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Development of evaluation framework for the selection of run-of-river hydropower potential sites to be included in the Zambian Hydropower Atlas

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ABSTRACT

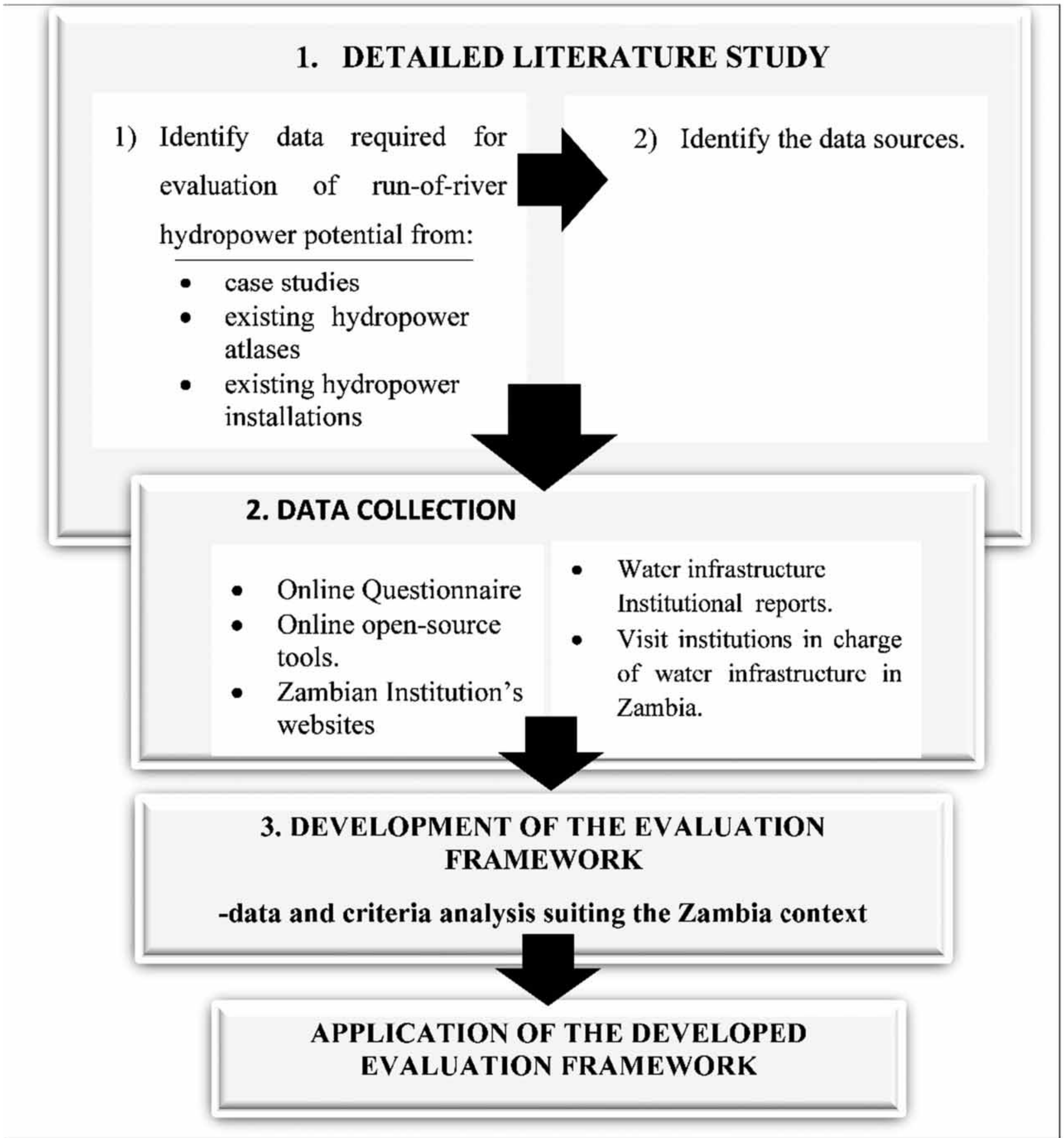
Hydropower is a source of renewable energy, which provides clean electricity around the world with lower greenhouse gas emissions than other sources of energy. Zambia's electricity deficit has been increasing in recent years. As of 2019, over 1.9 million households (57.6%) had no access to electricity and over 96% of the rural population are still without electricity. This calls for attention and sustainable solutions to electrification as reinforced by goal number 7 of the sustainable development goals. Such solutions include the development of a Zambian Hydropower Atlas that can showcase the country's hydropower potential including small-scale technologies, which can boost Zambia's electrification by providing green electricity. The aim of this study was to develop a run-of-river evaluation framework for the selection of hydropower potential sites to be included in the Zambian Hydropower Atlas. The data and formulas required to evaluate hydropower potential were identified and evaluated to develop the evaluation process in the Zambian context. The developed evaluation framework was applied to an existing run-of-river hydropower site located in Zambia to show its application, and it estimated the hydropower potential at the site within a deviation of 14%. The developed evaluation framework can give a first-order evaluation of hydropower potential.

Key words: evaluation framework, hydropower potential, renewable energy, run-of-river, selection criteria, Zambian Hydropower Atlas

HIGHLIGHTS

- The development of a Zambian Hydropower Atlas can showcase Zambia's hydropower potential.
- The run-of-river hydropower evaluation framework was developed as a first step in the development of the Zambian Hydropower Atlas.
- The developed evaluation framework can provide a first-order selection of hydropower potential sites to be included in the Zambian Hydropower Atlas within a deviation of 14%.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Hydropower is a vital source of renewable energy, which provides electricity around the world. Other renewable energy resources include biomass, biogas, solar radiation, and wind power (Department of Energy 2017). Hydropower 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; however, recent studies proved the advantage of using the same equipment to harness energy in water, thereby providing a renewable and decentralized form of energy (Angelakis *et al.* 2022).

