130.5 kW	Include the WWTW site in the Zambian Hydropower Atlas

6.6 CANAL FRAMEWORK EVALUATION

6.6.1 Case Study: Sioma Irrigation Scheme Canal

The Sioma Irrigation Scheme (SIS) shown in Figure 6-6 is located in the Sioma district in the Western Province of Zambia. It falls in the Zambezi river catchment of Zambia. The irrigation scheme was designed to provide water for more than 65 hectares of cropland for about 70 households in the rural areas of the Sioma district. The irrigation canal draws water from the Zambezi river and feeds into the fields by gravity.

Figure 6-6: Location of the Sioma Irrigation Scheme Site (Source: Google Earth Pro)

Application of the evaluation framework

The developed canal hydropower evaluation framework was applied to the Sioma irrigation canal site. The application process together with the data parameters is shown in Table 6-5. The Sioma irrigation is currently non-hydropower generating. Farmers depend on firewood and diesel for energy. This site was selected as a case study due to data availability required in the application of the canal evaluation framework and to show the application of the framework in the rural setting where the need for electricity is urgent. The application process could be followed at any other canal in Zambia. Appendix E1 shows the technical layout of the Sioma Irrigation Scheme.

The process demonstrated in Table 6-5, shows that the application of the framework at the Sioma Irrigation canal site in Zambia estimated the hydrokinetic power potential at the site to be 220 W and entails that the site could not be included in the Zambian Hydropower Atlas since the potential is less than 500 W. Similarly, several irrigation canals in Zambia could be assessed and those that meet the criteria could be included in the Zambian Hydropower Atlas.

Furthermore, the procedure followed in Table 6-5 shows that the framework can be used to provide a first-order estimation of hydrokinetic power potential in the canals in Zambia without requiring a detailed assessment and field measurements. The weakness of the framework is that it does not consider the evaluation of hydrokinetic power potential in a natural stream or river channels where such potential could also be tapped. This was due to the lack of data associated with stream channels in Zambia. Detailed assessment of hydrokinetic potential such as the methodology in Jacobson (2012) can be followed to assess hydrokinetic potential in natural streams.

Table 6-5: Application of the canal hydropower evaluation framework to the Sioma Irrigation Scheme site in Zambia

Name of site: Sioma Irrigation Scheme (SIS) canal		**Coordinates:** Latitude: 16°37'2.68"S Longitude: 23°31'23.36"E	
Step No.	**Framework Step**	**Explanation**	**Result**
1	Consider all lined irrigation canals in Zambia	The Sioma main drainage/ irrigation canal channel is lined and is located in the Western Province of Zambia	-
2	Determine the Top Width (b) and Depth (h) of the Canal	Top width (b) = 1 m, Depth $(h) = 1$ m See appendix D1	b = 1 m, h = 1 m
	Are b & h ≥ 1 m?	Yes. b = 1 m, h =1 m	Can proceed to step 3
	Velocity Evaluation		
3	Is the canal gauged?	No, the site is not gauged	Consider the site to be ungauged
4	Estimate the hydraulic radius $R_h=0.5h$	Hydraulic radius: $R_h= 0.5 \times 1$	$R_h= 0.5$ m
5	Calculate the Velocity $V=\frac{1}{n} R_h^{2/3}(S_0^{1/2})$ Assume: n = 0.019, S_0= 0.005	Velocity: $V=\frac{1}{0.019}\ 0.5^{2/3}(0.005^{\frac{1}{2}})$	Consider the weir to be ungauged V=2.34 m/s
6	Calculate the hydrokinetic turbine area $A_t=\frac{\pi D^2}{4}$ Assume turbine diameter:	$D=\frac{1}{3}\times 1 = 0.33$ m $A_t = \frac{\pi \times 0.33^2}{4}$	$A_t = 0.086$ m^2

	$D = \frac{1}{3} h$		
	Calculation of Hydropower Potential		
8	Calculate Hydropower potential $P = 0.5 \rho A_t V^3 C_P$ *Assume* $C_P = 0.4$	$P = 0.5 \times 1000 \times 0.086 \times 2.34^3 \times 0.4$	P = 220.4 W
	Inclusion in the Zambian Hydropower Atlas		
9	Is the hydropower potential ≥ 500 W?	No. The hydropower potential is 220.34 kW	Do not include the SIS canal site in the Zambian Hydropower Atlas

6.7 BULK WATER SUPPLY SYSTEMS FRAMEWORK EVALUATION

6.7.1 Case Study: LWSC Water Supply Chelstone Service Reservoir

The Chelstone service reservoir (Figure 6-7) is located in Lusaka. It is used by the Lusaka Water Supply and Sewerage Company (LWSC) to supply the township of Chelstone. It is a ground reservoir with a storage capacity of 5,000 m^3 and provides about 9hours of storage in the systems. The water in the reservoir is transported from the Stuart Main Distribution Reservoir which draws water from the Kafue River via the Iolanda WTW in Kafue. The Stuart reservoir is the largest storage reservoir in Lusaka which is used to transport potable water to the Chelstone and High Court Reservoirs.

