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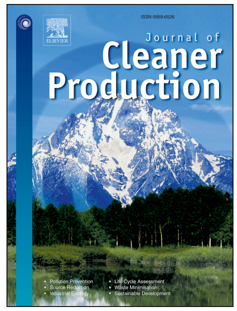

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Original Article

Framework development for the evaluation of conduit hydropower within water distribution systems: A South African case study

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FRAMEWORK DEVELOPMENT FOR THE EVALUATION OF CONDUIT HYDROPOWER WITHIN WATER DISTRIBUTION SYSTEMS: A SOUTH AFRICAN CASE STUDY

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Abstract: The universal lack of access to available water infrastructure data restricts the quantification of hydropower potential and thus the identification of new potential sites. Furthermore, limited research on methods to alleviate the problem associated with hydropower evaluation using limited data exists. To address this deficit, a generic framework was developed to quantify the potential and to identify conduit hydropower sites in bulk water supply systems when limited data poses a challenge. This paper describes the development of the first generic method of evaluating hydropower potential in water infrastructure and provides an example of implementation to verify/validate the range of recommended assumptions using a South African case study. The developed conduit hydropower framework was applied to five case studies to estimate the potential available for three scenarios with different levels of data availability. The analyses showed that on average the variance between the actual potential and the estimated potential available using the developed framework ranges between 6% to 18%. The newly-developed conduit hydropower framework can thus be used to identify hydropower potential in water distribution systems.

Keywords: hydropower, conduit hydropower, hydropower evaluation, renewable energy, hydropower potential

1. Introduction

There is a global shift towards harvesting energy from renewable sources as the price of electricity generated from fossil fuels is increasing. Thus the world is becoming more aware of the need to reduce carbon emissions in order to mitigate climate change. Furthermore, an increase in population and, therefore, an increased demand for electricity generation as well as mitigating issues regarding the provision of electricity to rural and isolated communities places additional pressure on developing countries such as South Africa (SA) to find sustainable and renewable energy generation alternatives.

Since 2010 the annual global growth rates for renewable energy have been 8-9% (IEA, 2018), with wind and solar power the front- runners with regard to installed capacity for the year of 2018 (GWEC, 2019). This is especially the case with SA's current and forecasted renewable energy capacity. The 2018 energy statistics of SA show that approximately 76% of the installed renewable energy capacity was generated from wind and solar (Eskom, 2018). Of the 18 GW of renewable energy capacity that has been committed to by 2030, approximately 86% will be generated by wind and solar (DoE, 2019). Furthermore, the global energy forecast indicates that by 2050 86% of electricity generation should be from renewable energy, and approximately 60% of the renewable energy contribution will be from solar and wind (IRENA, 2019). Some contradicting research, however, states that hydropower is the greatest renewable energy contributor to the world's electricity generation. The installed hydropower capacity is forecast to exceed 1 400 GW by 2035, which will be the largest renewable energy source in terms of installed capacity (Spänhoff, 2014).

The top ranked countries with regard to installed hydropower capacity are the United States, Brazil, Canada and China, with the latter having an installed capacity (249 GW in 2012) exceeding the cumulative capacity of the three former countries (Hennig et al., 2013). Furthermore, the global hydropower potential as reported in the World Hydropower Atlas, published by the International Journal of Hydropower and Dams is approximately 14 400 TWh/year (International Journal of Hydropower and Dams, 2000). According to Paish, (2002), only 18% of the total amount of hydropower potential was exploited in 1999. This equates to approximately half the installed hydropower capacity of today (IHA, 2019). Literature indicates that even though the world's installed hydropower capacity has almost doubled in the last 30 years, there is still a significant amount of hydropower potential to be exploited.

Hydropower can be considered an important renewable energy type due to the water-energy nexus principle. This describes the proportional relationship between water supply and energy demand (the increase in energy-use causes an increase in the demand of water and conversely an increased demand in clean, potable water, increases the energy demand). It is, therefore, recommended to explore technologies that can couple water and energy supply (Gilron, 2014). Hydropower is considered a clean, renewable form of energy that harnesses the energy already available for electricity generation (Van Vuuren et al., 2011) without using the water itself (Frey and Linke, 2002). There are several advantages pertaining to hydropower generation, including operational flexibility, long operating lifetimes of plants and the ability of the plants to respond to a change in load demand (Egré and Milewski, 2002; Loots et al., 2014). Hydropower plants are also considered the most feasible renewable energy type, when compared to solar, wind, tidal and photovoltaic energy types (Pérez-Sánchez et al., 2017).

Although there is no internationally agreed definition of different hydropower sizes (Paish, 2002), the distinction in SA between large and small hydropower centers around the installed capacity being larger than 10 MW. Mini hydropower plants refer to installations with a capacity between 100 kW and 1 MW. Additionally, micro hydropower plants usually have an installed capacity between 20 kW to 100 kW, where hydropower plants with an installed capacity below 20 kW are usually referred to as pico hydropower (Loots et al., 2014; Pérez-Sánchez et al., 2017).

Over the last decades the development of mini hydropower plants has been considered an effective means of providing electricity to isolated communities. As such, it is predicted that hydropower will expand in developing countries such as India and Pakistan, as the demand for rural electrification increases (Bhutto et al., 2012). Spänhoff (2014) supports the statement by arguing that countries with increased demand for rural electrification will benefit economically from small hydropower and will, therefore, have the highest contribution to the expansion of small hydropower sites. An increased trend in the development of hydropower plants (with an installed capacity less than 300 kW) is currently observed in Africa as the social benefit associated with these smaller installations are significant (Miller et al., 2015). As such, mini, micro, and pico hydropower can be utilized as part of the solution to provide electrification to the a ±2.5 million households without power in SA (Statistics SA, 2017).

It is believed that there is a large amount of untapped hydropower potential in SA (Loots et al., 2015), yet realizing this potential poses a challenge. Moreover, the expected contribution of hydropower to SA's future energy mix is low (4%) and the expected future contribution of hydropower to SA's electricity supply remains unclear. Such uncertainty is mainly due to the potential for hydropower development in SA currently not being known. This is illustrated by the Integrated Resource Plan (IRP 2019) (DoE, 2019), where run-of-river hydropower was listed as the only potential hydropower in SA with no other potential hydropower generation listed. However, even though SA is a water-scarce country, multiple locations where hydropower can be generated exist including irrigation canals, water distributions systems, wastewater treatment works, transfer schemes, and dams. As previously mentioned, locations where less hydropower potential is available (micro and pico) should also not be neglected as these types of installations can provide electricity to rural and/or isolated communities.