Zambia's small energy requirements have always largely been 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 the Kabwe district of the central province of Zambia (Mihalyi 1977). Currently, 80.5% of the country's electricity requirements are supplied by hydropower plants, which are managed by ZESCO (ERB 2020). Hydropower is dependent on the topographic, climatic, and hydrometerological conditions of an area. Thus, the availability of this data is important in hydropower estimation studies. A study conducted by Mohammad *et al.* (2020) emphasized that accurate hydrometeorological records and observations with different timelines are crucial to assess climate evolution and weather forecast. The study further reviewed that although the science of hydrometeorology has significantly improved recently, there is still a lack of adequate knowledge to accurately forecast extreme hydrometeorological events (Mohammad *et al.* 2020). Thus, innovations and processes such as the development of evaluation frameworks for easy and accurate estimation of hydrologic data at river systems are important to enable the determination of the available hydropower potential.

Climate change continues to be a major threat to African countries. This is evident in the study conducted by Almazroui *et al.* (2020), which projected a continuous increase in annual temperature over all of Africa in the 21st century. Together with the world's focus on renewable energy goals as set out in the Paris Agreement, which encourages the accelerated stationing of renewable energy measures to meet the 90% decarbonization goal by 2050, emphasis has been placed on harvesting energy from renewable sources. With the signing of the Paris Agreement on climate change during the United Nations treaty signing in September 2016, the government of Zambia committed itself to focus on scaling up the use of renewable energy sources and energy efficiency in Zambia (GRZ 2016). 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 1MW), to possibly supply a school or clinic, a cultural village centre, or even a whole community (Klunne 2009). Therefore, various potential sources of small-scale hydropower potential must be 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 us aware of the opportunities that small-scale hydropower technologies bring, and the efforts required to get this technology to be successfully implemented.

Hydropower atlases have been developed and implemented for some African countries. These include Madagascar, Tanzania, Rwanda and the 14 Economic Community of West African States (ECOWAS) (Pöyry & ECREEE 2017b; World Bank 2017b, 2018; Rwanda Water Portal 2019). The hydropower atlases for these countries have been developed mainly for run-of-river types of hydropower. The evaluation frameworks followed in the development of these existing hydropower atlases were developed specifically for the respective countries and regions, in which the topological, terrain, climatic, and hydrologic parameters were analysed. Since these parameters vary from place to place, the frameworks could not be applied directly to the Zambian situation. However, these existing atlases provide good examples of successfully developed hydropower atlases and therefore provide applicable information regarding hydropower potential and the data selection process. This paper presents the evaluation framework that is specific to the Zambian topology, climatic, terrain, and hydrologic conditions and the currently available information. The main objective of this study was to develop the data selection criteria and evaluation frameworks for the selection of run-of-river sites with hydropower potential to be included in the Zambian Hydropower Atlas (ZHA). This was similarly done by other researchers as a first step in the development of the existing hydropower atlases.

2. STUDY AREA

Zambia is a landlocked country, which is located in Southern Africa (Figure 1). It has a total of eight neighbouring countries. 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 1,400 mm/year in the northern areas (MEWD 2010). The rainfall regime in the country is unimodal, occurring mainly between October and April (Figure 2). 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).

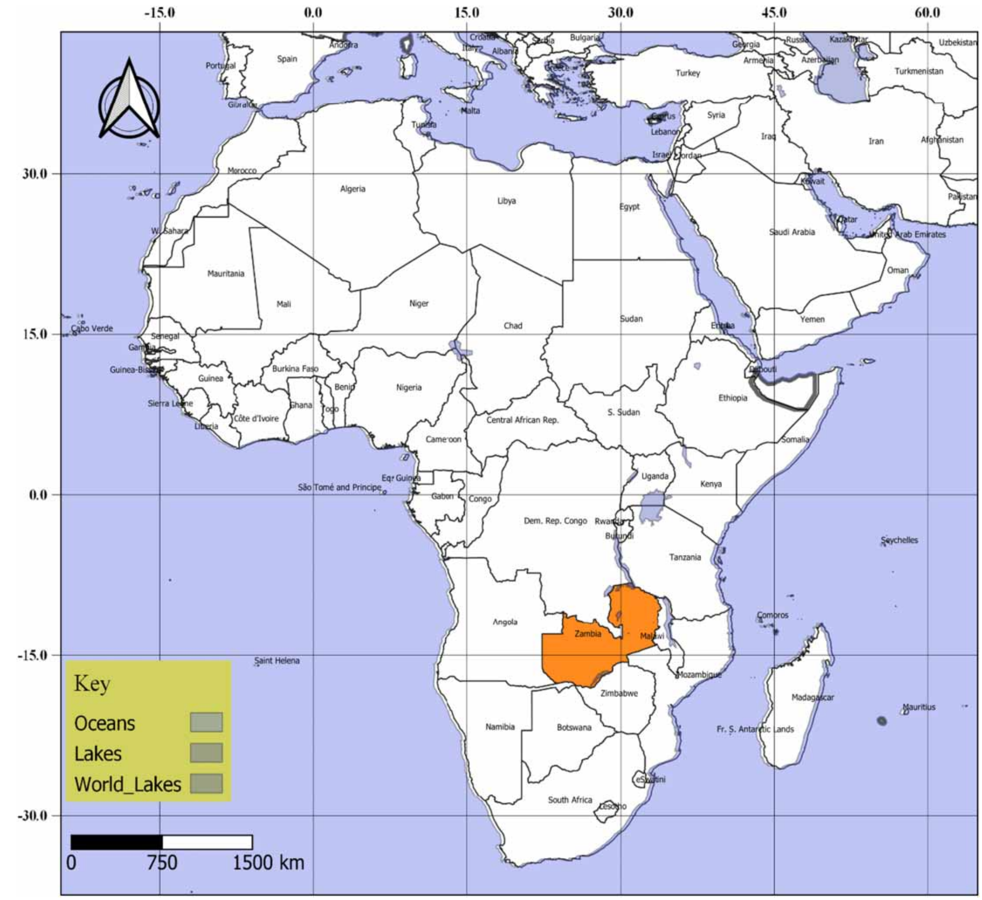


Figure 1 | Location of Zambia (in orange). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2022.262.