Figure 6-7: Location of the Chelstone Service Reservoir Site (Source: Google Earth Pro, 2022)

Application of the evaluation framework

The developed conduit hydropower evaluation framework was applied to the LWSC at Chelstone service reservoir in Lusaka. The application process together with the data parameters is shown in Table 6-6. The LWSC bulk water supply system currently has no conduit hydropower technologies installed. The utility depends on ZESCO to meet its high energy requirements. The LWSC site was selected as a case study because Lusaka is generally a flatland, therefore, the estimated potential would give the worst-case scenario as compared to other parts of Zambia. The application process could be followed at any other bulk water supply system in Zambia. Appendix E shows the layout of the LSWC bulk water supply system.

The process followed in Table 6-6, shows that the application of the framework at the Chelstone service reservoir site estimated the hydropower potential at the site to be 39 kW and this entails that the site should be included in the Zambian Hydropower Atlas since the potential is greater than 3 kW.

Similarly, other bulk water supply systems in Zambia could be assessed and those that meet the criteria in the framework could be included in the Zambian Hydropower Atlas. Furthermore, the procedure followed in Table 6-6 shows that the framework can be used to provide a first-order estimation of conduit hydropower potential in the bulk water supply systems in Zambia without conducting detailed feasibility assessments and field measurements. The limitation of the framework is that it does not consider the evaluation of conduit hydropower potential at WTWs and PRVs where such potential could also be tapped. This was due to a lack of data associated with evaluating hydropower potential at these such Zambian infrastructures. Detailed evaluation of conduit hydropower potential such as the evaluation framework developed by Bekker, et al. (2021) in South Africa can be followed to assess the conduit hydropower potential at PRVs within the bulk water supply systems.

Table 6-6: Application of the bulk water systems hydropower evaluation framework to the LWSC Chelstone service reservoir site in Zambia

Name of site: Chelstone Service Reservoir		**Coordinates:** Latitude: 15°22'30" S Longitude: 28°22'56" E	
Step No.	**Framework Step**	**Explanation**	**Result**
1	Consider all bulk water supply systems in Zambia	The LWSC bulk water supply system is located in the Lusaka Province of Zambia	-
2	Identify the main distribution reservoirs, downstream service reservoir and pipeline system	Identified are Stuart main distribution reservoir, Chelstone service reservoir. See appendix E2	-
	Flow Evaluation		
3	Is the design storage capacity (V_r) of downstream service reservoir known?	Yes, the storage capacity (V_r) of the Chelstone service reservoir is 5,000 m^3 (LWSC, 2014).	V_r=5,000 m^3
4	Estimate the design flow $Q=\frac{0.8\ V_r}{10\times3600}$	Design flow: $Q=\frac{0.8\times5{,}000}{8\times3600}$	Q=0.14 m^3/s
	Effective Pressure Head Evaluation		
5	Determine the static head H_s	The Stuart main reservoir elevation = 1311 m The Chelstone service reservoir elevation = 1245 m	H_s=66 m
6	Are the diameter and length of pipe data available?	No, the pipe network lengths and diameters are unavailable	
	Calculate the effective pressure head as $H_n = 0.5H_s$	The effective pressure head: $H_n=0.5\times66$ m	H_n= 33 m
	Turbine Selection and Efficiency		
7	Select Turbine Type	With Q=0.14 m^3/s, H_n=33 m, A cross-flow turbine is selected	From Table 3-2, η=86 %
	Calculation of Hydropower Potential		
8	Calculate Hydropower potential $P=\rho gQH_n\eta$	P=1000 ×9.81 ×0.14×33×0.86	P=39 kW
	Inclusion in the Zambian Hydropower Atlas		
9	Is the hydropower potential ≥ 3 kW?	Yes. The hydropower potential is 39 kW	Include the Chelstone reservoir hydropower site in the Zambian Hydropower Atlas

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Zambia has over 45% of Southern Africa's surface water resources, however, the country is still facing electricity challenges which are associated with frequently occurring blackouts and load shedding. As of 2019, over 1.9 million households (57.6%) had no access to electricity. Furthermore, over 96% of the rural population are still without electricity. This calls for attention and sustainable solutions to electrification, especially the rural population as also reinforced by goal number 7 of the sustainable development goals.

Zambia's electricity supply largely comes from a few large hydropower plants. The country is reported to have the potential of over 6000 MW with the available water resources. The small-scale hydropower potential has not been completely quantified in Zambia, especially at the existing water infrastructure. The small-scale hydropower plants can play a huge role in boosting Zambia's electrification by providing electricity to isolated rural households, streets, clinics, schools or industries, buildings and within the existing water infrastructure to meet the energy requirements.