The different hydropower development options ranging from large to pico hydropower are illustrated in Figure 1 with Table 1 describing the most applicable hydropower locations in more detail.

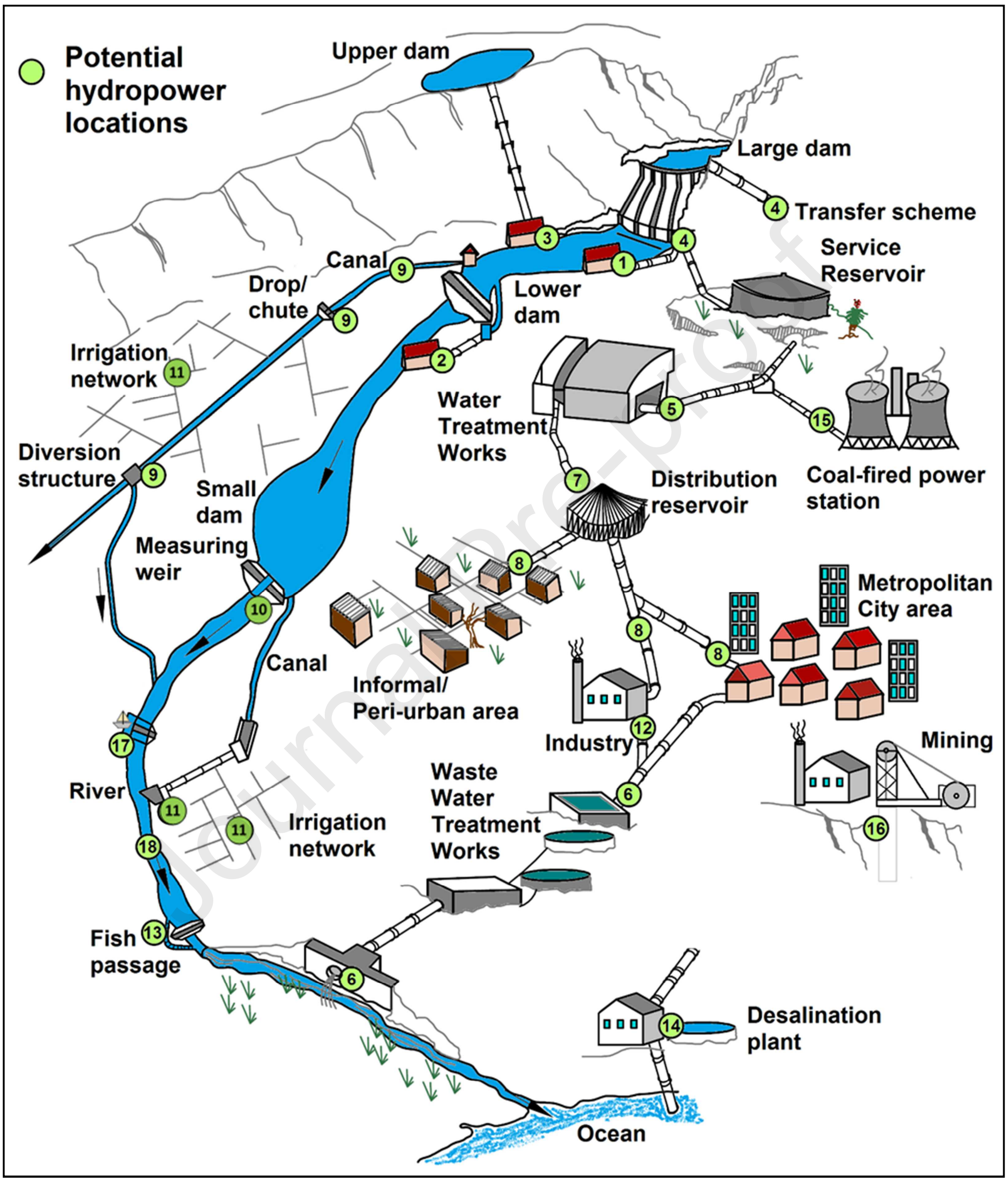
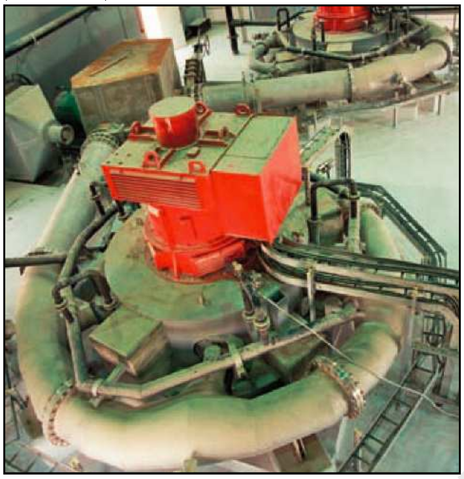


Figure 1: Potential energy generation locations (adapted from (Loots et al., 2015)) (Color)

Table 1: Hydropower types for which evaluation frameworks were developed (Color)

Hydropower Type	**Description**
① Storage schemes 	Conventional type of hydropower can be generated at dams by utilizing the available pressure (water level) and the discharge from the dam associated with the dam's fundamental use. This type of hydropower is normally associated with large environmental impacts, but small hydropower schemes can be retrofitted on existing dams.
② Run-of-river schemes 	Hydropower is generated from these types of schemes through the diversion of either all or a portion of the flow from the river combined with the head difference between the inlet to the diversion structure and the turbine unit(s). Rivers or streams that can sustain a minimum flow are usually ideal locations for run-of-river plants.
③ Pumped storages schemes 	Pumped storage schemes generate power based on the principle of pumping water to an upper dam during off-peak periods and releasing the water under gravity conditions to a lower dam during peak time to generate electricity.
④ Dam release into transfer schemes 	Excess pressure available when water is released from storage dams for industrial or irrigation purposes can be dissipated by installing a turbine to generate hydropower before the water enters the conveyance system or exiting it.