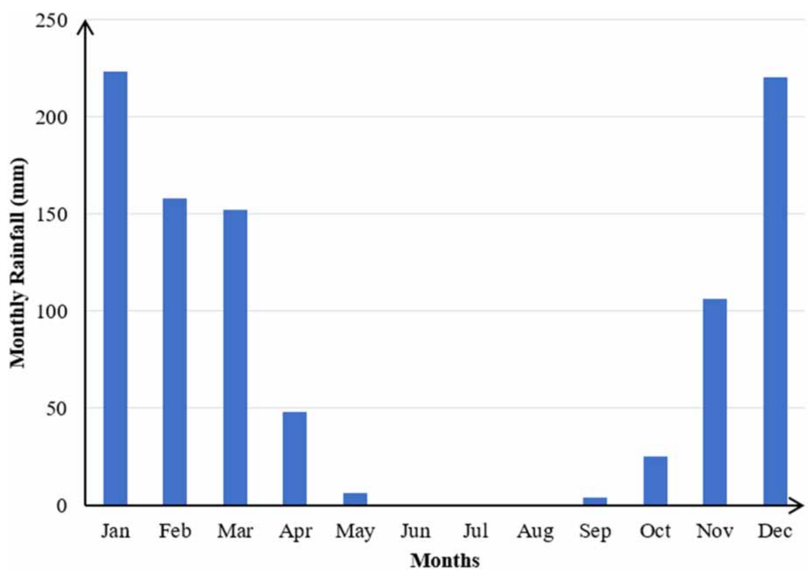


Figure 2 | Average monthly rainfall variation of Zambia for 1901–2016 (Harris & Jones 2017).

Zambia's electricity is abundantly sourced from hydropower resources making up to 80.5% of the electricity generation mix as shown in Figure 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 to develop a fully operational nuclear plant, which is expected to add 2,400 MW of electricity to the national grid (Mwape 2019). Additionally, there is an ongoing 40 MW biomass power project at Zambia Sugar, which will utilize sugarcane biomass (Gauri *et al.* 2013).

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 remaining 1.9 million households (57.6%) had no access to electricity (Figure 4). Out of the 42.4% of 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 still lack 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.

3. METHODS

3.1. Approach

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. The

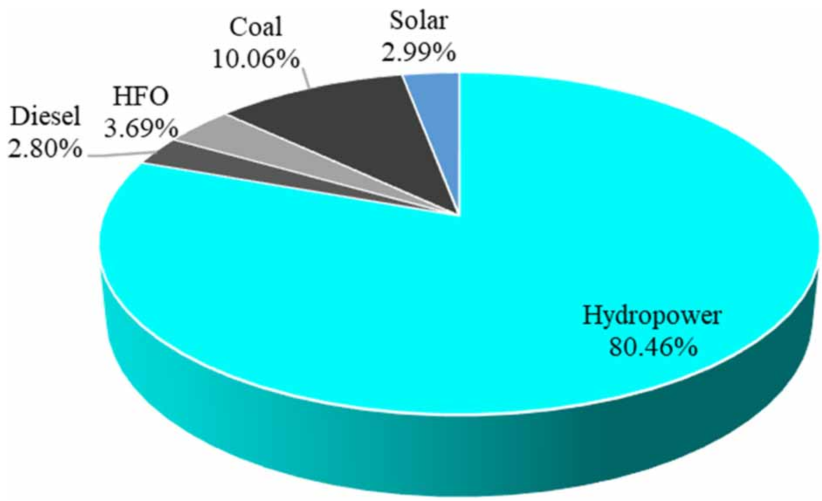


Figure 3 | Electricity generation mix in Zambia (ERB 2020).

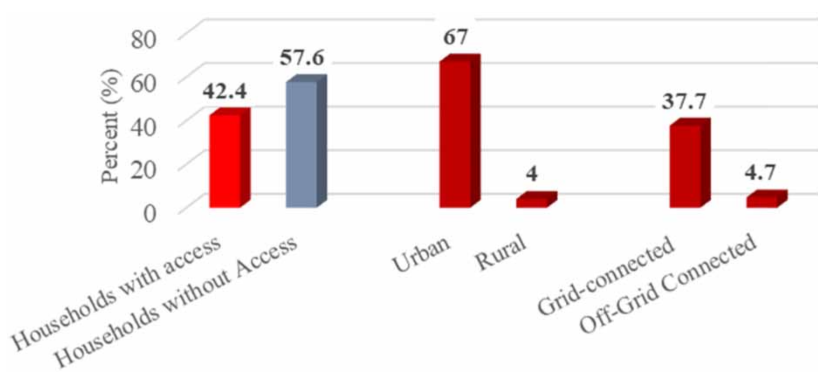


Figure 4 | Details of Zambia's access to electricity (World Bank 2019).

methodology followed in the studies conducted by Bekker *et al.* (2020, 2021) and van Dijk *et al.* (2021) was reviewed and modified to fit the Zambian context. 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.

Initially, 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, were considered for criteria development; however, in this paper, the run-of-river evaluation framework is presented. The run-of-river (layout shown in Figure 5) was selected due to data availability and the abundance of rivers in Zambia with untapped hydropower potential. The framework was evaluated by applying it to a selected case study to show the step-by-step process of its application. It has been recommended that the developed evaluation frameworks should be considered only to give a first-order evaluation of hydropower potential as data limitations largely affect the accuracy of the frameworks.

3.2. 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 (1). This equation was the basis for data evaluation and criteria development for the run-of-river hydropower.