Other African countries such as Madagascar, Tanzania and Rwanda have developed and implemented hydropower atlases which made aware of the untapped small scale hydropower potential to the government and private investors. The hydropower atlas as a unique tool can showcase a country's hydropower potential including the efforts required to implement the technologies. Therefore, it is an important tool for the government and investors who wish to develop hydropower plants.

Zambia has not developed a hydropower atlas and therefore, its hydropower potential has not been quantified in detail. Thus, there is a need to develop a hydropower atlas for Zambia, however, there is little technical information and literature regarding the evaluation of hydropower potential and hydropower at existing water infrastructure in Zambia. This study attempted to address this problem by developing data selection criteria and evaluation frameworks to be followed in the development of the Zambia hydropower atlas. The data selection criteria and evaluation frameworks show a step-by-step process to be followed in the evaluation of hydropower potential and the criteria to be met for a site to be included in the Zambian hydropower atlas. Criteria development as a first step was also done by other researchers in the development of other existing hydropower atlases. These include the development of the Tanzania hydropower atlas, Madagascar hydropower atlas and South African hydropower atlas (World Bank, 2015; World Bank, 2017a; Bekker, et al., 2021).

The methodology outlined in this report was followed in detail. This included conducting a detailed literature review on existing hydropower atlases and the evaluation of hydropower potential conducted by other researchers. The methodology also included the use of an online Google Forms questionnaire as a tool for the further development of the Zambian hydropower atlas with regard to data sources. Water infrastructure institutions like Lusaka Water and Sewerage Company, Mulonga Water and Sewerage Company, Wild Wide Fund (WWF) Zambia were visited to obtain data and reports which were used in the development of the data selection criteria. Through these steps, the data and formulas required to evaluate hydropower potential were identified and evaluated to develop the Zambian context evaluation.

By following the outlined methodology and with respect to the objectives of this study, the following conclusions have been made:

- The data required to evaluate the hydropower potential was determined. This data was determined for 6 types of hydropower outlined in the scope of this study.
- The various available sources of the required data were identified. These included online data sources, reports, and institutions in charge of water infrastructure in Zambia.
- The data required data were collected from the various identified sources to ensure easy accessibility of the data for the further development of the Zambian Hydropower Atlas. Furthermore, the online Google Forms questionnaire forms a basis for the continuous collection of data for the further development of the atlas.
- The evaluation frameworks and data selection criteria to which a specific water infrastructure or river scheme should conform to, to be included in the atlas were developed. As per the scope of this study, a total of 6 evaluation frameworks were developed.
- The developed evaluation frameworks and data selection criteria were evaluated. All evaluation frameworks were applied to selected case studies to show a step-by-step application of the frameworks. Weaknesses of the frameworks were also identified at this stage.

The above conclusions entail that all the specific objectives of the study were met and therefore it can be concluded that the main objective of this study which was to develop the criteria for the selection process of hydropower potential sites to be included in the Zambian Hydropower Atlas has been achieved.

Finally, In line with the hypothesis of this study, it can be concluded that depending on the available data on existing water infrastructure in Zambia, the data selection criteria and evaluation frameworks for hydropower potential can be developed. The developed criteria and evaluation frameworks can provide preliminary guidance in the evaluation of hydropower potential sites to be included in the Zambian Hydropower Atlas. It is important to note that while these conclusions have been made, the study had limitations and challenges. The limitations of the study were:

- Field testing and installation of flow measuring instruments on ungauged water infrastructure and rivers were not conducted.
- The study did not consider the cost-benefit analysis of the hydropower potential evaluated.
- The financial analyses were not considered.
- The assessment on the impact of temporal variations in discharge as per river catchment characteristics and rainfall patterns were considered were not conducted.
- Criteria development for the pumped storage hydropower was not considered in this study.
- Existing commercial tools for selecting hydropower plants such as SiteFinder (developed by SHER Ingénieurs-Conseils) were not used in this study, however, the results reported by other authors who used such tools were used in this study.

The main challenge encountered in this study was the lack of data availability. This is somewhat commonly experienced by other researchers, especially where hydrological data is concerned. This challenge could also be attributed to the Covid-19 pandemic since most institutions were closed during country lockdowns.

7.2 RECOMMENDATIONS

Based on the findings of this study, the following recommendations have been made for further research:

- This study did not develop the evaluation frameworks for pumped hydropower. Future research should consider developing the data selection criteria and evaluation frameworks for this.
- Future research should conduct detailed environmental, social, and economic studies associated with each type of hydropower. The evaluation frameworks developed in this study could be updated to incorporate such information.
- The evaluation frameworks developed in this study should be considered only to give a first-order evaluation of hydropower potential. Future research should consider validating these frameworks and updating them. The frameworks can be updated with the availability of more data.
- Existing water infrastructures such as canals can generate small-scale hydropower which can boost Zambia's electricity problems, however, monitoring at these infrastructures in terms of measurable parameters such as flow and velocity is poor. Future research should conduct detailed assessments on how to improve data monitoring at these water

infrastructures including installing flow measuring instruments and dam water levels. With the availability of measured data, the evaluation frameworks developed in this study could be updated and improved.