Hydropower Type	Description
⑤ Water Treatments Works (WTW) 	Hydropower can be generated at WTW if the water source of the WTW is located at a higher elevation compared to the plant. The potential for hydropower exists in the conveyance system, usually at the end of the conduit where the water enters the WTW.
⑥ Wastewater Treatment Works (WWTW)  (Image source: Vincent Denis and Punys, (2012))	The constant head and the outflows at WWTW make this an ideal location for hydropower development. The opportunity for energy recovery could exist at the inlet or at the outflow from the WWTW into the natural river system.
⑦⑧ Water supply and distribution systems 	Pressure reducing stations (PRS) are constructed on gravity fed bulk water supply lines to dissipate excess pressures that might exist by means of a pressure reducing valve (PRV). The opportunity for energy recovery exists at the PRV, where the hydropower installation bypasses the PRV and uses the excess pressure for energy generation.
⑨ Irrigation canals and rivers 	Hydrokinetic turbines in rivers and canals are referred to as zero head installations as energy is generated from kinetic energy in the flowing water. Some irrigation canal systems have potential for low-head hydropower installations either through a diversion channel or chute or in the canal itself.

Hydropower Type	Description
⑩ Weirs 	Measuring weirs provide an example where hydropower installations can be considered. The potential available at this type of location can be attributed to the large flow and elevation difference created by the weir. The challenge, however, would be to install a hydropower plant without affecting the accuracy of the measuring weir.

The first step in realizing hydropower potential includes finding appropriate methods to evaluate this hydropower potential, to assist with the quantification and identification of potential hydropower sites.

Some comprehensive studies carried out in similar fields entail the development of methodologies for the evaluation of hydropower development within existing water infrastructure (Gallagher et al., 2015; Howe, 2009; Power et al., 2014). However, even though important, these studies do not address limitations associated with hydropower evaluation when the lack of access to data poses a challenge. This is an identified gap in hydropower research as lack of access to available data for water utilities remains a global challenge (Strazzabosco et al., 2020), even outside rural areas (Chini and Stillwell, 2018).

A selection of studies on the evaluation of hydropower are given in Table 2.

Table 2: Selected studies on hydropower evaluation

Hydropower Type	Source	Description
Run-of-river	(Ballance et al., 2000; Gergel'ová et al., 2013)	Assessment of hydropower potential using GIS and available rainfall or runoff data.
	(Arriagada et al., 2019; Fujii et al., 2017; Reichl and Hack, 2017; Rojanamon et al., 2009)	Hydropower assessment methods using patched flow records or discharge estimation methods to alleviate problems consistent with hydropower evaluation (e.g. availability of data).
	(Hidayah et al., 2017; Kusre et al., 2010; Sammartano et al., 2019)	Assessment of hydropower potential using GIS and/or hydrological models.
	(Alterach et al., 2009; Ehrbar et al., 2018; Hoes et al., 2017; Korkovelos et al., 2018)	Description of methodology to identify potential hydropower sites and mapping of total potential identified.
	(Moldoveanu and Popescu, 2017; Popescu et al., 2012)	Hydropower evaluation using exiting hydropower software
	(Monk et al., 2009)	The development of the run-of-river identification tool, rapid hydropower assessment model (RHAM).
Pumped storage	(Connolly et al., 2010; Fitzgerald et al., 2012; Larentis et al., 2010; Loots et al., 2015; Vakalis et al., 2020; Xu et al., 2020, 2019)	The identification of potential for the development of pumped storage schemes from existing hydropower reservoirs and non-hydropower reservoirs.
Conduit	(Chacón et al., 2018; García et al., 2018;	Assessment of potential of energy recovery in pressurised pipes or networks.

	Gómez-Llanos et al., 2018; Loots et al., 2014; Samora et al., 2016; Soffia et al., 2010; Viccione et al., 2018)	
Hydrokinetic	(Behrouzi et al., 2016; Niebuhr et al., 2019)	Identification of hydrokinetic potential in rivers and municipal infratutrure.
Storage schemes	(Ballance et al., 2000)	The macro-hydropower potential assessment entails the identification of locations suitable for damming of rivers.
	(Sule et al., 2018)	A hydrological investigation to determine the hydropower potential of the existing dam (using the available flow records).
WWTW	(Bousquet et al., 2017; Gallagher et al., 2015; Power et al., 2014)	Assessment of potential of energy recovery in waste water systems.
WTW	(Culwick and Bode, 2011)	Assessment of potential for energy recovery in the City of Cape Town (SA) bulk water infrastucture system.

This study is the first to have developed a generic method of evaluating hydropower potential in water infrastructure. This work will support the development of hydropower within rivers and water distribution systems and will enable water owners and utilities to realize the hydropower potential available within their various water infrastructure with different levels of data available.

In this research project, methods for evaluating hydropower potential in rivers and water infrastructure were determined. In section 2, the methodology is presented, which includes the process involved in developing the evaluation framework for conduit hydropower sites and selecting the appropriate criteria, which were validated using South African data. The conduit hydropower evaluation framework is then applied to five case studies and compared with the actual potential available at the pressure reducing station (PRS).

The aim of developing the conduit hydropower framework was to bridge the gap between hydropower evaluation and data availability through the provision of a generic method to assist with the procedures that need to be followed when identifying and quantifying conduit hydropower potential when faced with limited available data.

2. Methodological approach

2.1. Hydropower development options and review of existing hydropower evaluation methods

Hydropower frameworks were initially developed for storage schemes, run-of-river, pumped storage, water treatment works (WTW), wastewater treatment works (WWTW), water distribution systems (WDS), irrigation canals, weirs, and transfer schemes as described in Table 1.

Selected studies on the evaluation of hydropower potential were assessed with the aim of providing a basis from which initial evaluation criteria could be utilized. Table 2 summarizes the selected studies analyzed during the development of the initial evaluation frameworks. The major challenge during the development of the evaluation frameworks, however, was the lack of existing studies on the evaluation of hydropower potential using limited data, specifically on the evaluation of conduit hydropower. This study, therefore, aims to address this specific deficit.