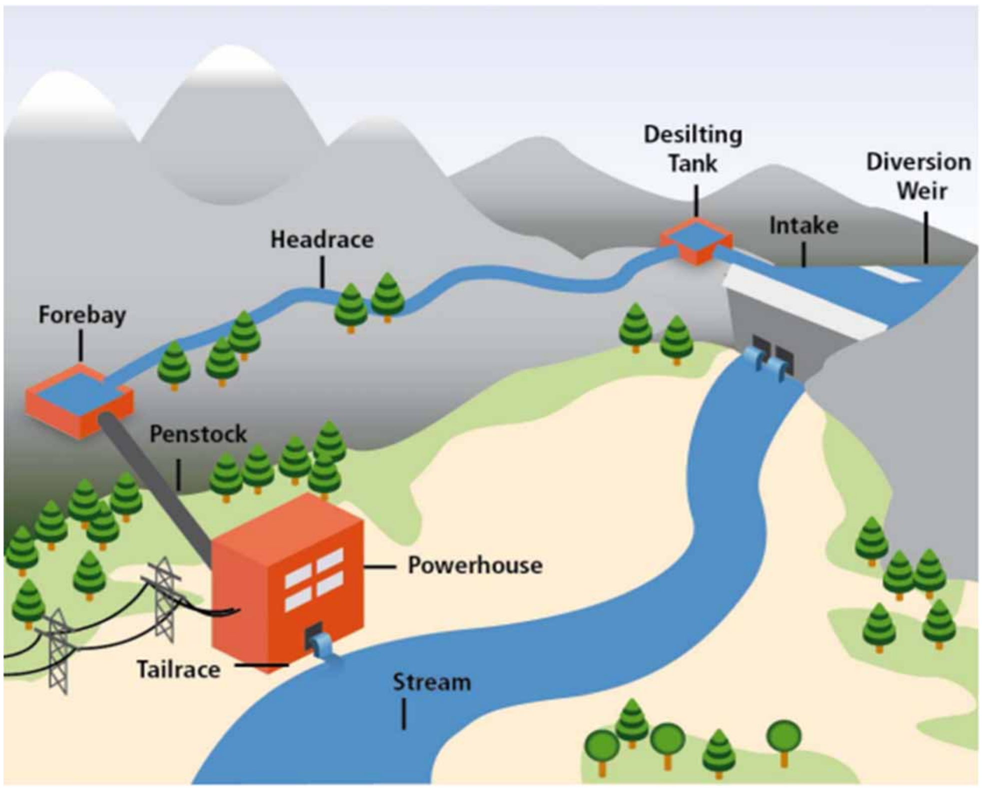


Figure 5 | Typical layout of a run-of-river hydropower plant (Kumar *et al.* 2011).

$$P = \rho g Q H \eta \tag{1}$$

where

P is the hydropower potential (W),
ρ is the density of water (1,000 kg/m^3),
g is the acceleration due to gravity (9.81 m/s^2)
Q is the discharge (m^3/s),
H is the effective head (m), and
η is the efficiency of the turbine (%) that can be obtained from Table 1 depending on the turbine type.

3.3. Existing data selection criteria

Table 2 outlines the evaluation criteria used in the data selection process for the calculations of the hydropower potential of the sites included in the existing atlases for other countries. The table also includes data criteria from other studies on the run-of-river hydropower potential evaluation. These existing criteria were used in the analysis of datasets and the development of the selection criteria in the Zambian context.

3.4. Calculations for run-of-river criteria development

The hydropower potential at a run-of-river hydropower potential site can be computed using Equation (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 (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.

3.4.1. Head evaluation

According to the existing criteria presented in Table 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.

(a) 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 six-existing run-of-river hydropower plants in Zambia with slopes shown in Table 3 would imply that only one site (Victoria falls) would be considered. The criterion discards the five sites with significant hydropower potential ranging from 0.75 to 14 MW. Similarly, applying Kusre *et al.* (2010)'s criterion discards the Zengamina hydropower plant that has a significant capacity of 750 kW 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 3, some sites with steeper slopes have lower hydropower potential than some sites with less steep slopes. For these reasons, the 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 potential head and therefore should be

Table 1 | 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
Cross-flow	2–200	86	High	High
Turgo	50–250	85	Low	High

Table 2 | 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). – 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.	Tanzania Hydropower Atlas (World Bank 2015)
	– considered the design discharge to be equal to the median (Q_{50}) of the interannual mean flows. – sites with design flow (Q_{50}) $< 50\ m^3/s$ were considered.	Tanzania, Madagascar Atlas (World Bank (2015, 2017a)
	– 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. – 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.	Rojanamon *et al.* (2009)
	– assumed that 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. – considered sites with a gross head of 3 m and above. – the effective head was set at 90% of the gross head.	JICA (2009)
	– the head was calculated at intervals of 100 m using the GIS for the selected sites.	Vincenzo *et al.* (2019)
	– the head was assessed based on the elevation difference (derived from the DEM) between the selected point and its closest upstream neighbour, which in this case was located at a distance of 1,000 m.	Korkovelos *et al.* (2018)
	– the maximum distance from the weir to the powerhouse was set at 5 km (head was calculated within this range) in the study.	Kusre *et al.* (2010)
	– the head was assessed at 400 m 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 400 m for the selected sites.	Ballance *et al.* (2000)
	– slopes for the river stretches were derived from ASTER GDEM v.2 DEM with a spatial resolution of 30 m.	World Bank (2015)
	– slopes were calculated and analysed at intervals of 100 m for the selected sites.	Vincenzo *et al.* (2019)
Distance between nearest sites	– selected sites were required to be at least 1,000 m apart.	Ballance *et al.* (2000)
	– distance between small hydropower plants maintained at 100 m.	Garegnani *et al.* (2018)
	– the minimum distance for the consecutive sites selected was set at 500 m.	Kusre *et al.* (2010)
River data	– rivers within the country's borders were considered.	World Bank (2015, 2017a)
	– rivers with flow accumulation of 100,000 cells (50 × 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 3 | Slopes at existing run-of-river hydropower plants

Name of plant	Capacity MW	Slope (%)
Victoria falls[a]	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

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

considered when identifying the location of hydropower potential sites, especially when using GIS-based methods (Kusre *et al.* 2010).