- Future research should investigate the best suitable factor for evaluating effective head as the used factor (0.9) in this study may not be suitable for low head hydropower assessments that are applicable at WWTWs.
- Future research should include field testing of water pressure at residential distribution reservoirs to improve the conduit flow criteria reported in this study. The reported values are somewhat higher and need to be adjusted in future research.
- The responses from the google form online questionnaire were poor. While this could be attributed to the impact of Covid-19, future research should consider developing methods and means by which the questionnaires can easily reach the target respondents.
- Future research should conduct cost-benefit assessments for each hydropower site evaluated using these frameworks.

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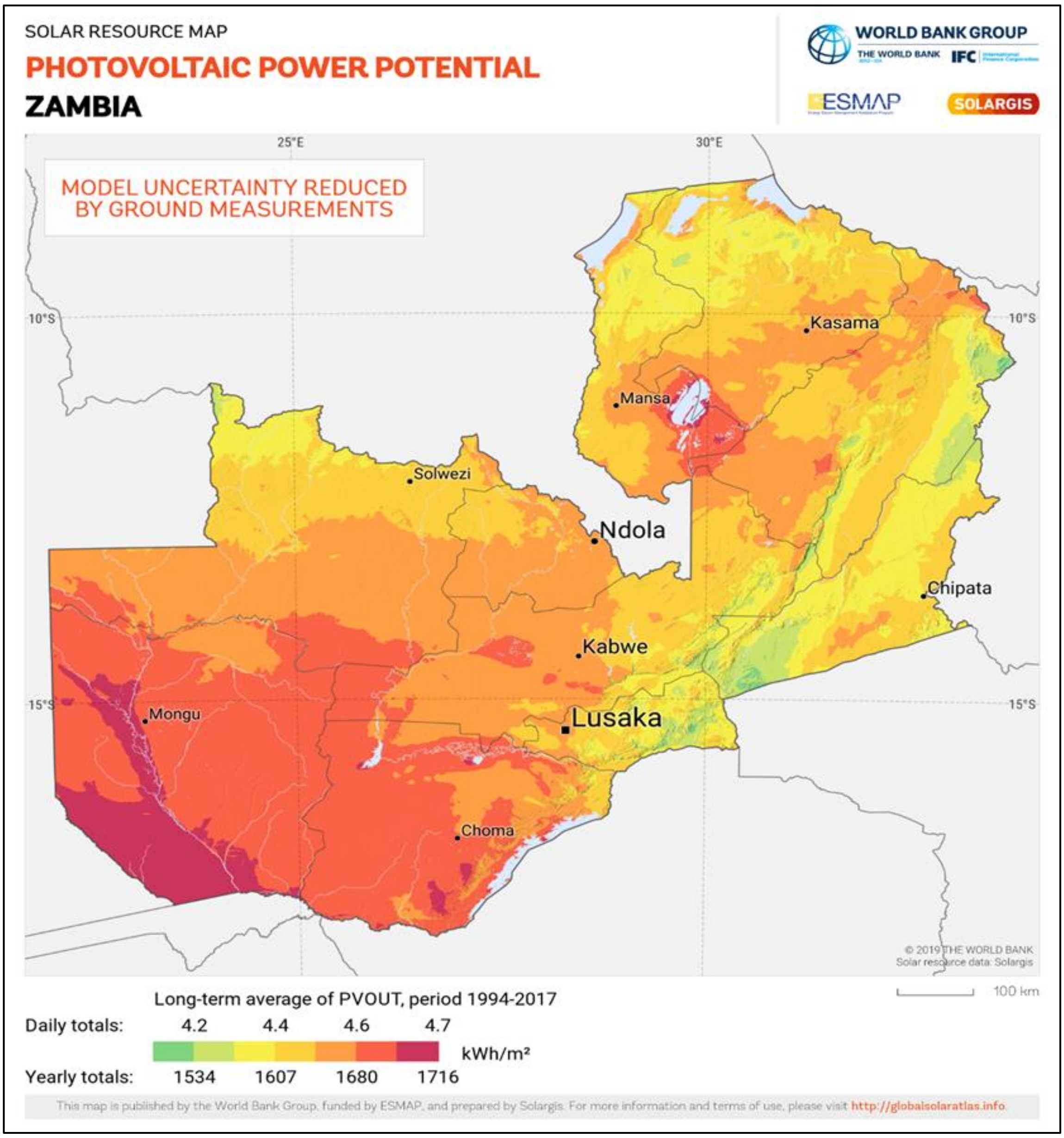
APPENDIX A: SOLAR RESOURCE ATLAS FOR ZAMBIA

Source: World Bank (2019)



APPENDIX B: QUESTIONNAIRE

B1: GOOGLE FORMS QUESTIONNAIRE

Development of the Zambian Hydropower Atlas (ZHA) Data Collection Questionnaire

This questionnaire contains two Parts A and B.