2.2. Development of frameworks to evaluate hydropower potential

Evaluation frameworks were developed for all the hydropower types (hydrokinetic, transfer schemes, pumped storage conduit, storage schemes, WTW, WWTW, and weirs) to assess the hydropower potential in water infrastructure and provide a first order estimate of the potential available. The evaluation frameworks were compiled by setting initial evaluation criteria and using various river and water infrastructure data sources, which should be used to either quantify or estimate the parameters necessary for hydropower quantification where the necessary data are not available.

Figure 2 provides a summary of the hydropower types with their respective data sources and criteria included in each evaluation framework for the South African case study. A summary of the data sources is provided in Table 3. As can be seen from this table, evaluation frameworks for specific hydropower types already exist, such as those for hydrokinetic, storage schemes, run-of-river, and WWTW. For others (transfer schemes, pumped storage, and WTW), criteria are yet to be validated. Evaluation of conduit hydropower sites with limited availability or limited access to data is a research problem that has not yet been adequately solved. As such, a more detailed discussion of the evaluation framework for conduit hydropower regarding limited data is presented in this paper.

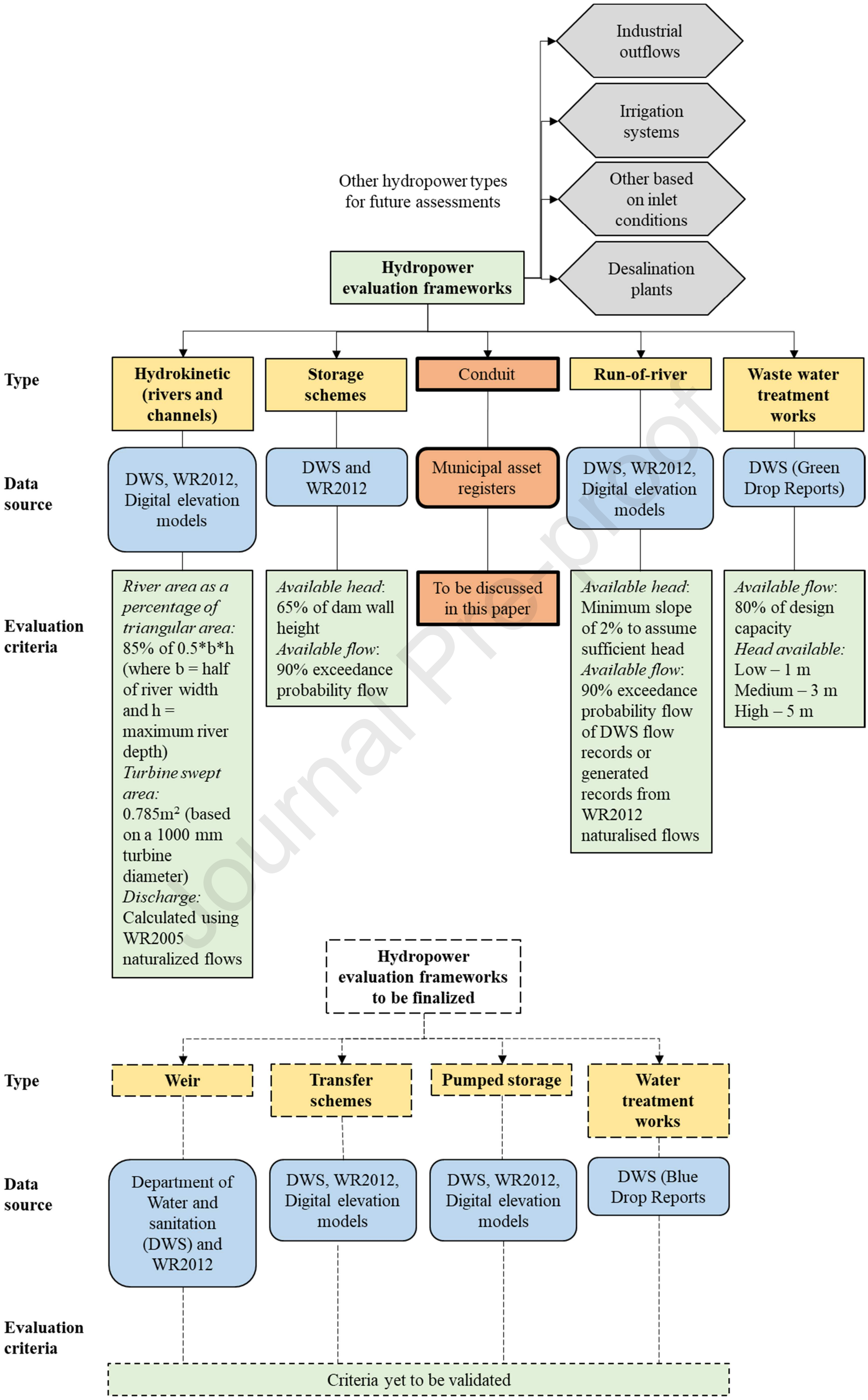


Figure 2: Data sources and criteria included in the frameworks refined for a South African application

Table 3: Description of data sources included in evaluation frameworks for the South African case study

Data Source	Description
Department of Water and Sanitation (DWS)	The DWS website provides information on all DWS-owned water infrastructure and rivers in SA. Verified data (containing primary or daily average flow data or water levels) as well as locations for rivers, canals, closed conduits and reservoirs are provided.
WR2005 and WR2012	The Surface Water Resources of SA studies (WR2005 AND WR2012) provide rainfall, observed streamflow and water data at quaternary catchment level for the entire SA, Lesotho and Eswatini (Bailey and Pitman, 2015).
Green drop reports (DWS)	The Green Drop Reports consist of 9 separate reports for each province. Each report contains a list of the WWTW in every municipality within the province, the design capacity (ML/day) and operational capacity of each WWTW expressed as a percentage of the design capacity, as well as a cumulative risk rating for each WWTW.
DEM	Digital evaluation models (DEMs) with a 30 m resolution can be freely downloaded for any area in the world from the Unites States Geological Survey (USGS) website. Other sources exist where DEMs, such as JAXA ALOS, SRTM, or ASTER can be downloaded and utilized for the same purpose.
Municipal asset registers	Asset Registers (AR) are databases that contain the data on all the significant infrastructure owned by the organization and supports the Asset Management Plan (AMP). According to the Water Services Act, every municipality in SA is required to have an AMP for their water infrastructure and sanitation (Bonthuys et al., 2018).

