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Conduit-hydropower potential in the City of Tshwane water distribution system: A discussion of potential applications, financial and other benefits

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In water distribution networks, water is often fed under gravity from a higher reservoir to another reservoir at a lower level. The residual pressure head at the receiving reservoir is then dissipated through control valves (mechanically or hydraulically actuated), sometimes augmented by orifice plates where there is a propensity for cavitation. There are possibilities to add turbines in parallel and generate hydroelectricity at these locations using the flow and head available.

The benefit of this hydropower generating application is that minimal civil works need to be done, as the control valves are normally inside a control room/valve chamber. No negative environmental or social effects require mitigation, and the anticipated lead times should be short.

From a topographical perspective the City of Tshwane has a lower elevation than the bulk service reservoirs of Rand Water, which is the main water supply. Water is distributed through a large water system that includes 160 reservoirs, 42 water towers, 10 677 km of pipes and more than 260 pressure reducing stations (PRS) that operate at pressures of up to 250 m.

The top ten hydropower potential sites in the City of Tshwane water distribution network have a total energy generating capacity of approximately 10 000 MWh/a. A number of potential conduit-hydropower sites have shown promise of short payback periods. The identifying and development of these sites in Tshwane to convert water pressure to electricity is ongoing and exploited further.

Various challenges currently exist with reservoir communication in isolated areas due to vandalism and theft of necessary infrastructure, including electricity cables and solar panels. Because conduit-hydropower systems can be housed completely inside chambers, vandalism and theft can be mitigated. Therefore, one of the major benefits of hydropower turbines at these sites is that the hydroelectric potential could be exploited to power telemetry, pressure management, flow control and monitoring/security systems.

Alternatively or additionally, other local demand and/or (depending upon the quantum of energy available) off-site energy demand clusters, or even a municipal or national grid, could also be serviced by these power stations. The capacity of hydroelectric installations can vary to suit the application for the amount of power needed or to be generated.

Short payback periods, especially when using pumps as turbines, also make conduit-hydropower systems attractive.

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INTRODUCTION

Energy is the lifeblood of worldwide economic and social development. The current status of global energy shortages and the emphasis to reduce CO_2 emissions stimulate the development of alternative electricity generation methods at all levels of the South African economy. The demand for energy is increasing continuously, primarily due to changing lifestyles and the increase in population. These demands need to be met in order to stimulate worldwide development. They can be satisfied by developing alternative, particularly renewable, energy resources using well-researched technologies. Renewable energy technologies will have to be exploited to effectively support future economic development and satisfy energy demands. Among targeted renewable energy sources available for energy generation in South Africa are solar radiation, biomass, wind and also (rather underrated) hydropower (DoE 2011).

Energy efficiency, optimisation of existing systems and seeking new approaches in conversion of one energy form into another are also spheres of electricity generation where

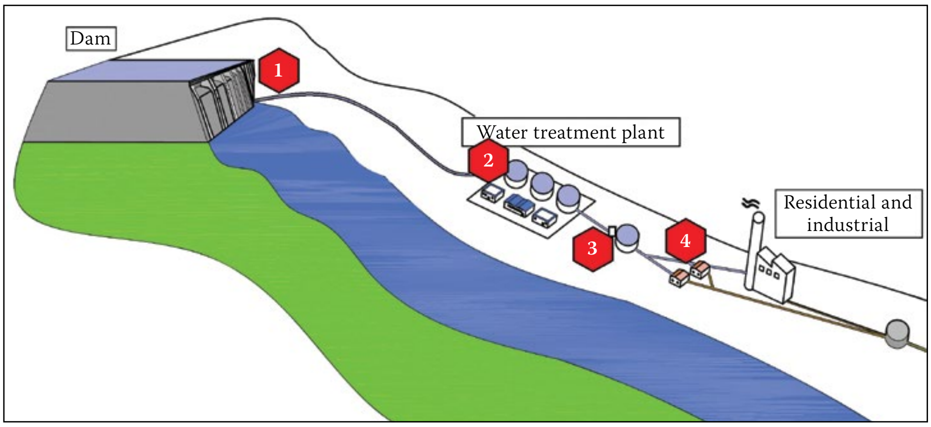


Figure 1 Location of electricity generation potential (adapted from Briggeman 2011)

individual citizens, universities and various utilities seek new ways to generate electricity.

Renewable energy is the way of the future, and the potential for its development is of great magnitude. Hydropower contributes only 3% of global energy consumption, which is only a fraction of its potential. **Africa is the most underdeveloped continent with regard to hydropower generation, with only 6% of the estimated potential exploited**. This is not a burden, but an opportunity. Although South Africa has below-average conventional hydropower potential, large quantities of raw and potable water are conveyed daily under either pumped or gravity conditions over large distances and high elevations. The water is supplied typically to residential, industrial and irrigation areas, commonly requiring high security of supply. These water transport systems have to be operated under sustainable water supply regimes, which is a very important aspect in the operation of any hydropower generation system.

There are basically four areas where electricity generation can occur in the water supply and distribution system (WDS), as shown in Figure 1 (adapted from Briggeman 2011).

1. Dam releases – conventional hydropower.
2. At water treatment works (raw water) – the bulk pipeline from the water source can be tapped.
3. Potable water – at inlets to service reservoirs where pressure reducing stations (PRS) are utilised to dissipate the excess energy.
4. Distribution network – in the distribution network itself where residual energy is dissipated (typically with pressure reducing valves (PRV)).

The University of Pretoria (UP), supported by the Water Research Commission (WRC), is engaged in a research project to investigate the potential of extracting the available energy from existing and newly installed water supply and distribution systems.
The project aims to enable the owners and administrators of the bulk water supply and distribution systems to install small-scale hydropower systems to generate hydroelectricity for on-site use and, in some cases, to supply energy to isolated electricity demand clusters or even to the national electricity grid, depending on the location, type and size of installation.

To distinguish the type of hydropower that will be generated it is called "conduit-hydropower" (NHA 2011), as shown in Figure 1 at locations (2), (3) and (4).

There are numerous benefits provided by hydropower over other energy sources (BHA 2005; USBR 2011):

- Hydroelectric energy is a continuously renewable energy source.
- Hydroelectric energy is non-polluting – no heat or noxious gases are released.
- Hydroelectric energy is detached from fossil fuel escalation and has low operating and maintenance costs – it is essentially inflation proof.
- Hydroelectric energy technology is proven technology offering reliable and flexible operations.
- Hydroelectric stations have a long life – many existing stations have been in operation for more than half a century and are still operating efficiently.
- Hydropower stations achieve high efficiencies.
- Hydropower offers a means of responding quickly to changes in load demand.
- Conduit-hydropower uses the available water distribution infrastructure and thus, as long as there is a demand for water, hydroelectric energy can be generated.
- Conduit-hydropower "piggybacks" onto existing water infrastructure, resulting in minimal environmental impact.