Your responses in this questionnaire will be used for the purpose of this study only and will be kept confidential as required.

Kindly complete the questionnaire as far as possible as any information collected would be useful in this research study.

If you have any questions or require feedback regarding this questionnaire, kindly contact: u20639122@tuks.co.za

Part A: Existing Water Infrastructure

This part contains 9 Questions regarding the existing water infrastructure. Please answer as much as possible.

1. Please indicate the name of your institution

____

2. Please indicate the address of your institution (Town, District, Province)

____

____

____

____

____

3. Please select the type of your institution from the list below.

Tick all that apply.

- [ ] Government Organization
- [ ] Non-Government Organization (NGO)
- [ ] Private

Other: [ ] ____________________

4. Please select the existing water infrastructure available at your institution

Tick all that apply.

- [ ] Weir
- [ ] Irrigation canal
- [ ] Dam
- [ ] Wastewater Treatment Plant (WWTP)
- [ ] Water Treatment Plant (WTP)
- [ ] Bulk Water Storage Reservoirs
- [ ] Conduits / Bulk Water Pipelines
- [ ] None of the Above

5. Are there documents and /or written reports on the above-selected water infrastructure?

Mark only one oval.

( ) Yes

( ) No

6. If your answer is Yes in (5) above; Would you be willing to share the reports?

Mark only one oval.

( ) Yes

( ) No

7. If your answer in (6) is Yes, kindly provide your email address or Phone number for a follow up, or you can alternatively send an email to u20639122@tuks.co.za

8. If your answer is No in 6 above, Please provide the contact details of personnel who can provide data related to the water infrastructure at the institution.

9. Kindly recommend other means through which data related to existing water infrastructure could be collected from the institution (e.g. websites, offices, etc.)

Part B: Hydropower Plants and/or Potential sites data

This part contains 4 questions. Please answer as much as possible, Thank you.

10. Are there any existing hydropower plants at your institution?

Mark only one oval.

- Yes
- No

11. Are there ongoing hydropower projects or planned hydropower projects at your institution?

Mark only one oval.

- Yes
- No

12. Has your institution identified any hydropower potential sites in Zambia?

Mark only one oval.

- Yes
- No

13. If your answer in (10), (11), or (12) is Yes, kindly download the Data Entry Form (download link: https://tinyurl.com/y6dcua7m) containing the required data and parameters helpful in this study: Kindly complete the form as far as possible and email it to u20639122@tuks.co.za once completed.

The End: Thank you so much for your time and participation

The questionnaire is available at:

https://docs.google.com/forms/d/1e5YT34lFOnf9doEdLNMe8ZFnV9zMUBM6Aq-2I1NiL7o/edit

B2: POSSIBLE SOURCES OF WATER INFRASTRUCTURE DATA FROM THE GOOGLE FORMS QUESTIONNAIRE

1. Ministry of Energy
2. Ministry of Agriculture
3. Universal Mining and Chemical Industries Limited (UMCIL)
4. Mulonga Water Supply and Sanitation Co.
5. Federal Institute for Geosciences and Natural Resources /BGR/ Groundwater Resources Management program(GReSP)
6. Saloba Limited
7. AMS Engineering
8. Vubwi Town Council
9. Kasempa Town Council
10. Zambian Irritech
11. University of Zambia Engineering Section
12. Ministry of Local Government DHID
13. FQM (First Quantum Minerals)
14. Chibombo Town Council
15. Lupososhi council
16. ZESCO
17. LWSC
18. WWF Zambia
19. Hydro-Geo-Smart Engineering & Consultancy Ltd
20. WARMA
21. Zambia Sugar @Nakambala Estates