2.3. Conduit hydropower evaluation framework

A generic conduit hydropower evaluation framework was developed with the aim of assisting in the identification of hydropower sites and quantifying a first order estimate of the hydropower potential available in bulk water supply systems. There are various other opportunities where excess pressure can be harnessed in WDS for conduit hydropower generations. However, the scope of the study only included conduit hydropower at the inlets to reservoirs in PRSs and break pressure tanks (BPT). The development of the evaluation framework entailed an investigation into existing studies on the evaluation conduit hydropower potential, the development of a preliminary framework and the validation of the criteria contained within each framework using data specific to the country under investigation. Future detailed studies and assessments could be used to further enhance the framework and the adopted criteria.

3. Conduit hydropower criteria and validation for the South African case study

Initial criteria included in this evaluation framework were assumed as the topic of conduit hydropower potential estimation methods using limited data is a somewhat unexplored area within the hydropower research field. The initial criteria were validated using data obtained from a collection of sources including Information Management Query Systems (IMQS), DEMs and a study conducted by Loots et al., (2014). The validation process is illustrated in Figure 3. Furthermore, Table 5 describes the criteria included in the conduit hydropower evaluation framework and the results of the validation process using the data summarized in Table 4. The selection criteria for selecting a validation site are:

- The site must be a PRS located at the inlet to a reservoir or a BPT with installed PRVs used to dissipate excess pressure;
- There must be flow and pressure data available from which the actual hydropower potential can be calculated; and
- Important data such as static head, PRV size, pipeline layout (length, diameter, number and location of abstractions, etc.), and downstream pressure should be available.

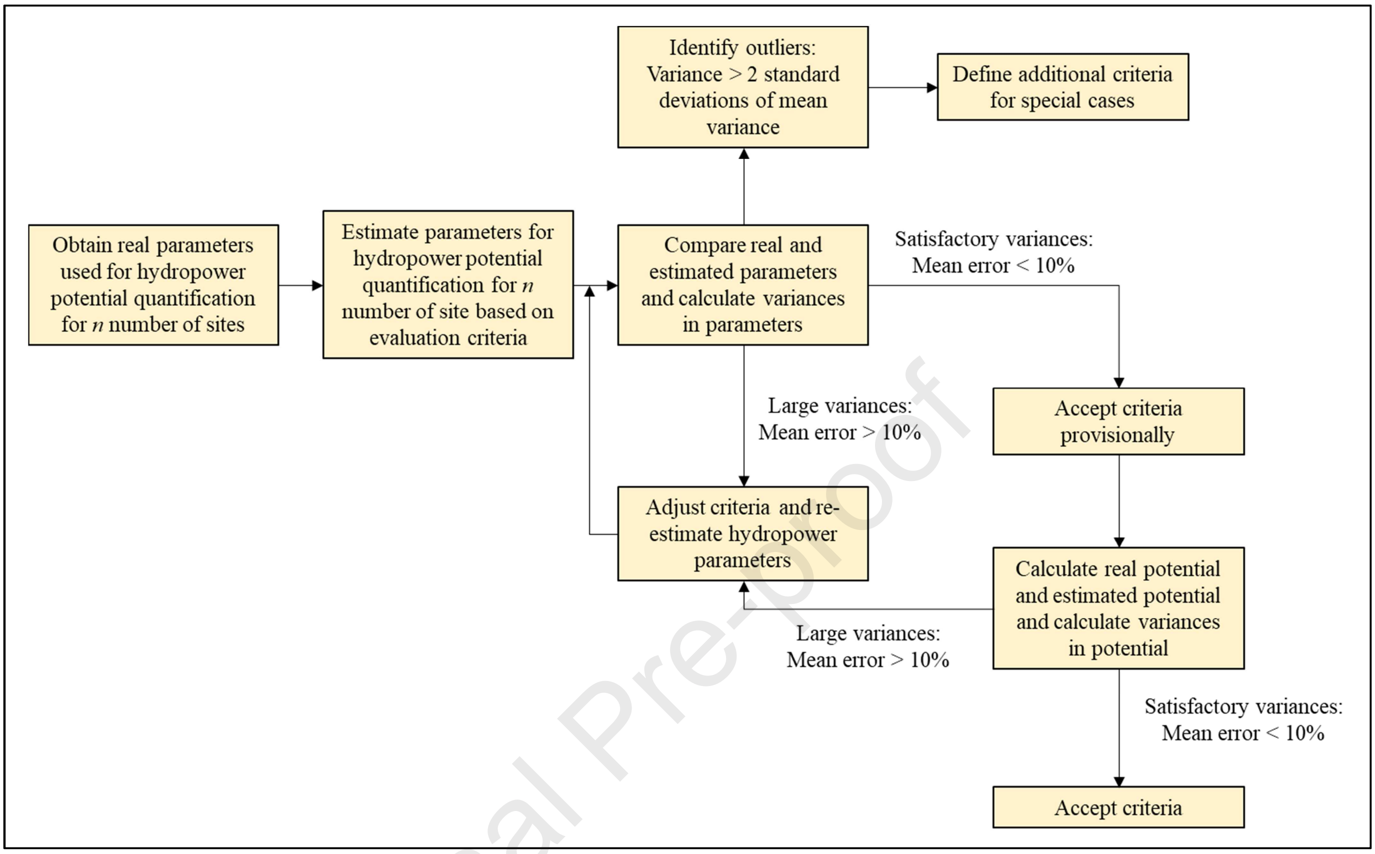


Figure 3: Explanation of validation of evaluation criteria

Table 4: Summary of validation data

PRS	Flow (l/s)	Upstream pressure (m)	Downstream pressure (m)	PRV size (mm)	Static head (m)
Akasia	314	119	6.07	600	190
Doornkloof	250	77	15.9	300	83.6
Garsfontein	907	132	9	1200	154
Heights HL	560	110	10.2	675	188
Heights LL	225	124	4.2	700	146
Salvokop	217	91	12	450	90

Table 5: Criteria and validation data included in conduit hydropower evaluation framework