(b) 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 system buyer's guide by the CETC (2004) recommends a minimum head of 1 m. 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 3 m. 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.

(c) 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 (2009) 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 were available. As shown in the data presented in Table 4, the existing criterion underestimated the effective head by less than 5% at four sites and overestimated the effective head by less than 10% at one 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

Table 4 | Effective head as a percentage of the gross head at five existing run-of-river hydropower plants in Zambia

			Victoria falls at stations		
Name of site	Zengamina	Shiwang'andu	A	B	C
Capacity (MW)[a]	0.750	1	8	60	40
Design discharge[a] (m^3/s)	8.0	11	10.5	64	43
Gross head (m)[a]	18.0	12.0	105.77	112.77	112.77
Effective head (m)[a]	17.0	10.9	86.30	106.18	105.36
Effective/gross head (×100%)	94.4%	90.8	81.6%	94.2%	93.4%
% Deviation from 90% criterion	4.89%	0.09%	−9.33%	4.67%	3.78%

[a]Technical data adopted from MEWD (2011).

scheme can be calculated using Equation (2).

$$H_n = 0.9H \tag{2}$$

where

H_n = the effective head (m), and
H = the available gross head (m).

3.4.2. 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 Figures 6 and 7 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.

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

(a) 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. Various factors 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).

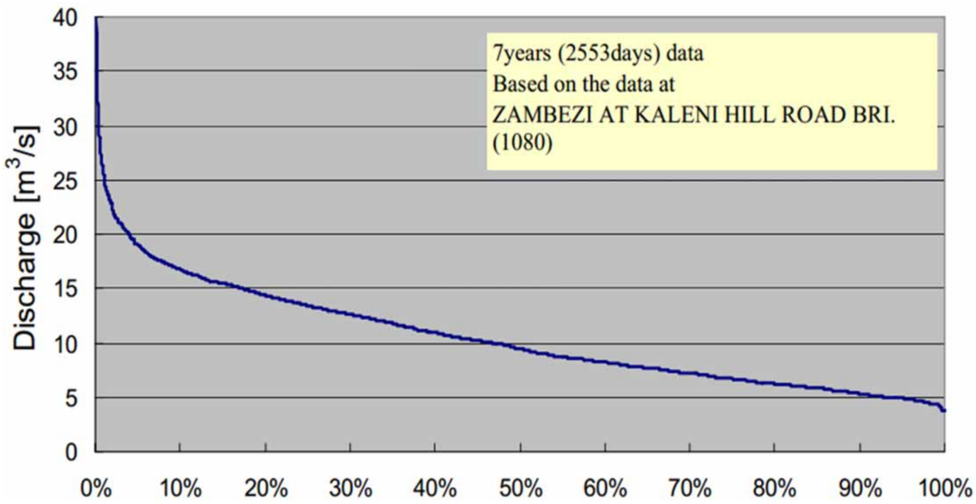


Figure 6 | An FDC at Kalene Hill Road Bridge Gauging Station (JICA 2009).

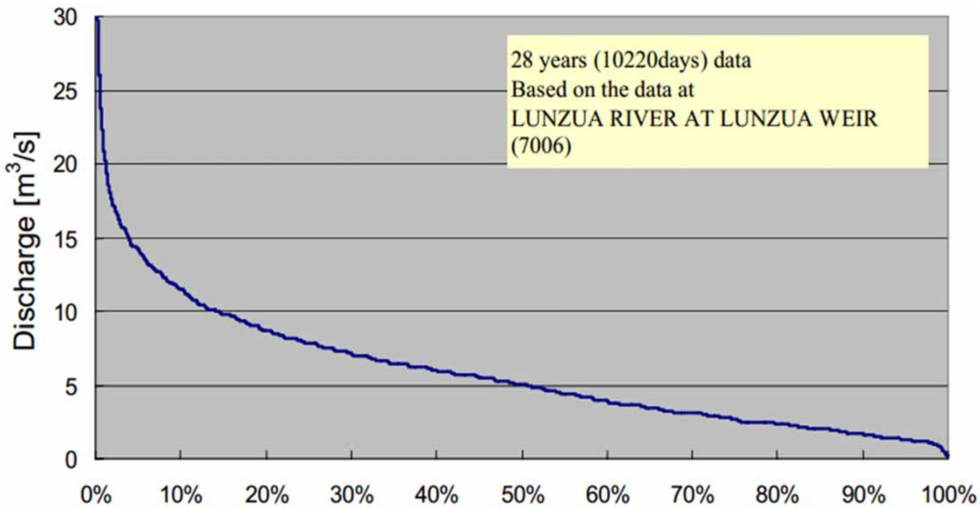


Figure 7 | An FDC at Lunzua Weir on the Lunzua River (JICA 2009).

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.

(b) 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 HydroATLAS of Zambia (HAZ) provided by WWF-Zambia. 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) 100–1,000 m^3/s
(e) 1,000–2,000 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 5. The HAZ is available at https://hydroatlas-zambia.weebly.com/. Figure 8 shows the annual average discharge of Zambian rivers as displayed in the HAZ datasets. Zambia has several river systems and tributaries with substantial flows suitable for hydropower generation (Tena *et al.* 2021).

To evaluate the mentioned criteria, the discharge was compared with the known design discharge values at three existing run-of-river hydropower plants in Zambia as shown in Table 6. As can be seen in Table 6, the criteria estimated the available

Table 5 | Criteria for available discharge at ungauged stations based on the HydroATLAS-Zambia data

River discharge category (m^3/s)	Mean discharge: Q (m^3/s)[a]	Discharge available for hydropower generation (m^3/s)[b]
0.1–1	0.55	0.165
1–10	5.5	1.65
10–100	55	16.5
100–1,000	550	166.5
1,000–2,000	1,500	450

[a]Calculated as an average of upper limit and lower limit of the range.
[b]Calculated as 30% of the mean discharge.