APPENDIX C: SERVICE RESERVOIRS

MULONGA WATER AND SEWERAGE COMPANY SERVICE RESERVOIRS AND ESTIMATED VELOCITIES

SN #	Location	Capacity (m^3)	Emergency Purpose(m^3)	Available Volume (m^3)	Q (m^3/s)	V(m/s)
City of Chingola						
1	E1 Ground Reservoir	3,785	757.0	3,028.0	0.11	2.14
2	A1 Ground Reservoir	3,785	757.0	3,028.0	0.11	2.14
3	A2 Ground Reservoir	1,892	378.4	1,513.6	0.05	1.07
4	A3 Ground Reservoir	1,892	378.4	1,513.6	0.05	1.07
5	Lulamba Ground Reservoir	1,892	378.4	1,513.6	0.05	1.07
6	Kabundi Ground Reservoir,K1	1,892	378.4	1,513.6	0.05	1.07
7	Kabundi Ground Reservoir (top), K2	4,500	900.0	3,600.0	0.13	2.55
8	Kabundi Main Ground Reservior,K3	6,800	1,360.0	5,440.0	0.19	3.85
9	Roberts Ground Reservoir	6,800	1,360.0	5,440.0	0.19	3.85
10	Kasompe 1 Ground Reservoir	4,500	900.0	3,600.0	0.13	2.55
11	Kasompe 2 Ground Reservoir	4,500	900.0	3,600.0	0.13	2.55
City of Mufurila						
1	Mopani Reservoir 1	3,500	700.0	2,800.0	0.10	1.98
2	Mopani Reservoir 2	3,500	700.0	2,800.0	0.10	1.98
3	Kamuchanga Ground Reservoir 1	4,500	900.0	3,600.0	0.13	2.55
4	Kamuchanga Ground Reservoir 2	5,000	1,000.0	4,000.0	0.14	2.83
5	Kamuchanga Tank (Tower)	900	180.0	720.0	0.03	0.51
6	Fairview Ground Reservoir 1	4,500	900.0	3,600.0	0.13	2.55
7	Fairview Ground Reservoir 2	5,000	1,000.0	4,000.0	0.14	2.83
8	Fairview Tank (Tower)	900	180.0	720.0	0.03	0.51
City of Chililabombwe						
1	Chililabombwe WTP	1,350	270.0	1,080.0	0.04	0.76

2	Kamenza Hill Top	1,350	270.0	1,080.0	0.04	0.76
3	Hill Side Reservoir	4,546	909.2	3,636.8	0.13	2.57
4	Konkola WTP	1,136	227.2	908.8	0.03	0.64
5	Konkola Top Reservoir	1,125	225.0	900.0	0.03	0.64

Total number of reservoirs 24

APPENDIX D: DAM DATA

SAMPLE DATA COLLECTION FROM THE ZAMBIAN DAM DATABASE INVENTORY

N.B: Itezhi-tezhi dam average discharge is highlighted

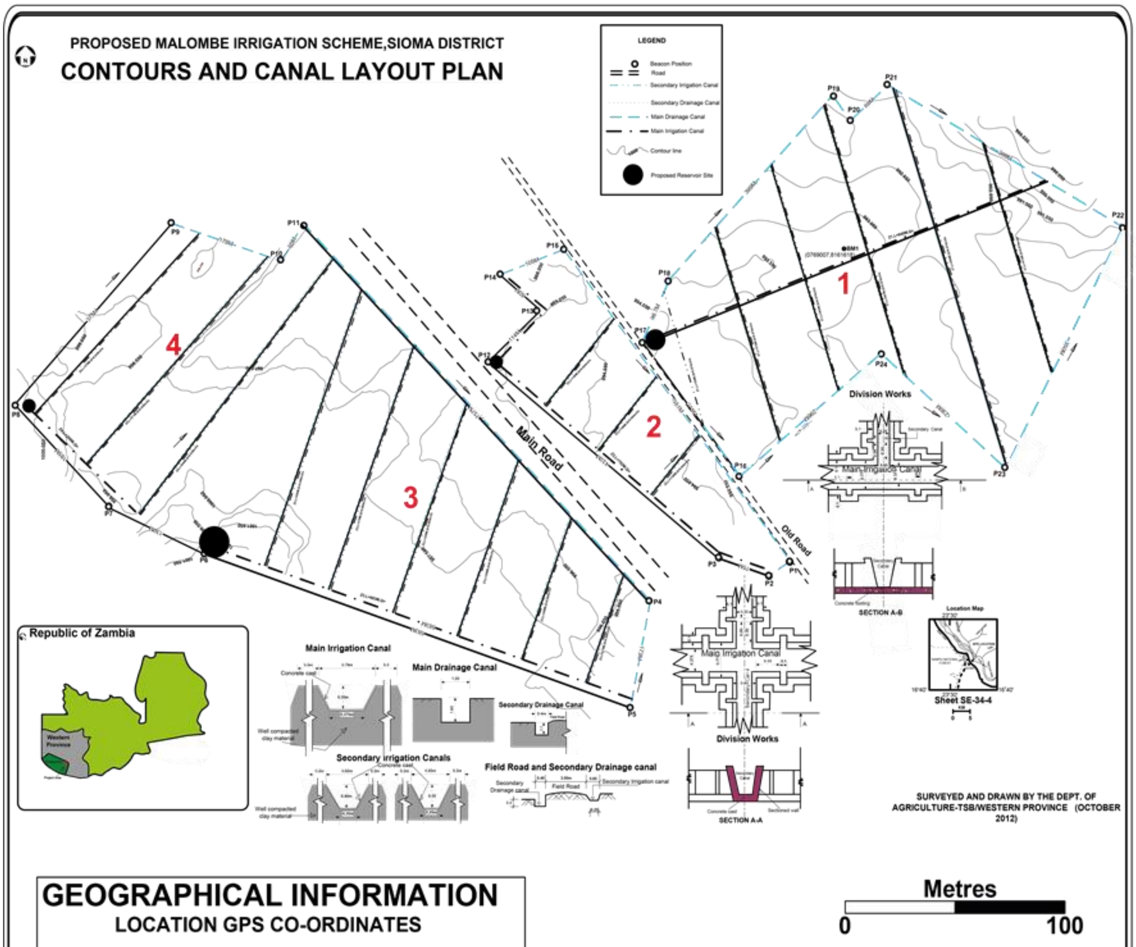
Dams_for_HydroATLAS Zam_Dams_HydroATLAS — Features Total: 1047, Filtered: 1047, Selected: 0