A number of water authorities throughout the world have realised the potential of conduit-hydropower and implemented generating schemes (NHA 2011; Möderl *et al* 2012; Fontana *et al* 2012 & White 2011). These conduit-hydropower plant (CHP) installations were generally stand-alone systems.

An initial scoping investigation highlighted the potential hydropower generation at the inlets to storage reservoirs (i.e. the bulk water distribution systems) in the City of Tshwane. A low budget pilot hydropower generation installation was erected at Queenswood Reservoir. Although this installation was not optimised, the initial trial runs reflected the benefit and expected return from such an investment (Van Vuuren 2010). The results from this scoping study highlighted the untapped hydropower-generating potential from pressurised conduits, specifically in the City of Tshwane WDS.

NEED FOR RENEWABLE ENERGY DEVELOPMENT IN SOUTH AFRICA

The awareness of a need for renewable energy development in South Africa was boosted significantly in November 2003 when the South African government introduced the White Paper on Renewable Energy (WP on RE). This document set a 2013 target of 10 000 GWh to be generated annually from renewable sources. Among targeted renewable energy sources available for energy generation in South Africa are solar radiation, biomass, wind and also, rather underrated, hydropower (DoE 2011).

South Africa, as one of the signatories of the Kyoto Protocol (February 2005), committed itself to reducing emissions by 34% below projected emissions level in 2020. The emissions level from all sources in South Africa is currently estimated at about 500 000 000 tons of carbon dioxide equivalent (CO_2e) per annum. Accordingly, South Africa has committed itself to an emissions trajectory that peaks at 34% below a "Business as Usual" trajectory in 2020 and 40% in 2025, remaining stable for around a decade, and declining thereafter in absolute terms. To provide a suitable enabling environment for emissions reduction and reliable energy supply for the South African economy, the Department of Energy (DoE), with endorsement from the National Energy Regulator of SA (NERSA), introduced the Integrated Resource Plan (IRP) for electricity in South Africa 2010–2030. The IRP 2010 had been subjected to public scrutiny and comments, and eventually the whole process manifested in the Final Policy Adjusted IRP 2010: New-build Technology Mix. The DoE subsequently allocated different capacities across various renewable energy technologies from the total development capacity of 3 725 MW. The hydropower sector has been allocated overall capacity of 75 MW to be commercially operational by June 2014. One of the critical qualification requirements is that only small-scale hydropower installations above 1 MW are to be included in the forthcoming selection process. Effectively all pico (up to 20 kW as shown in Table 1), micro (20 kW to 100 kW) and mini (100 kW to 1 MW) renewable energy installations are below the level of interest of the authorities at this stage.

Internationally, small hydro is considered to be the best proven of all renewable energy technologies, ideal for the electrification of remote communities, assisting in peak supply, and can be used to balance out variations present in wind and solar power production. Both wind and solar technologies require energy storage facilities, typically provided by hydraulic infrastructure (e.g. dams, reservoirs, pipelines, canals, etc).

Hydroelectricity generation from small-scale installations is gaining unprecedented world-wide interest, mainly due to its social, environmental and financial benefits, particularly if hydropower technology is added to existing infrastructure.

Various challenges currently exist with reservoir communication in isolated areas due to vandalism and theft of necessary infrastructure, including electricity cables and solar panels. Because conduit-hydropower systems can be housed completely inside chambers, vandalism and theft can be mitigated. Therefore, one of the major benefits of hydropower turbines at these sites is that the hydroelectric potential could be exploited to power telemetry, pressure management, flow control and monitoring/security systems.

Alternatively, or additionally, other local demand and/or (depending upon the quantum of energy available) off-site energy demand clusters, or even a municipal or national grid could also be serviced by these power stations. The capacity of hydroelectric installations can vary to suit the application for the amount of power to be generated or needed.

Table 1 Hydroelectric capacity applications from small-scale categories

Hydropower category	Capacity in power output	Potential hydropower use either as a single source or in a hybrid configuration with other renewable energies
Pico	Up to 20 kW	10 kW network to supply a few domestic dwellings
Micro	20 kW to 100 kW	100 kW network to supply small community with commercial/ manufacturing enterprises
Mini	100 kW to 1 MW	1 MW plant can offset about 150 000 tons of CO_2 annually and will provide about 1 000 suburban households with reliable electricity supply
Small	1 MW to 10 MW	1 MW to 10 MW network – electrical distributions will be at medium voltage ranging from 11 to 33 kV and transformers are normally needed; the generation must be synchronised with the grid frequencies (typically to 50 or 60 Hertz)
NB: All installations above 10 MW are classified as macro (or large) hydropower plants		

CONDUIT-HYDROELECTRIC INSTALLATIONS

The turbine/generator set is typically installed just upstream of the inlet pipe to the service reservoir or could be placed inline. Water is discharged into the service reservoir under atmospheric pressure. There are a few technical issues to be borne in mind when developing conduit-hydropower:

1. The service reservoir operates as a tailrace.
2. The water inflows into the reservoir should equal the outflows.
3. The head fluctuation within the service reservoir and the system head losses dictate the operating head of the turbine installation.
4. The flow available for hydroelectricity generation is dependent on the water demand, which in turn is subject to community water use patterns, and seasonal variations.
5. The base demand determines likely flow available to the turbine installation.
6. There are transient pressures which could be developed, typically caused by load rejection (i.e. danger of damage if water hammer exceeds design conditions).
7. A turbine installation will not be feasible if the water pipeline is not structurally sound (e.g. age, type of material, etc).
8. A turbine by-pass piping system might need to be installed to allow for excess water flows to be diverted directly into the reservoir.
9. Operational optimisation of series-connected systems may prove difficult.
10. Reliability of supply should not be compromised.
11. Further upgrading of a pipeline system could be offset against potential income from the generated hydropower.

In South Africa there are several inter-basin water transfer schemes (WTS) that can be considered for hydroelectric development. The systems identified to date are mainly under corporate administration of Eskom and the Department of Water Affairs (DWA) and include: Assegaai to Vaal (Kwazulu-Natal to Mpumalanga), Vaal River Eastern Sub-system Augmentation Project (VRESAP), and the Orange-Fish Tunnel WTS. Eskom is currently conducting feasibility studies to install hydropower capacity in the latter.

Several water supply utilities (former water boards) and metropolitan municipal water supply systems, with configurations comprising a gravity pipeline connecting two reservoirs, are suitable for in-line hydroelectric installation. The turbine/generator set can be installed on the delivery or by-pass and the excess pressure can be exploited for hydroelectricity generation.