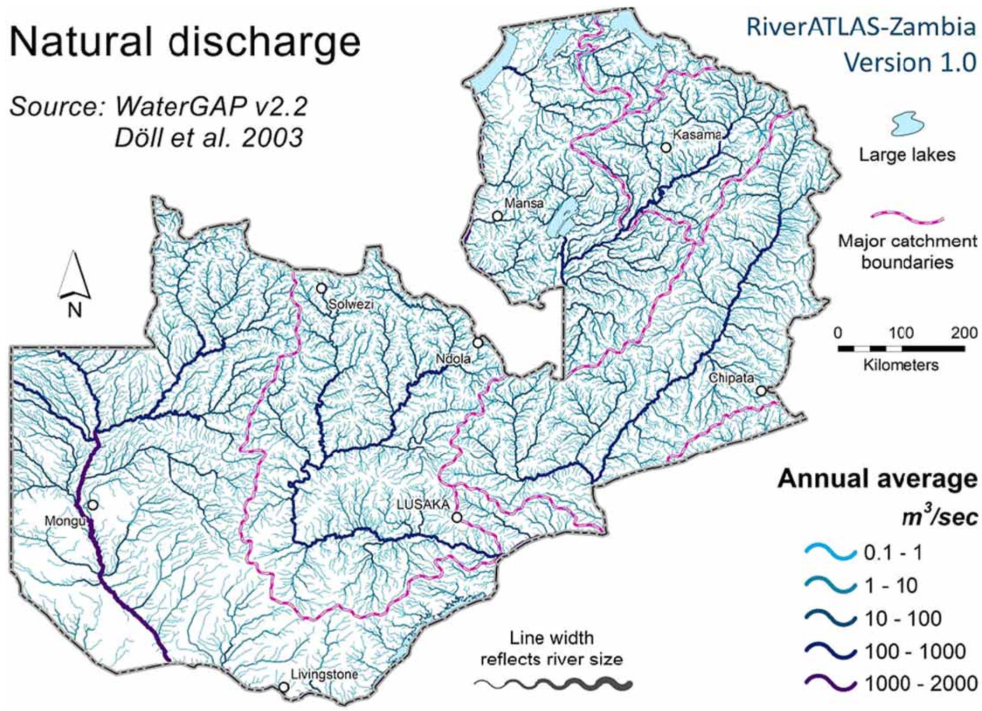


Figure 8 | Annual average discharge of Zambian rivers as displayed in the HAZ datasets (WWF 2019).

Table 6 | 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	100–1,000	166.5[a]	117.5	29.43

[a]Calculated as the sum of discharge at Victoria falls sites A, B, and C.

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 fall 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.

3.4.3. 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 50 kW 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 30 kW 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.

3.4.4. National regulation restrictions

Protected areas (Figure 9) are considered environmentally sensitive, and siting of hydropower projects in these areas is discouraged because they are heavily managed through various national regulations. Zambia has a high density of protected areas that 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 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. The activities are regulated by the Zambia Wildlife Authority (ZAWA) that is mandated by law to manage the protected areas. It was, therefore, 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. RESULTS

4.1. Run-of-river evaluation framework

The run-of-river data selection criteria 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

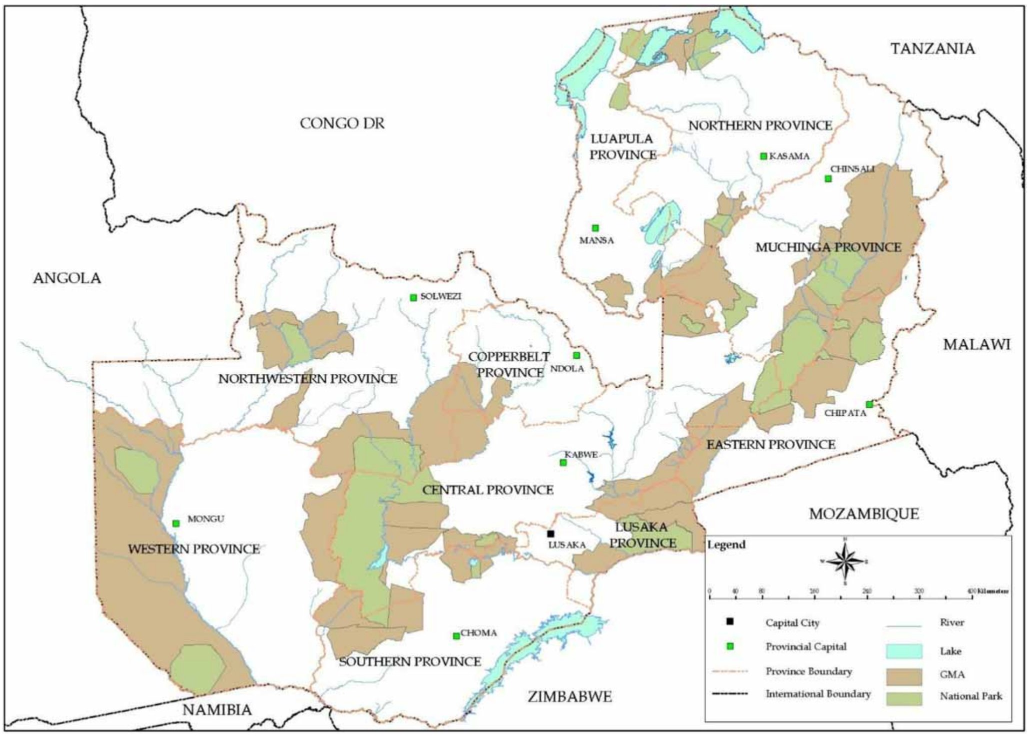


Figure 9 | Zambia's network of protected areas (GRZ 2014).

hydropower is shown in Figure 10. The framework starts with providing guidance on the rivers to be considered. Zambia has six main river catchments that serve as administrative units for the Water Resources Management Agency (WARMA) and the Zambezi River Authority (ZRA). For ungauged stations, the framework suggests using the average annual discharge data available in the HAZ. It should be noted that this framework only provides a first-order or preliminary selection of potential sites. Table 7 shows the relevant abbreviations used in the run-of-river evaluation framework.