	JECTID_	OBJECTID	Continent	BAS_ID	BAS_NAME	Longitude	Latitude	BarrierId	BarrierNam	Lake_ID	NOID	BarrierTyp	Status	'ear	torageMCI	AP_M	Source	RAND_I	KCL_ID	Zarfl_ID	omme	INC	DIS_AVG_CMS	ZamID
925	1134	0		0		0	0	0	Sikalongo Mission	0	0		EXI	1970	0	0	WAR...	0	0	0		1	0	
926	1009	0		0		0	0	0	Silukwiya	0	0		EXI	1970	0	0	WAR...	0	0	0		1	0	
927	1117	0		0		0	0	0	Makalanguzu	0	0		EXI	1970	0	0	WAR...	0	0	0		1	0	
928	1102	0		0		0	0	0	Demu 2B Dam	0	0		EXI	1970	0	0	WAR...	0	0	0		1	0	
929	4	4055	Africa	3750986	Zambesi	28.42125	-15.80875	4055	Kafue Gorge	0	1306110	Hydroelect...	EXI	1971	785	0	GRanD	4055	0	0		1	484.957	
930	659	0		0		0	0	0	Sibajene	0	0		EXI	1971	0. 0395643	0	WAR...	0	0	0		1	0	
931	661	0		0		0	0	0	Mayobo Mupulisa	0	0		EXI	1972	0. 0417882	0	WAR...	0	0	0		1	0	
932	1114	0		0		0	0	0	Kadolobyo	0	0		EXI	1972	0	0	WAR...	0	0	0		1	0	
933	986	0		0		0	0	0	Raphael	0	0		EXI	1973	0. 0693355	0	WAR...	0	0	0		1	0	
934	858	0		0		0	0	0	Kabeleka	0	0		EXI	1975	0	0	WAR...	0	0	0		1	0	
935	963	0		0		0	0	0	Mukaziwa Dam2	0	0		EXI	1976	0	0	WAR...	0	0	0		1	0	
936	3	4054	Africa	3750986	Zambesi	26.012917	-15.762917	4054	Itezhi-Tezhi	0	1304248	Hydroelect...	EXI	1978	5700	0	GRanD	4054	0	0		1	554.079	
937	906	0		0		0	0	0	Siampondo	0	0		EXI	1978	0. 0038522	0	WAR...	0	0	0		1	0	
938	636	0	Africa	3750986	Zambesi	26.9565...	-16.65898...	636	B1 Dam1	0	1325290		EXI	1980	0	0	LOCAL	0	0	0		1	0.378	
939	874	0		0		0	0	0	Mukangala	0	0		EXI	1980	0. 0258303	0	WAR...	0	0	0		1	0	
940	665	0		0		0	0	0	Kanyameza Dam4	0	0		EXI	1980	0	0	WAR...	0	0	0		1	0	
941	959	0		0		0	0	0	Mukaziwa Dam6	0	0		EXI	1980	0	0	WAR...	0	0	0		1	0	
942	866	0		0		0	0	0	SDPA 3	0	0		EXI	1980	0	0	WAR...	0	0	0		0	0	
943	849	0		0		0	0	0	Dam	0	0		EXI	1980	0. 028339	0	WAR...	0	0	0		0	0	
944	1069	0		0		0	0	0	Siachisumo	0	0		EXI	1980	0	0	WAR...	0	0	0		1	0	
									Simunkobwe															

APPENDIX E: SAMPLE LAYOUTS

E1: SIOMA IRRIGATION SCHEME (SIS) CANALS LAYOUTS

Source: CRIDF (2016)