Current conduit-hydropower projects under way include:

- **Rand Water** – the utility determined that among its 58 service reservoirs there is a firm hydroelectric potential of 15 MW. It has subsequently been estimated that a further 50 MW of capacity is hidden within the utility's water supply and distribution systems. A tender recently closed where this type of energy generation is planned at four locations, totalling almost 13 MW.
- **eThekwini's Water and Sanitation Department** – the department is considering installation of six mini hydroelectric sets within the eThekwini potable water system. These proposed reservoir sites are situated at Sea Cow Lake, Kwa Mashu 2, Aloes, Phoenix 1, Phoenix 2 and Umhlanga 2 Reservoirs.
- **Bloem Water** – the water utility is considering micro hydropower installations at the Uitkijk and Brandkop Reservoirs on the Caledon–Bloemfontein pipeline. These two sites could generate approximately 400 kW each. Currently a 96 kW installation at Brandkop is being developed.
- **Lepelle Northern Water** – various hydropower options have been investigated and it was found that the supply conduit to the purification works at Ebenezer Dam is a viable economic development option, with potential in excess of 100 kW.
- **City of Tshwane** – various sites are under investigation and will be described in more detail below.

CITY OF TSHWANE WATER DISTRIBUTION SYSTEM DESCRIPTION

The City of Tshwane (now including Metsweding) receives bulk water from Rand Water, Magalies Water and from own sources including boreholes, water purification plants and springs. Water is then distributed as shown in Figure 2, through a large water system that includes 160 reservoirs, 42 water towers, 10 677 km of pipes and more than

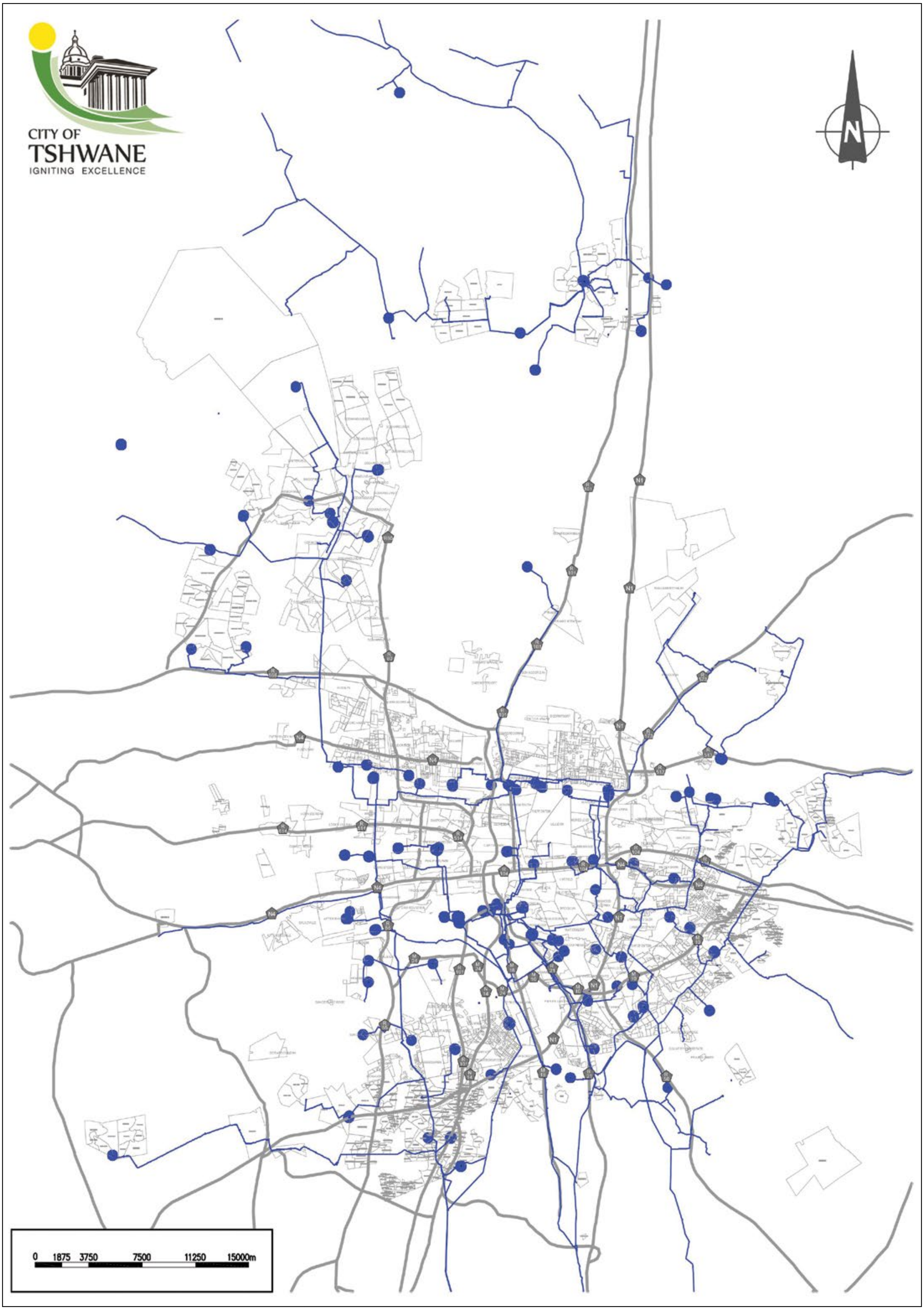


Figure 2 Reservoirs and bulk pipelines in the City of Tshwane Water Distribution System

260 pressure reducing stations (PRSs) that operate at pressures up to 250 m.

The investigation into the development of potential hydroelectric sites in the Tshwane WDS started in 2008 when the first low-cost pilot plant was constructed and tested at the Queenswood Reservoir (Van Vuuren 2010). This was followed up with a 15 kW installation at the Pierre van Ryneveld Reservoir that was completed in October 2011.

IDENTIFYING HYDROPOWER POTENTIAL IN A WDS

A decision support system (DSS) that can be used to identify conduit-hydropower potential in South Africa, developed as part of the WRC research project, provides guidance for the development of identified potential sites (Loots 2013). A system of flow diagrams and tools has been compiled to identify and develop conduit-hydropower sites.