5. DISCUSSION

The developed run-of-river evaluation framework was applied to the existing Zengamina site in Zambia (Figure 11) as a case study. The Zengamina hydropower plant is a run-of-river off-grid micro-hydropower plant based in the Ikelenge district of North-Western Province of Zambia on the upper Zambezi river. It has a hydropower potential of 1,400 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 the 14th of July 2007.

The application process and calculations, together with the data parameters, are shown in Table 8. The step number in the table corresponds to the number indicated in 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 also be used to evaluate similar sites in Zambia.

The application of the framework at the Zengamina site estimated the hydropower potential at the site to be 1,629 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 1,400 kW. The framework, therefore, overestimates the hydropower potential by 14%. This error can be attributed to the accuracy of both head and discharge data since hydropower potential depends on these two parameters as they are related in Equation (1). In terms of discharge data, 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 of the HydroATLAS developed by WWF-Zambia. This data could contain some uncertainties that were not evaluated in this study. Therefore, this framework should be considered as a first-order estimation in the evaluation of hydropower potential at Zambian river schemes. More accurate methods of obtaining hydrometerological data as outlined in the study conducted by Mohammad *et al.* (2020) should be followed to confirm the actual existing hydropower potential once the potential sites have been sifted.

Furthermore, in terms of the head at the Zengamina site, there is an underestimation of 5 m. With this developed framework, the gross head was 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 that is not accurate due to its resolution; therefore, the user must be aware of its limitations. The result shows that the estimation of hydropower potential depends significantly on the accuracy of the head and discharge data parameters. With the availability of more of this data in future, the evaluation framework can be updated and improved. The developed 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. The process followed above can similarly be applied to another river site in Zambia. If the estimated hydropower potential is found to be greater than or equal to 30 kW, the site will be included in the Zambian Hydropower Atlas. The potential sites identified using this method will need further investigation using field assessments during the detailed feasibility studies for design purposes.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

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

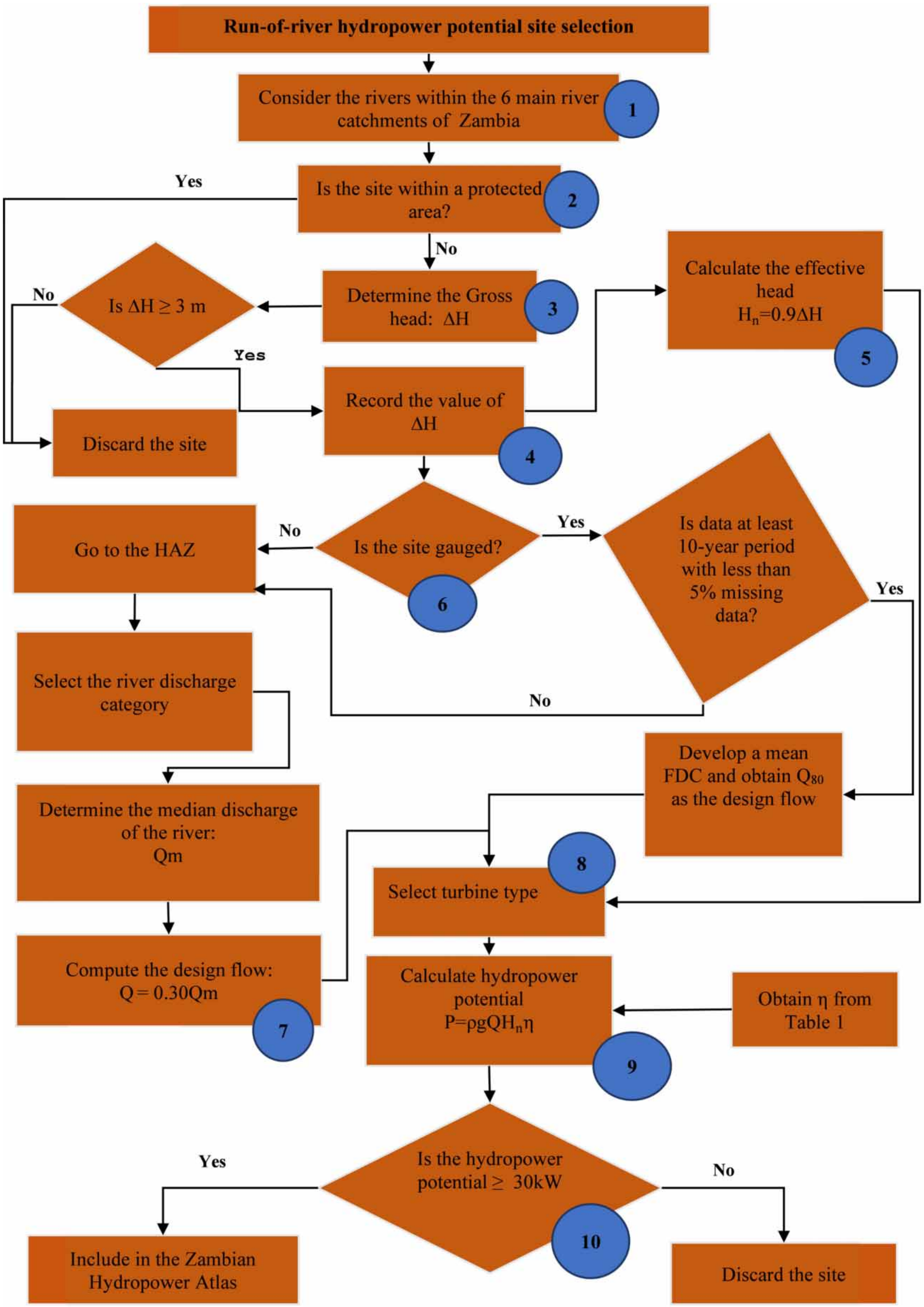


Figure 10 | An evaluation framework for the selection of run-of-river hydropower potential sites to be included in the Zambian Hydropower Atlas.