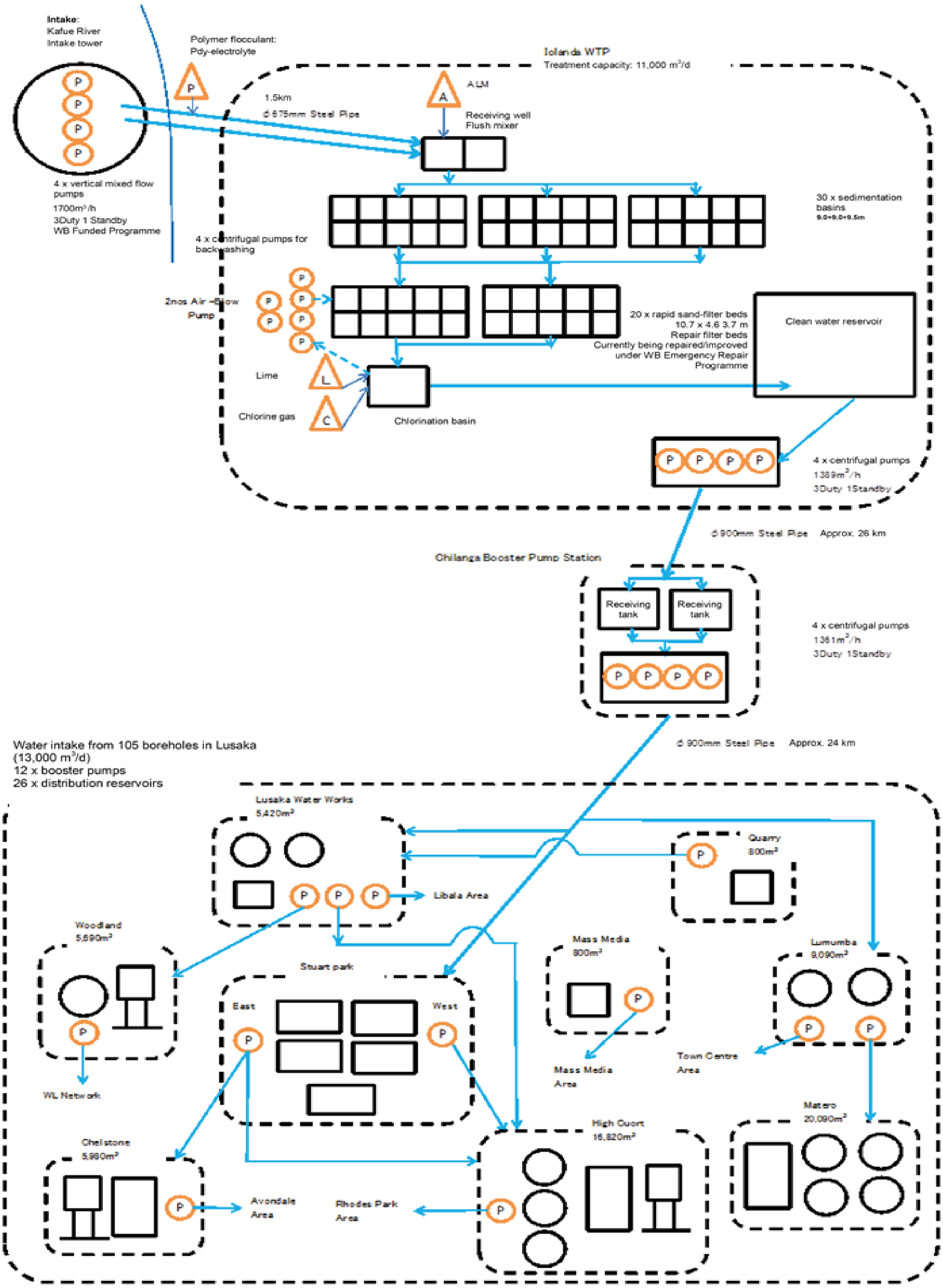
GEOGRAPHICAL INFORMATION

LOCATION GPS CO-ORDINATES

S/N	BEACON POSITION	LONGITUDE 34K	LATITUDE UTM
01	P1	0768891	8161170
02	P2	0768861	8161131
03	P3	0768796	8161170
04	P4	0768756	8161082
05	P5	0768731	8160911
06	P6	0768050	8160900
07	P7	0767925	8160943
08	P8	0767759	8161019
09	P9	0767893	8161367
10	P10	0768069	8161350
11	P11	0768073	8161406
12	P12	0768402	8161350
13	P13	0768467	8161445
14	P14	0768415	8161503
15	P15	0768502	8161559
16	P16	0768798	8161266
17	P17	0768620	8161439
18	P18	0768632	8161541
19	P19	0768909	8161825
20	P20	0768951	8161815
21	P21	0768974	8161880
22	P22	0769304	8161734
23	P23	0769202	8161405
24	P24	0768988	8161510

E2: LAYOUT OF LUSAKA WATER AND SEWERAGE COMPANY BULK WATER SUPPLY SYSTEMS

Source: JICA (2014)



E3: VIEW OF THE EXISTING ZENGAMINA HYDROPOWER PLANT

Source: ERB (2015)