Pressure head (if no pressure data exists or length and diameter of pipeline is unknown)	It should be assumed that 70% of static head is available for energy generation. Initially Loots et al., (2014) used 50%, but a subsequent study shows 70% to be more reliable (City of Tshwane (CoT) and Department of Civil Engineering (Water Division), 2015). Data from six reservoirs were used to get an estimate of the relationship between static head and the pressure head available for energy generation. If no pressure data are available and the length and the diameter of the pipeline are unknown, 70% of the static head will give a reliable estimate of the potential available for energy generation.
Generation capacity	A study conducted by Loots et al., (2014) assumes that energy can only be generated for 6 hours per day. There was no criterion included in the framework that accounts for a lower generation capacity as a result of fewer operational hours per day.
Downstream pressure	Data from six reservoirs were used to get an estimate of the downstream pressure that can typically be expected (City of Tshwane (CoT) and Department of Civil Engineering (Water Division), 2015). A downstream pressure of 8 m will provide a reliable estimate based on the available validation data. This assumes that most storage reservoirs are above ground with the PRS also at ground level.
Flow	An estimate of the relationship between the PRV and the flow through the PRV were obtained using data from six reservoirs. Assuming a flow parameter equal to 55% of the PRV size will provide a reliable estimate of the flow available in the system.
Flow velocity	1.5 m/s – assumed to be the velocity in the pipe if flow data are not assumed or available. Assumption was not validated.
Friction factor	0.015 – assumed and not validated.
Secondary loss coefficient	3 for short pipelines (Length < 5 km) – assumed and not validated 5 for short pipelines (Length 5 km - 20 km) – assumed and not validated 15 for short pipelines (Length > 20 km) – assumed and not validated
Minimum potential	5 kW – assumed and not validated.
Turbine efficiency	75% – typical value (Van Vuuren et al., 2014) and could be adjusted (based on turbine size) after first evaluation

The criteria included in the framework is dependent on the origin of the validation data. This study illustrates the validation of criteria using South Africa data. Moreover, the reliability of the criteria included in the final framework is subject to the amount of data used during the validation process. As more sites are evaluated in feasibility studies, the reliability of the criteria used in the assessments increase. The final conduit hydropower framework is shown in Figure 4.

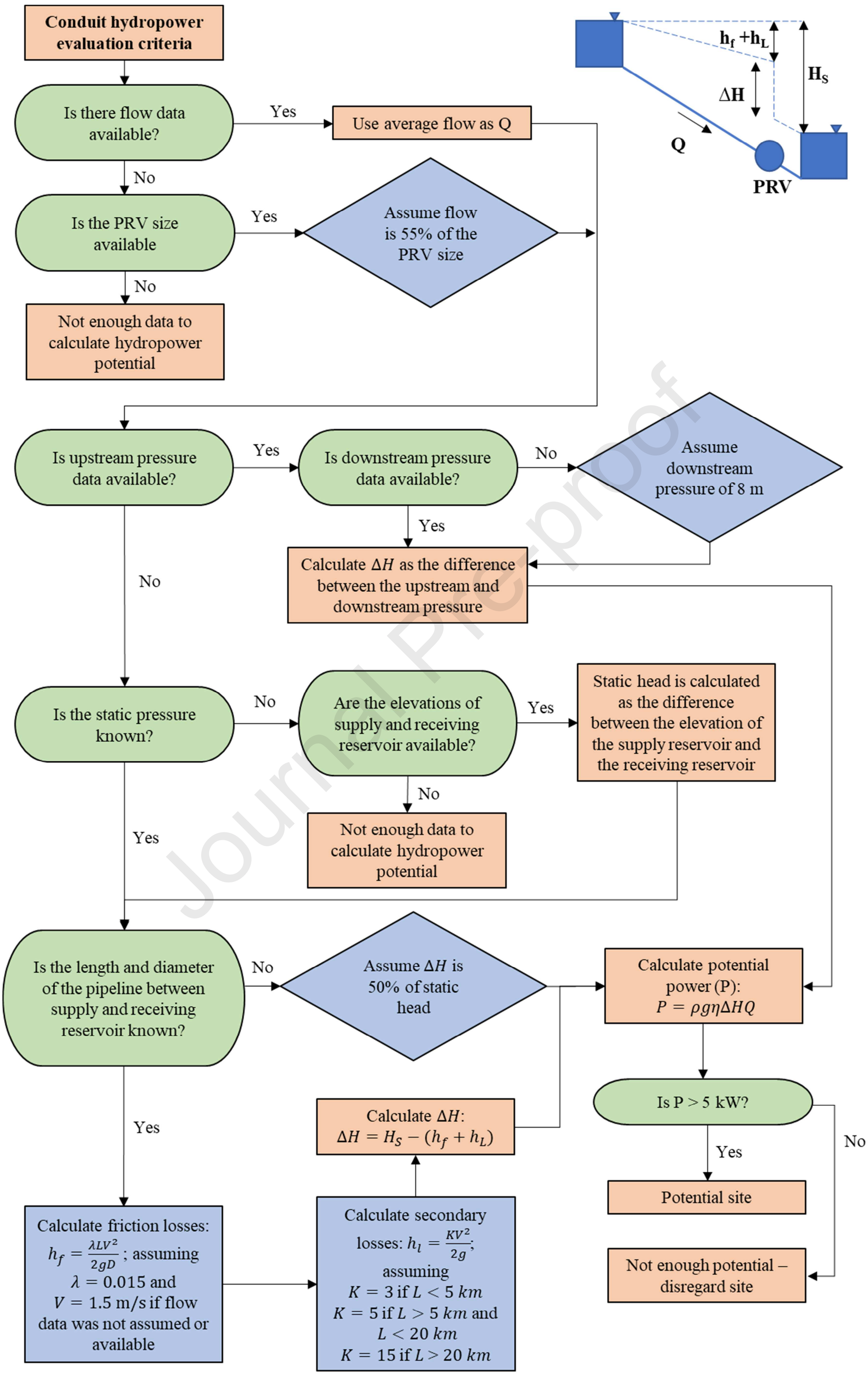


Figure 4: Conduit hydropower evaluation framework for South African water distribution systems

4. Framework evaluation: Case study

4.1. Analysis of Salvokop Reservoir using conduit hydropower evaluation framework

The Salvokop Reservoir complex is located south of the Pretoria Central Business District (CBD), SA. A feasibility study was conducted, as per the collaborative objective of the City of Tshwane (SA) and the City of Aarhus (Denmark), to evaluate the potential for hydropower generation at the existing 27 ML reservoir. The Salvokop PRS is shown in Figure 5.