A systematic approach, consisting of the following three phases, is followed when assessing hydropower potential in a distribution network to ensure that all relevant factors are considered:

- **First Phase (Pre-feasibility Investigation):** The only input required in this section is the average daily flow, the average pressure head, if available, the static energy head (if the average head is not known) and, if applicable, the distance to the grid connection and power demand. The output in this section includes the theoretically available power and the ratio of the energy demand vs available energy, in the case of on-site or islanded systems. The Economic Analysis Section does not require any input, except the design life of the project, unless better information than the default values is available. The output from this section includes initial estimates of the net present value (NPV), internal rate of return (IRR) and payback period of the proposed project.
- **Second Phase (Feasibility Study):** The input at this stage becomes more detailed, with measured flow and pressure records required. Some of the output in Phase 2 includes an optimum design flow and head, initial turbine selection, flow rating curve and economic analysis based on the turbine selected. Environmental, social and regulatory assessments are also conducted during this phase.
- **Third Phase (Detailed Design):** The input and output of Phase 3 are to some extent similar to that of Phase 2, but with additional detail input required. Specifically, a complete flow and head data set, all costs and income expected in the life cycle of the project, and criteria for when the system should be functional, are needed. This phase also requires detail design of all civil and electro-mechanical components and infrastructure.

Each phase has its own process flow diagram linked to the Conduit-Hydropower Potential Tool (CHD Tool). Some of the aspects of the study will occur in two or more of the phases, but are dealt with in increasing detail as the project progresses. A fourth phase, dealing with operation and maintenance aspects, falls outside the scope of this system, but is also an important phase to consider when designing a conduit-hydropower facility.

The first phase of the DSS was utilised in the identification and analyses of the viability of developing the sites.

Table 2 Potential annual hydropower generation capacity at the ten most favourable reservoirs in the City of Tshwane Water Distribution System

Reservoirs	TWL (m.asl)	Capacity (kl)	Pressure (m)	Flow (l/s)	Annual potential power generation (kWh)
Garsfontein	1 508.4	60 000	165	1 850	3 278 980
Wonderboom	1 351.8	22 750	256	470	1 292 471
Heights LL	1 469.6	55 050	154	510	843 673
Heights HL	1 506.9	92 000	204	340	745 062
Soshanguve DD	1 249.5	40 000	168	400	721 859
Waverley HL	1 383.2	4 550	133	505	721 483
Akasia	1 413.8	15 000	190	340	693 930
Clifton	1 506.4	27 866	196	315	663 208
Magalies	1 438.0	51 700	166	350	624 107
Montana	1 387.6	28 000	82	463	407 829
Total calculated annual power generation in Tshwane					± 10 000 000

HYDROPOWER POTENTIAL IN THE CITY OF TSHWANE WDS

As a first step a desktop study was conducted where the ten larger reservoir sites in the City of Tshwane were identified (Van Vuuren 2010). The use of the potential energy stored in the pressurised closed conduit water systems in Tshwane is, however, not limited to the 10 larger sites as listed in Table 2. The scope of using all available pressurised water systems in Tshwane to convert potential water energy to electricity is still to be investigated and exploited further.

In the Tshwane water supply area (TWSA), there are a number of reservoirs receiving water from Rand Water at a pressure of up to 250 m. The initial conservative assumptions which were used to calculate the potential annual hydropower generation from these pressurised supply pipelines were:

- The fraction of the available static head that can be used to generate power is 0.5.
- The hours per day when power can be generated are only six hours

Based on the above assumptions, the potential annual hydropower generation at reservoirs in the TWSA was calculated. This analysis is a conservative low estimate of the hydropower generating capacity. In the case of the power generation from reservoirs in the TWSA, the fraction which has been used to calculate the hydropower generation is only 12.5% (0.5*6/24*100) of the potential maximum power generation.

Figure 3 indicates the potential hydropower generation capacity at different reservoirs in the TWSA. This analysis was based on utilising the available data in the IMQS information system.

The capacity of hydroelectric installations can vary to suit the application for the amount of electricity to be generated or needed. An example may be the necessity to have communication with reservoirs in isolated areas due to various operation, maintenance and infrastructure management reasons. It is not practical to have personnel driving hundreds of kilometres at high costs to inspect installations and monitor water levels in these isolated areas on a daily basis, while the potential for hydro energy is available. To supply electricity only a relatively small power source for these reservoirs and PRV installations in isolated areas is required to power telemetry, pressure management, flow control and 24-hour monitoring/security systems.

The use of hydropower generators in water installations also has the security benefit that the installation is inside chambers and buildings. The City of Tshwane