Table 7 | 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)
Q_m	Mean discharge of the river (m^3/s), see Table 5
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 (%) obtained from Table 1

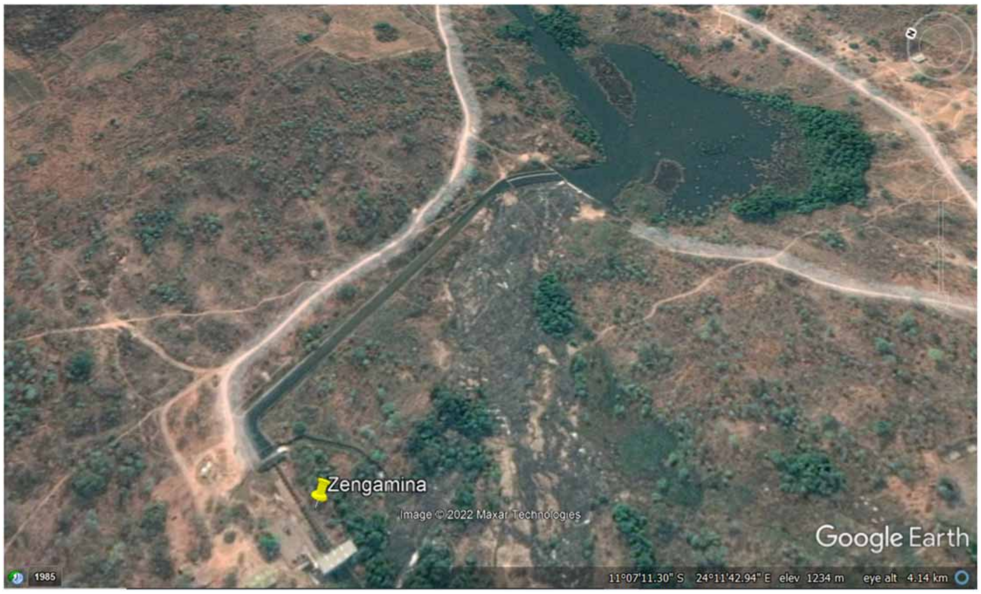


Figure 11 | View of the Zengamina Hydropower Site (Source: Google Earth Pro).

regarding the evaluation of hydropower potential and hydropower in the existing water infrastructure in Zambia. This study attempted to address this problem by developing the data selection criteria and evaluation frameworks to be followed in the development of the Zambia Hydropower Atlas. To achieve this objective, the data required to evaluate the run-of-river hydropower potential were identified and the various available sources of this data were also identified. These included online data sources such as USGS explorer, institutional reports, and institutions in charge of water resources in Zambia. These data were collected from the various identified sources to ensure easy accessibility of the data for the further development of the Zambian Hydropower Atlas.

The run-of-river hydropower evaluation framework and selection criteria, to which a specific river scheme should conform to, to be included in the Zambian Hydropower Atlas were developed. The developed framework was applied to the existing Zengamina run-of-river hydropower scheme located in the North-western Province of Zambia to demonstrate a step-by-step application process of the framework. The framework overestimated the hydropower potential at the Zengamina river scheme by 14% as compared to the estimation from the feasibility study report.

Finally, it can be concluded that depending on the available data on water infrastructure in Zambia, the data selection criteria and evaluation frameworks for hydropower potential can be developed. The developed criteria and evaluation

Table 8 | 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 six 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 9.	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., 1,222–1,209 m) over a horizontal distance of approximately 500 m.	$\Delta H = 13\,\text{m}$
	Is $\Delta H \geq 3\,\text{m}$?	Yes. The gross head is 13 m.	Can proceed to compute the effective head
4	Record the value of ΔH		$\Delta H = 13\,\text{m}$
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 are considered.
	Select the river discharge category (Figure 8)	The Upper Zambezi River in the Ikelengi district falls in the river category of 10–100 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: $Q = 0.30\,Q_m$	$Q = 0.30 \times 55$	$Q = 16.5\,m^3/s$
Turbine selection and efficiency			
8	Select turbine type	With $H_n = 11.7\,\text{m}$ and $Q = 16.5\,m^3/s$. A cross-flow turbine is selected.	From Table 1, $\eta = 86\%$
Calculation of hydropower potential			
9	Calculate hydropower potential $P = \rho g Q H_n \eta$	$P = 1,000 \times 9.81 \times 16.5 \times 11.7 \times 0.86$	$P = 1,629\,\text{kW}$
Inclusion in the Zambian Hydropower Atlas			
10	Is the hydropower potential ≥ 30 kW?	Yes. The hydropower potential is 1,629 kW.	Include the site in the Zambian Hydropower Atlas

framework can provide preliminary guidance in the evaluation of hydropower potential sites to be included in the Zambian Hydropower Atlas. 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 are concerned. This challenge could also be attributed to the Covid-19 pandemic since most institutions were closed during country lockdowns.

6.2. Recommendations

Based on the findings of this study, the following recommendations have been made for further research: (i) future research should conduct detailed environmental, social, and economic studies associated with each site selected using the evaluation framework developed in this study. The framework could be updated to incorporate such information: (ii) 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 the frameworks and updating them. The frameworks can be updated with the availability of more data: (iii) future research should conduct cost–benefit assessments for each hydropower site identified using the developed evaluation framework.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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