The feasibility study proposes a Francis turbine to be installed parallel to the existing inlet pipe and pressure reducing valves. The available head is ±78 m and the average flow rate ±246 l/s, which indicates that approximately 152 kW power can be generated.

Figure 5: PRS located at the inlet to the Salvokop reservoir (Pretoria, South Africa) (Color)

The Salvokop feasibility study was used to provide an example of implementing the conduit hydropower framework. The framework was implemented using three scenarios: scenario 1, where flow and pressure data collected for 43 days was used to evaluate the potential available; and scenario 2, where it was assumed that no data flow or pressure data was available, but the length, diameter and static head are known; and scenario 3, where only the static head and PRV size are known.

The implementation of the framework and analysis results for scenario 1, scenario 2 and scenario 3 are discussed in Table 6, Table 7 and Table 8 respectively.

Table 6: Results of conduit hydropower framework implementation for scenario 1

Framework step	Analysis result
Is there flow data available? → Use average flow as Q	The average flow of the dataset is 246 l/s. This flow takes into consideration the fluctuation of flow as a result of the transition between 1 and 2 PRVs being open.
Is upstream pressure data available? → Is downstream pressure data available? → Calculate ΔH as the difference between the upstream and downstream pressure	An average head of 77.4 m is available for energy generation based on the average recorded 88.7 m upstream pressure and 11.3 m downstream pressure.
Calculate potential power (P): $P = \rho g \eta \Delta H Q$	The potential available at the Salvokop reservoir based on the parameter averages and a 75% turbine efficiency is approximately 140 kW.

Is P > 5 kW? ↓ Potential site	The potential available at the Salvokop reservoir is greater than 5 kW and is, therefore, a potential hydropower site.

Table 7: Results of conduit hydropower framework implementation for scenario 2

Framework step	Analysis result
Is there flow data available? ↓ Is the PRV size available? ↓ Assume flow is 55% of the PRV size	No flow data are available, but the size of the PRV is 450 mm. Based on the PRV size, the flow was estimated as 247.5 l/s.
Is upstream pressure data available? ↓ Is the static pressure known? ↓ Is the length and diameter of the pipeline between supply and receiving reservoir known?	No pressure data are available, but the static pressure (90 m), length and diameter of the pipeline is known.
Calculate friction losses: $h_f = \frac{\lambda L V^2}{2gD}$; assuming $\lambda = 0.015$ and $V = 1.5$ m/s if flow data was not assumed or available ↓ Calculate ΔH: $\Delta H = H_S - (h_f + h_L)$	The Salvokop pipeline consists of a 675 mm diameter pipeline section which reduces after 2 577 m to a 450 mm diameter pipeline (1 303 m long). The calculated head loss for the pipeline is 7.2 m. The head loss was calculated using a calculated a velocity (based on the assumed flow of 247.5 l/s), a pipeline friction factor of 0.015 and a secondary loss coefficient of 3. The pressure head available is 82.8 m.
Calculate potential power (P): $P = \rho g \eta \Delta H Q$	The potential available at the Salvokop reservoir based on estimated parameters and an 75% turbine efficiency is approximately 151 kW.
Is P > 5 kW? ↓ Potential site	The potential available at the Salvokop reservoir is greater than 5 kW and is, therefore, a potential hydropower site.

Table 8: Results of conduit hydropower framework implementation for scenario 3

Framework step	Analysis result
Is there flow data available? ↓ Is the PRV size available? ↓ Assume flow is 55% of the PRV size	No flow data are available, but the size of the PRV is 450 mm. Based on the PRV size, the flow was estimated as 247.5 l/s.
Is upstream pressure data available? ↓ Is the static pressure known? ↓ Is the length and diameter of the pipeline between supply and receiving reservoir known?	No pressure data are available and the pipeline characteristics (diameter and length) are unknown. The static pressure, however, is known.
Assume ΔH is 50% of static head	The static head of the system is 90 m and based on this value, the

	pressure head available was assumed as 63 m.
Calculate potential power (P): $P = \rho g \eta \Delta H Q$	The potential available at the Salvokop reservoir based on estimated parameters and a 75% turbine efficiency is approximately 115 kW.
Is P > 5 kW? → Potential site	The potential available at the Salvokop reservoir is greater than 5 kW and is, therefore, a potential hydropower site.

4.2. Analysis of five additional sites using conduit hydropower evaluation framework

Five additional validation sites have been included in the study to further illustrate the implementation of the conduit hydropower evaluation framework. Due to anonymity being requested, the sites included in the additional case studies will be referred to as site A to E, with the following description of each site:

- The **Site A** pipeline is a gravity system consisting of a 2 100 mm steel pipe, which eventually reduces to a 928 mm steel pipe. There is under static conditions approximately 157 m (16 bar) of pressure difference between the two reservoirs.
- The **Site B** pipeline is a gravity system consisting of two pipelines, Pipeline 1 and Pipeline 2. Pipeline 1 has an inside diameter (ID) of 610 mm and pipeline 2 a diameter (ID) of 900. There is under static conditions approximately 72 m (7 bar) of pressure difference between the two reservoirs.
- The **Site C** pipeline is a gravity system consisting of two pipelines, Pipeline 1 and Pipeline 2. Pipeline 1 has a diameter (ID) of 610 mm and pipeline 2 a diameter (ID) of 900. There is under static conditions approximately 99 m (10 bar) of pressure difference between the BPTs.
- The **Site D** pipeline is a gravity system consisting of two pipelines, with varying diameters. There is under static conditions approximately 198 m (20 bar) of pressure difference between the two reservoirs.
- The **Site E** pipeline is a gravity system consisting of two pipelines, which eventually bifurcate to become three lines: There is under static conditions approximately 97 m (10 bar) of pressure difference between the two reservoirs.

The data available of the five sites are summarized in **Table 9**.