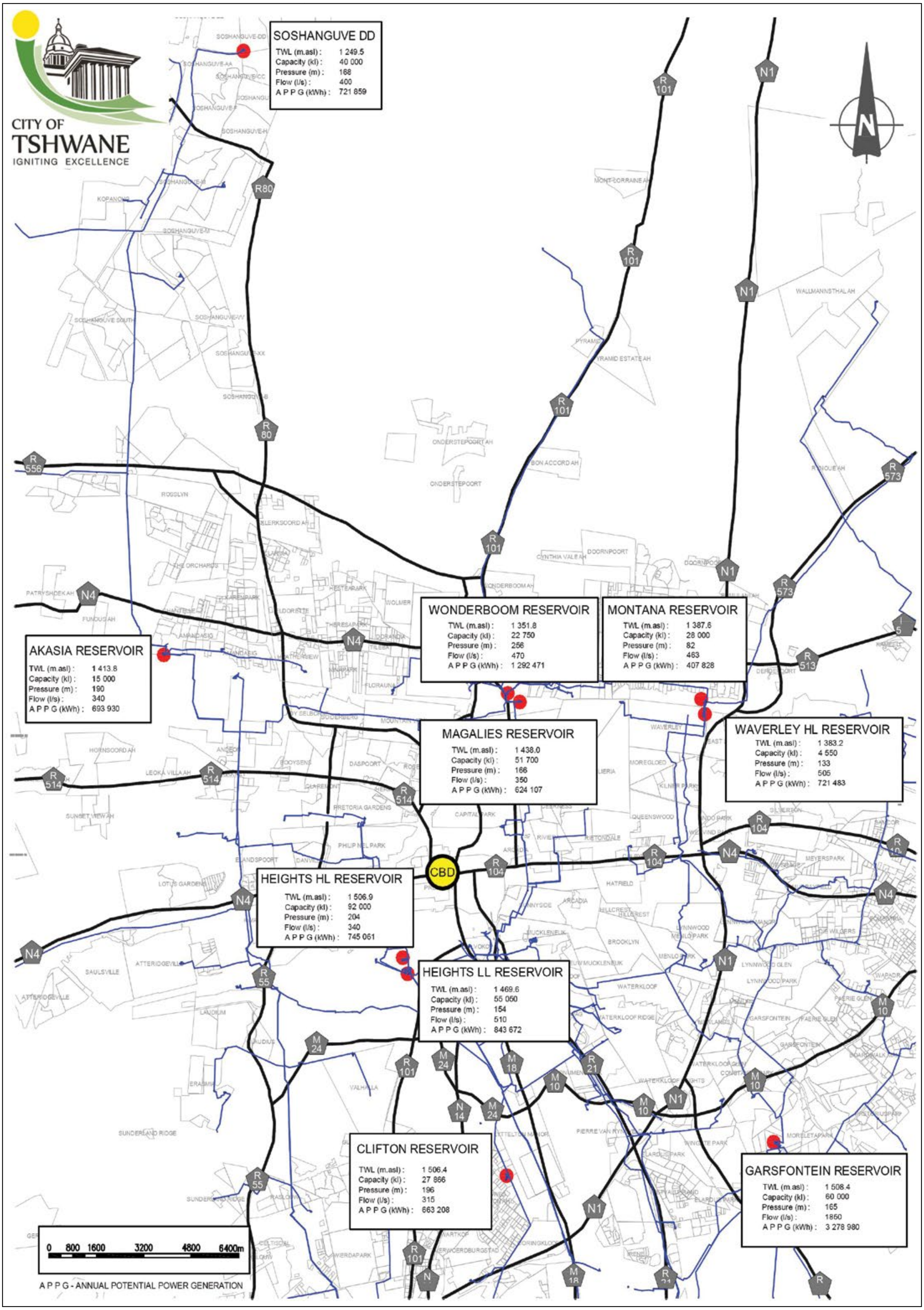


Figure 3 Hydropower generation capacity at different reservoirs in the City of Tshwane Water Distribution System

Table 3 Sensitivity analyses of the assumptions on the monetary value of power generation in the Tshwane Water Supply Area (10 reservoirs)

Variable	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Fraction of available head used for power generation	0.5	0.6	0.7	0.75
Generating hours per day	6	7	8	9
Fraction of total potential energy generated	0.125	0.175	0.233	0.281
Yearly generation capacity, MWh	10 000	14 000	18 640	22 480

Figure 4 Hydropower generation on the inlet side of the Queenswood Reservoir

Figure 5 Zinc basin with geyser elements used as ballast loads

Table 4 Potential yearly income from power generation at the Queenswood Reservoir

Variable		Value	Units
Head		80	m
AADD		181.03	m^3/h
		0.050286	m^3/s
Efficiency		40	%
Maximum available power		39.46	kW
Available head (m)	Potential annual energy production (kWh)		
	% of AADD that could be used to generate electricity		
	40	45	50
40	27 657	31 114	34 571
50	34 571	38 892	43 214
60	41 485	46 671	51 856
70	48 399	54 449	60 499
80	55 314	62 228	69 142

experiences frequent vandalism and break-ins in all of its isolated infrastructure (removal of solar panels, batteries, electronic equipment and precious metal components).

Table 3 indicates the sensitivity of the assumption used in the calculation of hydropower generation at the ten reservoirs listed in Table 2 for a number of alternative scenarios.

PILOT PLANT AT QUEENSWOOD RESERVOIR

The only civil works that were required at the Queenswood Reservoir (location shown in Figure 3) were the installation of a bypass onto the existing pipeline and the fitting of a turbine, generator and other essential electrical equipment.

As turbines used in small-scale hydropower are fairly difficult to procure, are expensive and have long delivery periods, it was decided for the preliminary investigation to use a pump as a turbine (PAT), i.e. to utilise the pump in reverse.

The pump which was used in the setup as shown in Figure 4 is a Sulzer AZ–100/400 pump. Its best efficiency point (BEP) is at a flow rate of 180 m^3/hour and a 50 m head, with 34 kW power required. It should be noted that, because the pump was operated as a turbine, the inlet of the pump became the outlet and vice versa.

Estimates of characteristic curves for the selected pump operating as a turbine have been provided by Sulzer SA for the purpose of this pilot project. An approximation of

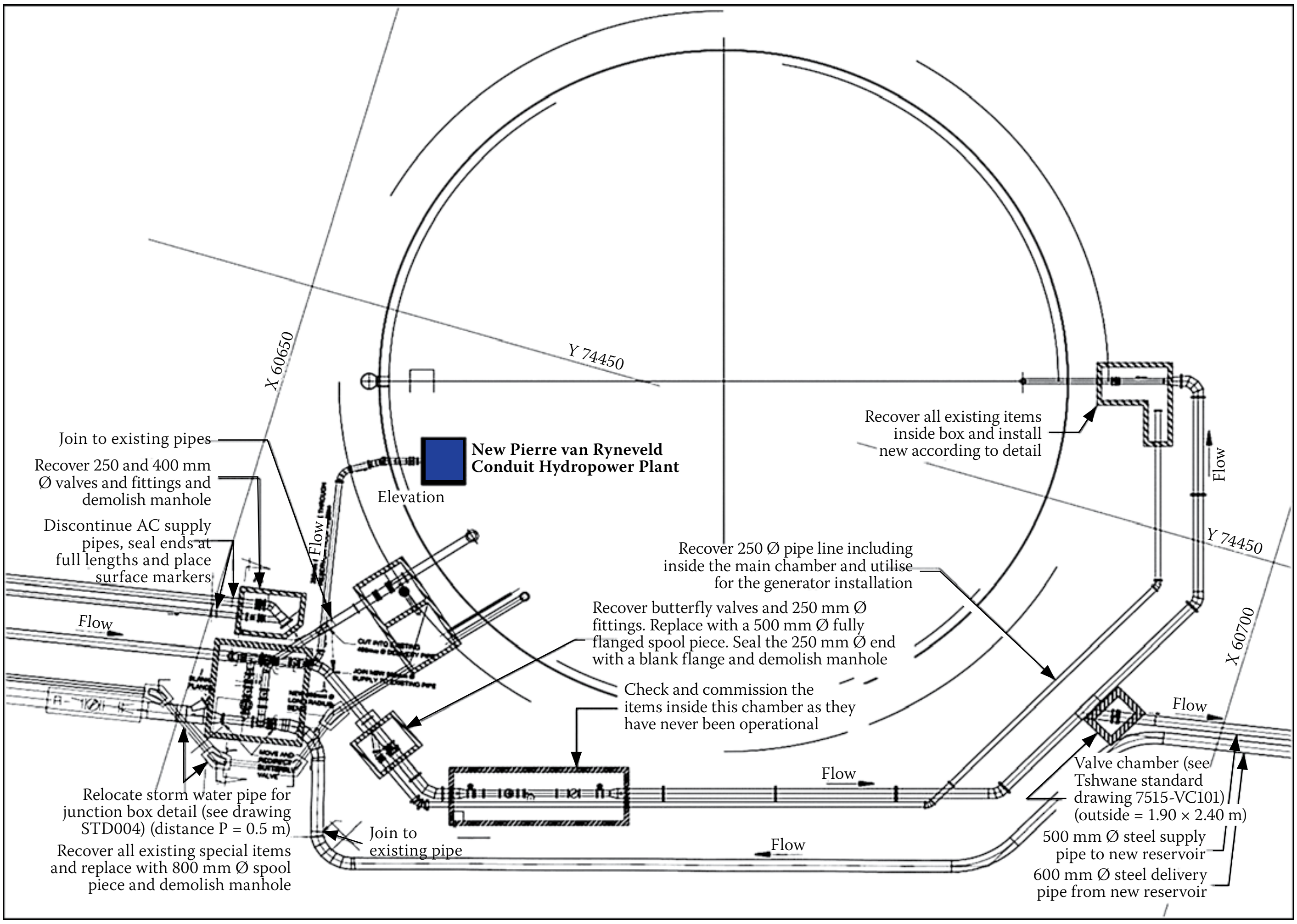


Figure 6 Layout of pipe system at old reservoir

the operational characteristics of a pump, operating as a turbine in comparison to the original BEP (best efficiency point), is that the required flow rate and head would have to be increased by about 30% to obtain similar hydropower.

The turbine (pump) was connected to a motor operating as a generator in order to generate electricity. The motor size required was estimated to be in the order of 25–30 kW. Alstom donated a 37 kW, four-pole induction motor to the University of Pretoria to be used for this research project.

The pump and motor were connected using a flexible coupling; this allowed for certain tolerances regarding vertical, horizontal and rotational misalignment of the shafts of the pump and motor.

In order to determine the power output of the generator, a ballast load was connected directly to the generator, effectively 'throwing away' the electricity generated. A load has to be connected in order to be able to measure the current and the voltage produced so that the power output can be calculated. The ballast load used was six 4 kW geyser elements connected to the generator in pairs (in series) as shown in Figure 5. The geyser elements were placed in a tank with water, therefore consuming the electricity generated.

In the case of a permanent installation, the output of the generator would have to be regulated to ensure that it is at the correct frequency (50 Hz). The generator output is an alternating current (AC), but because of the fluctuations in turbine operating conditions, the output of the generator also fluctuates and a variable frequency and voltage output is produced. For on-site generation the generator would have to be connected to a rectifier which converts the current into direct current (DC), and then connected to an inverter which converts the current back into AC but regulates the frequency to a constant and stable 50 Hz.

Based on the AADD (Average Annual Daily Demand) from Queenswood Reservoir of ± 180 m^3/hr, the potential energy generation can be determined as shown in Table 4.

PILOT PLANT AT PIERRE VAN RYNEVELD RESERVOIR

The Pierre van Ryneveld (PvR) Reservoir is located south of Pretoria, as shown in Figure 3. Although the site is not one of the top ten favourites listed in Table 2, the site was selected due to the construction of a new 15 ML reservoir near the existing reservoir. This provided the opportunity to construct the second conduit-hydropower pilot plant on the existing reservoir in the Country Lane Estate.

The generated power is utilised on-site for lighting, alarm, communication, etc. The home owners association of the Country Lane Estate has also indicated that they would like to utilise the power for street lighting.

In order to identify the generation potential at this site, some basic data needed to be recorded. The variation in flow rate and available head at the site needed to be captured. The basic set-up was to measure and record pressure heads at relevant points along the supply line from the off-take of a Rand Water bulk supply line up to the reservoir.

The outcome of the three extensive field experiments provided confirmation that there is sufficient flow and pressure at the inflow to the Pierre van Ryneveld Reservoir to generate electric power on a pico scale. The results of testing also indicated that small pressure surges occur in the system; this will be used as a benchmark to ensure that the hydropower plant does not become an increased risk for the pipe system.

The pilot plant was constructed on the roof of the old 7.6 Ml reservoir (see Figure 6), utilising a cross-flow turbine and a synchronous generator (Figure 7). The maximum capacity is ± 15 kW of renewable, zero-emissions

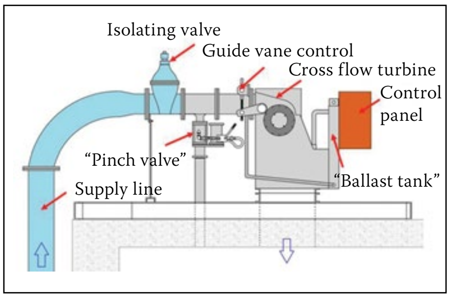


Figure 7 Cross-section of installed turbine

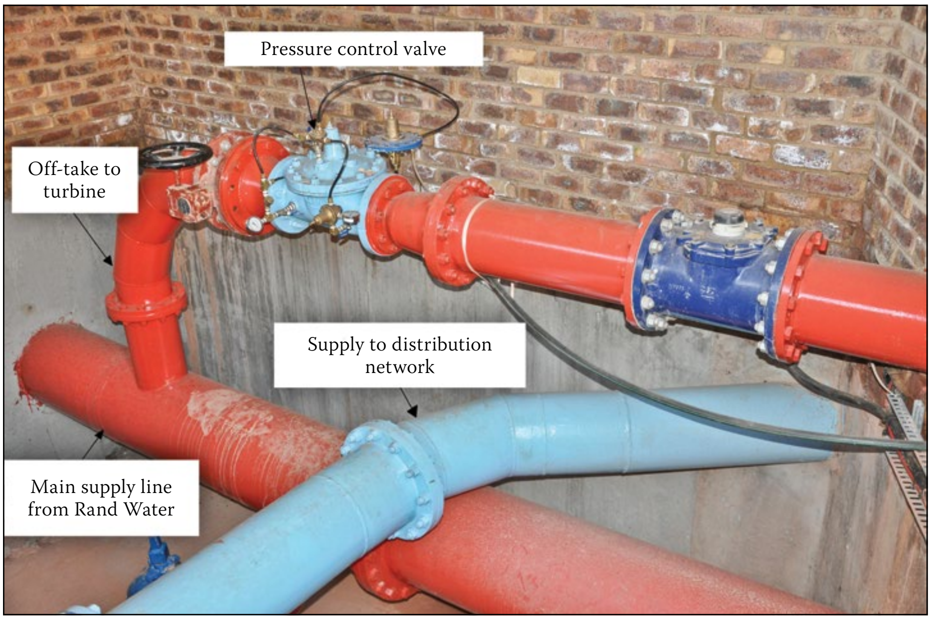


Figure 8 Providing an off-take from the main supply line

Figure 9 Completed installation of turbine, generator and electrical controls

electricity, but depends on the flow and head pressure conditions at any given time.

The off-take from the main supply line to the hydropower plant on the roof of the reservoir is shown in Figure 8, and the completed installation in Figure 9.

On 29 November 2011 the Pierre van Ryneveld Conduit Hydropower Plant was launched jointly by the City of Tshwane, the Water Research Commission and the University of Pretoria, where the City of Tshwane Metropolitan Municipality switched all the site lighting from the conventional municipal grid over onto the hydropower generated on-site.

Some of the problems and challenges faced at this installation, and that are currently being attended to, include:

- Frequency control of the generator
- Sudden load rejection of the system
- Hunting of the PRV due to slow response time
- Significant variability in supply (of flow and pressure head)
- The fact that the system had to be operated and controlled manually.

DEVELOPMENT OF HYDROPOWER SITES IN THE CITY OF TSHWANE

From the potential sites listed in Table 2, five sites were selected for possible development as listed in Table 5.

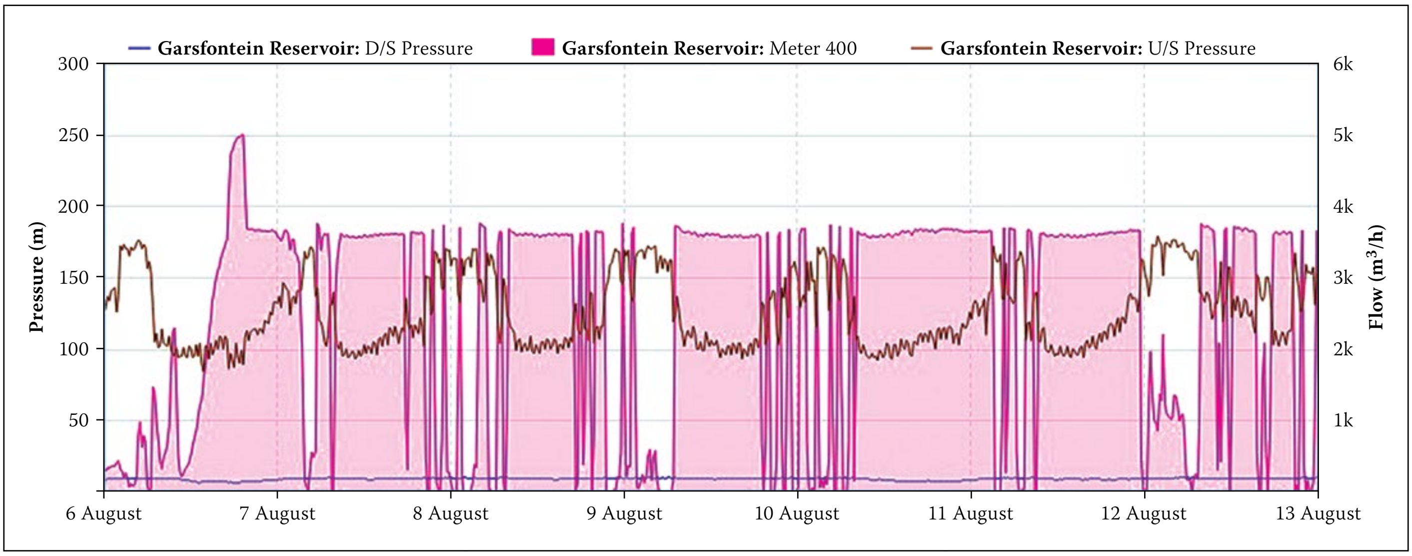


Figure 10 Example of historical pressure head and flow data record

Table 5 Selected sites for hydropower development in the City of Tshwane

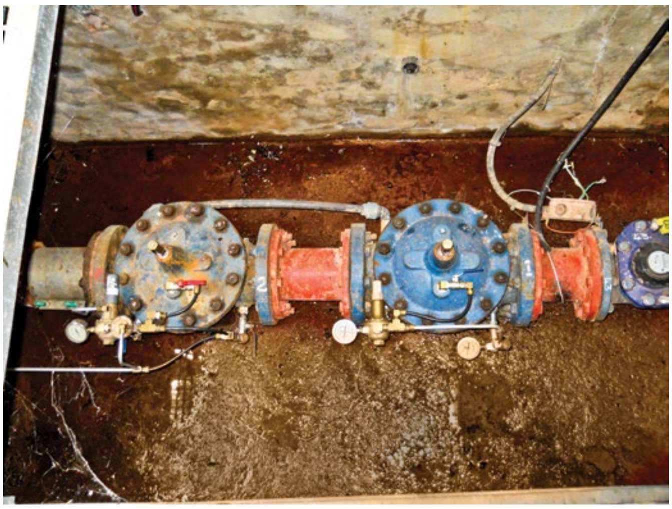
Wonderboom Reservoir
There is one reservoir on this site with a new reservoir being built a few hundred metres northwest of the existing reservoir.

Akasia Reservoir
There is one reservoir on this site. This site is situated just south of the Hartebeeshoek site of Rand Water, which is one of the reservoir sites of Rand Water being considered for hydropower development.

Garsfontein Reservoir
There are three reservoirs on this site.

Heights Reservoir
There are two reservoirs on this site – Low Level (LL) and High Level (HL).

Waverley Reservoir
There is one reservoir on this site.



It is considered that conduit-hydropower is the "low-hanging fruit" in terms of viable renewable energy which could be developed. The City of Tshwane is in the advantageous situation that excess energy is currently being dissipated, and this could be utilised to generate clean sustainable energy instead.

Table 6 Garsfontein Reservoir hydropower potential

Generation potential	Computation method	
	15-minute intervals	Weekly averages
Weekly potential	82 097 kWh	90 880 kWh
Annual potential#	4 257 309 kWh	4 712 825 kWh
Note: # Allowance for two days per year for reservoir maintenance		

As an example, a weeklong pressure and flow data record for the Garsfontein Reservoir (number one on the generation potential list in Table 2, i.e. the City of Tshwane's bulk reservoirs) is depicted in Figure 10. The average pressure upstream of the PRVs is 117.4 m and the average flow is equal to 0.671 m^3/s for this specific week. The required pressure downstream of the PRVs is 8 m. Data at this site has been recorded since April 2011, and the average pressure upstream of the PRVs is 120 m and the average flow is equal to 0.77 m^3/s.

The hydropower potential for this selected week based on a conservative low efficiency of 70% for the turbine/generator set is shown in Table 6. The two computation methods used are:

- 15 minute intervals – flow and pressure readings for every 15 minutes are recorded. The generation potential is calculated for each of these intervals and then totalled. This would require the selection of a turbine which could operate with a high efficiency over a wide flow and pressure range.
- Weekly averages – the average pressure and flow for this week is determined and used to calculate the generation potential. This would require operational changes to the supply and reservoir system to provide a more stable flow and pressure range. This would, however, result in an increase in potential electrical output.

The annual potential is simply an extrapolation of the recorded potential during this week.

A water supply distribution system consists of a complex network of interconnected pipes, service reservoirs and pumps that deliver water from the treatment plant to a consumer. The distribution of water through the supply system is governed by complex, non-linear, non-convex and discontinuous hydraulic equations (Keedwell & Khu 2005). Adding to this complex network, the hydropower plant from which the maximum benefit needs to be extracted requires a systematic procedure to evaluate the interrelationship between: storage volumes, supply/demand patterns, turbine selection, operational flexibility and reliability of supply.

The required turbine based on the average flow (0.77 m^3/s) and corresponding pressure (110 m) is 550 kW, but if a turbine is sought that follows the fluctuating supply patterns, a 950 kW system will be required. The final selection of the correctly sized turbine will depend on multiple factors. This still requires further investigation. Similar calculations were done for the other four sites.

FEASIBILITY OF DEVELOPMENT

South Africa does not have many turbine manufacturers, and thus turbines and generators must usually be imported. There is great disparity (factor of four) between purchase costs of turbines from different manufacturers across the world, with some developing countries supplying turbines at a much lower cost (although the durability of some of these machines could be questionable) (Van Vuuren *et al* 2011). A broad guideline is that a 1 MW hydropower installation would cost between R16.5 and R22 million. This is composed of the cost components as listed in Table 7.

As an alternative to the generally costly micro turbines, pumps-as-turbines (PATs) can be considered. Pumps have the advantages of being more readily available, easy to operate and maintain, and are generally less expensive than micro turbines. Various companies produce purpose-made PATs that can run at efficiencies of as high as 90% (Sanjay & Patel 2014), but in principle the impeller of a centrifugal pump can be turned around to produce a PAT with efficiency of around 30%. The application of PATs has been extensively documented (Sanjay & Patel 2014; Williams 2003).

Typically, all engineering projects will incur on-going revenue costs, maintenance costs and ultimately replacement costs. Therefore the long-term cost must be considered examining the relationship between the value of money and time. Life cycle costing (LCC) includes all costs associated with a system (or component) as applied over the defined life cycle. However, as a first order analysis, the expected payback period of

Table 7 Cost components of a conduit-hydropower scheme

Cost and formula	Description
Initial Planning Cost Initial Planning Cost (IPC) = $C_{investigation} + C_{enviroment\ \&\ social} + C_{legal\ \&\ regulatory}$	The essential components of initial planning costs are related to identification and defining of the costs associated with the initial site investigation, conceptual design, environmental and social impacts, and regulatory compliance investigation costs.
Capital Cost Capital Expenditure Cost (CEC) = $C_{design} + C_{purchase} + C_{installation} + C_{start\text{-}up}$	Every need generated by a society/community can be satisfied by an engineering solution in alternative design. The designer has a task of identifying the most desirable (near to optimal) way in satisfying a specific need that may arise. The alternatives differ normally in the capital cost, but are alike with respect to income, serviceability, general convenience, etc.
Operation and Maintenance Cost Operation and Maintenance Cost (OMC) = $C_{operation} + C_{maintenance} + C_{management} + C_{refurbishment}$	Operation and maintenance costs should be carefully broken down into all aspects, including spare parts, training and wages, and should allow contingencies of 50%. If untried or newly designed/manufactured equipment is used, a full replacement cost should be incorporated.
Retirement/Disposal Cost Disposal Cost (DC) = $C_{disposal} + C_{environmental}$	These costs will arise from the eventual disposal of no repairable items throughout the item's life span. The costs will manifest from the system retirement, material recycling and the logistics of system replacement if required. The disposal value can be negative where environment clean-up may be required.

capital cost could be calculated to provide an indication of feasibility.

The preliminary selected sites were sized, utilising a conservative load factor of 0.8 and a turbine system efficiency of 70%. The preliminary feasibility based on a Megaflex tariff (2013 base year) of 58 c/kwh indicates that all five these sites are feasible, as shown in Table 8. All these sites have a payback period of between six and seven years.

The preliminary feasibility results in Table 8 are based on the sizing of a turbine to operate at the average flow and pressure at the site. If a turbine is sought that follows the fluctuating supply patterns, a larger system will be required, which could increase the costs. The correct sizing and selecting of the turbine can only be done after flow and pressure data have been obtained, and the operating range of the system has been determined.

Table 8 Feasibility of sites

Reservoir site	Estimated average capacity (kW)	Estimated annual generation potential (kwh/a)	Estimated development cost (R)*	Estimated revenue (year 1) (R)##
Wonderboom#	330	2 312 640	7 260 000	902 000
Heights#	380	2 663 040	8 360 000	1 040 000
Akasia#	260	1 822 080	5 720 000	711 000
Waverley#	80	560 640	1 760 000	220 000
Garsfontein	550	3 854 400	12 100 000	1 504 000
Total	1 600	11 212 800	35 200 000	2 873 000

Notes:
* Initial planning, design and capital costs
\# Based on IMQS data (no historical data available)
\## Utilising a conservative load factor of 0.8, turbine system efficiency of 70%, averaged Megaflex tariff of 50 c/kwh and subtracting anticipated O&M costs

CONCLUSIONS

Hydropower represents a nexus of water and energy, and in municipalities and water utilities there are several locations where a feasible conduit-hydropower scheme could be implemented. A technically feasible scheme assists in reducing operating costs, mainly due to energy increases, and provides a sustainable solution whilst having a positive environmental impact. A number of water utilities have started taking the initiative in developing this type of hydropower and it is believed that there is significant potential in South Africa.

There are numerous benefits for developing conduit-hydropower in the City of Tshwane's water distribution network:

- Hydroelectric energy is a continuously renewable energy source.
- Hydroelectric energy technology is proven technology offering reliable and flexible operations.
- Hydroelectric stations have a long life – many existing stations have been in operation for more than half a century and are still operating efficiently (an example of this is in Cape Town).
- Micro hydropower stations achieve high efficiencies. Purpose-made PATs also operate on efficiencies of up to 90% at best efficiency point, but in general PATs achieve efficiencies of around 30%.
- Conduit-hydropower uses the available water distribution infrastructure, and thus, as long as there is a demand for water, hydroelectric energy can be generated.
- The operational life of the existing pressure reducing valves can be extended.
- Conduit-hydropower "piggybacks" onto existing water infrastructure resulting in minimal environmental impact.
- The preliminary feasibility studies indicate short payback periods.
- Conduit-hydropower has the potential of mitigating vandalism of local power sources (e.g. solar panels) at remote reservoirs required for reservoir status monitoring. Depending on the generating potential of the installation, local domestic energy clusters could also benefit.

The feasibility and construction of two pilot plants were also discussed, and it was shown that it is technically possible and feasible to install turbines in pressurised water supply pipes to utilise excess pressure head.

It is considered that conduit-hydropower is the "low-hanging fruit" in terms of viable renewable energy which could be developed. The City of Tshwane is in the advantageous situation that excess energy is currently being dissipated, and this could be utilised to generate clean sustainable energy instead.

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