Table 9: Summary of data for additional conduit hydropower framework implementation

Site	*Potential available (kw)	Flow (m^3/s)	Upstream pressure (m)	PRV Size (mm)	No. of PRVs	Static head (m)	Pipeline length (m)
A	675	0.94	85.5	600	4	157	45634
B	495	1.39	40.7	600	2	72	7071
C	318	0.92	31.1	600	1	99	24660
D	2400	2.875	124	600	7	198	34068
E	2000	4.20	56	600	6	97	18315

**Potential based on detailed analyses using extensive data records*

The conduit hydropower evaluation framework was again implemented using three scenarios as described in the previous section. The implementation of the framework and analysis results for scenario 1 to scenario 3 are summarized in Table 10.

Table 10: Results of framework implementation of five PRS/BPT case studies

Site	Potential (kW)		
	Scenario 1	**Scenario 2**	**Scenario 3**
A	591	695	1067
B	444	332	245
C	261	233	168
D	2798	2416	2536
E	1846	1381	989

4.3. *Discussion of results*

An estimated conduit hydropower potential of approximately 140 kW was identified at the Salvokop PRS based on the available pressure and flow data (scenario 1) and 151 kW based on scenario 2. The assumed efficiency used in the Salvokop feasibility study was 80%, which resulted in a higher estimated hydropower potential of 152 kW. Furthermore, a slightly lower potential of 115 kW was estimated when the framework was implemented on scenario 3 (no data available).

Based on the analyses of the Salvokop PRS the following conclusions were made:

- The flow assumption used in scenario 2 and 3 provided a reliable estimate of the flow available in the system;
- During scenario 2, where the length and diameter of the pipeline were known, a reliable estimate of the pressure head was provided;
- The 70% static head assumption provided a lower, but reliable estimation of the pressure head available;
- The variance between the actual potential and the estimated potential for scenario 3 exceeds the specified 10% variance limit;
- The conduit hydropower framework can be used to provide a relatively reliable estimate of the potential available at any given site, with different levels of data availability; and
- The framework can, therefore, be used to give a good indication of sites that have potential for conduit hydropower development and that are worth including in further detailed assessments.

Based on the conduit hydropower analyses of the five PRSs/ BPTs the following conclusions were made:

- The variance between the actual potential and the estimated potential increases with an increase in the number of parameters being estimated. This trend was also observed in the Salvokop PRS case study.
- The flow criterion underestimated the flow available for sites B to E resulting in a relatively large variance between the estimated pressure head and the actual pressure head available for scenario 2. This is largely due to the reduced velocity resulting in an underestimation of the losses in the system.
- The pressure head in scenario 3 was overestimated within an allowable range for all 5 sites indicating that the head criterion provides a reliable estimate of the pressure head available.
- Higher flows are observed when comparing the five additional PRVs/BPTs with the Salvokop PRS. This is largely due to the Salvokop PRS being part of a municipal WDS whereas the five PRSs/BPTs form part of a larger WDS transporting potable water to an entire province. This implies larger demand at possible larger velocities. The results obtained from the analyses indicates that adjustments to the flow criterion is required, especially where PRS/BPT forming part of a larger WDS is evaluated for conduit hydropower potential. Estimating a more reliable flow will result in a more reliable pressure head estimation for scenario 2.
- On average the variance between the actual potential available and the potential estimated when applying the framework for scenario 1, scenario 2 and scenario 3 is 6%, 18% and 18% respectively.

- The high variances for scenario 2 and 3 can be attributed to additional factors that can affect the estimated potential, such as the pipeline age and material, design capacity versus the actual capacity of the pipeline, the existence of more than one pipeline in the systems and additional off-takes along the pipeline affecting the estimated flow. These factors will be considered and the effect on the estimated flow and pressure determined as more sites are evaluated to enhance the developed framework. The more sites that are evaluated in detail and compared with the framework would further improve the reliability and set criterion.

5. Conclusions

Evaluation frameworks were developed for nine hydropower types (conduit, hydrokinetic, transfer schemes, pumped storage schemes, run-of-river, storage schemes, WWTW, WTW and weirs) to assist in the evaluation and quantification of hydropower potential in the various water infrastructure and rivers, especially where limited data poses a challenge in the quantification of the potential available. These frameworks were developed in the attempt to bridge the gap in the hydropower field between hydropower potential identification in areas where limited data is available.

The aim of the framework for conduit hydropower is to provide a first order estimate of the potential available at a given site based on municipal and national data available. The refinement of the framework as to be applicable to a specific country was illustrated using South African data. During the implementation of the framework on any WDS, the reliability of the first order estimate provided will be based on the reliability of the data used, as well as the reliability of the criteria included in the framework.

During the implementation of the framework, using an existing conduit hydropower case study in SA, it was concluded that the estimated potential can be used to indicate whether the site can be considered for hydropower development. The potential estimated at the Salvokop reservoir was 140 kW (using measured pressure and flow data) and 115 kW (assuming no pressure and flow data) in comparison to 152 kW potential identified during a detailed feasibility study conducted.

The hydropower potential was analyzed for five additional PRSs/BPTs using the developed conduit hydropower framework. Overall, from the analyses it was concluded that the framework can be used to provide a reliable estimate of the hydropower potential available, even though flow available was underestimated for four out of the five sites.

Some limitations of the current framework were identified that requires additional extensive research. These identified shortcomings include the estimation of flow for larger sites (with higher flow velocities in the system), the estimation of flow when there are abstractions along the pipeline system and the consideration of the age and material of the pipeline. Future directions of the study also includes the addition of more case studies to determine the effect on the pressure head and flow estimation with the introduction of more unknown variables (such as unknown pipeline length, unknown amount of abstractions along the pipeline etc.).

The frameworks can be used to identify hydropower potential in water supply systems. As more sites are evaluated by implementing the frameworks, the reliability of frameworks used in the assessments will be adjusted. In a South African context, the reliability of the criteria induced in the framework will be adjusted as more data is used for the validation process.

Author Contributions: All the authors have participated in any step of this research. A brief description is attached: Anja Bekker developed the evaluation frameworks for hydropower in South Africa. Marco van Dijk supervised the research and was involved in determining the conclusions. Chantel M Niebuhr and Christel Hansen have contributed by supervising the state of the art and revision of the paper.

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- Generic conduit hydropower evaluation framework to quantify potential
- Criteria within the framework alleviate problems associated with limited data
- Conduit hydropower framework provides a first order estimate of potential available
- The framework criteria are validated according to the study area under investigation

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: