Leveraging Water Infrastructure Asset Management for Energy Recovery and Leakage Reduction

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Highlights

- The highlight of this research is the novelty found in the exploitation of asset management data from Infrastructure Asset Management Plans and Asset Registers for the development of a hydraulic model to analyse energy recovery and leakage potential within a municipal water distribution system.
- The study presented a novel approach to the exploitation of asset management data from Infrastructure Asset Management Plans and Asset Registers for the development of a hydraulic model to analyse energy recovery and leakage potential within a municipal water distribution system.
- The study showed that adequate information exists within the asset management plans and asset registers of municipal water distribution systems to inform a hydraulic model for the preliminary identification of excess operating pressures within the system. These excess pressures can be converted into electrical energy through the process of energy recovery with hydro turbines, to effectively leverage asset management data for energy recovery.

Abstract

The purpose of this paper is to bridge the gap between the awareness of potential for energy recovery within Municipal Water Distribution Systems and the lack of knowledge of the extent and location of such potential so as to increase the sustainability and resilience of South African cities. This is done by leveraging asset management data, contained within municipal infrastructure asset registers and asset management plans, to identify energy recovery and leakage reduction potential. Data from asset registers and customer profiling within the municipal asset management plans were used to develop a hydraulic model for a municipal water distribution system. The customer service charter within the asset management plans describes the level of service, which was used in evaluating minimum operating pressures within the system. Comparing this to a pressure profile from the hydraulic analysis of the model, identifies excess pressure areas, exploitable for energy recovery. The novelty of this research is the exploitation of asset management data from Infrastructure Asset Management Plans and Asset Registers for the development of a hydraulic model to analyse energy recovery and leakage potential within a municipal water distribution system. Asset management data were used to identify an average annual preliminary energy recovery potential within the Polokwane Central District Metered Area of 2.3GWh, resulting in an average annual leakage reduction potential between 3.3% and 4.2% of potable water, adding to the asset management value chain.

Keywords

Energy Recovery, Leakage Reduction, Asset Management, Municipal Water Infrastructure

Nomenclature

AMP	Asset Management Plan
AMS	Asset Management System
AR	Asset Register
CoP	City of Polokwane
DMA	District Metered Area
MFMA	Municipal Finance Management Act
PFMA	Public Finance management Act
WDS	Water Distribution System

1. Introduction

The feasibility of small-scale hydropower technology as a means of supporting the urban energy sector with a particular focus on utilizing conduit hydropower applied in Water Supply Infrastructure was investigated and it was demonstrated to be a viable renewable energy to develop in South Africa (Loots et al., 2014; Van Dijk et al., 2017).

In a water distribution system, the pressure is generally managed and controlled by means of Pressure Reducing Valves (PRVs), dissipating energy in order to control the maximum admissible pressure in the system and to avoid rupture (Ramos, et al., 2010; Van Dijk et al., 2018). The hydraulic grade line principle associated with a PRV is similar to that of a turbine. In both cases, a pressure drop across the component allows downstream pressure control (Ramos, et al., 2010). The potential of energy recovery by means of conduit hydropower plants in water supply and distribution systems have been investigated by numerous researchers (Table 1) and there are already successful installations in many countries such as Switzerland, the Czech Republic, Spain, Hong Kong, Ireland, South Africa and the USA (Perez-Sanchez, et al., 2017; Güttinger, 2012; Gono, et al., 2012; Van Dijk, et al., 2015) . Table 2 shows examples of installed energy recovery installations in water supply and distribution systems, including turbine used, capacity and annual energy recovery potential.

Table 1 - Examples of energy recovery potential in water supply systems

LOCATION	ANNUAL POTENTIAL	REFERENCE
City of Tshwane, South Africa	10 GWh	(Loots, et al., 2014)
Dublin, Ireland	1.75 GWh	(McNabola, et al., 2014a)
Pompei, Italy	94 MWh	(Samora, et al., 2016)
Portugal	2.28 GWh	(McNabola, et al., 2014b)
New Jersey, USA	254 MWh	(Telci and Aral, 2018)

Table 2 - Examples of installed energy recovery installations in water supply and distribution systems

LOCATION	TURBINE	ENERGY RECOVERY		REFERENCE
		CAPACITY	ANNUAL POTENTIAL	
Portland, Oregon	Micro	30 kW	150 MWh	(Samora, et al., 2016)
La Zour, Switzerland	Pelton	465 kW	1.8 GWh	(ESHA, 2009)
Muhlau, Austria	Pelton	5.75 MW	34 GWh	(ESHA, 2009)
Wainuiomata, NZ	Turgo	318 kW	2.78 GWh	(Gilkes, 2016)
Bloemfontein, South Africa	Crossflow	96 kW	0.84 GWh	(Van Dijk, et al., 2015)

The exploitation of this potential will contribute to the city’s sustainability not only in terms of renewable energy recovery but also in terms of leakages reduction. Mckenzie and Wegelin (2009) has conducted extensive research into the reduction of leakages in Water Supply Infrastructure through pressure management. Since an increase in operating pressure increases water losses through leakages in a system (Gaius-obaseki, 2010), due to the direct proportionality of leakage to pressure (Gupta, et al., 2016), a reduction in pressure through conduit hydropower or energy recovery will reduce water losses through leakages similar to the effect of pressure management through pressure reducing valves. Giugni et al. (2009) also emphasized the leakage problem caused by excess pressures and showed similar reduction in leakage when replacing conventional PRVs with microturbines or pumps-as-turbines (PAT).

Service delivery in South African municipalities has been plagued by two major events over the past decade. Firstly, from 2008 the total electricity demand within the country started encroaching on the supply capacity (South African Government, 2015), starting a series of rolling blackouts or load-shedding (Bonthuys, et al., 2016). Secondly, since 2016/17 severe droughts have plagued the Kwa-Zulu Natal and Western Cape regions following poor rainfall during the 2014 to 2017 rainy seasons. These events adversely affected service delivery with regards to electricity and water supply both locally and nationally and sparked various studies on both alternative energy and leakage detection and reduction methods.

Within the South African municipal context, there are several statutory requirements regulating the responsibility of municipal institutions to manage the assets and liabilities of the municipality in order to maintain sufficient and sustainable service delivery. Regulatory initiatives relating to asset management in South African are driven largely by National Treasury and to a lesser extent by the Department of Cooperative Governance and Traditional Affairs and the Department of Water and Sanitation (Boshoff, 2009).

In 1999 the South African Government passed one of the first and most important pieces of legislation by the first democratic government in South Africa, i.e. the Public Finance Management Act (PFMA). The act promotes good financial management to maximise service delivery through the effective and efficient use of limited resources (National Treasury, 2018). Another important act to consider in the South African context is the Municipal Finance Management Act (MFMA) (Act No. 56 of 2003), which is similar to the PFMA with the exception that it encompasses the responsibilities relating to the management of municipal assets within local government. Both the PFMA and the MFMA requires every municipality to maintain a management, accounting and information system. These systems account for assets and liabilities of the municipality and essentially becomes the municipal asset management system (AMS).

Several other acts have different regulatory requirements for South African municipalities. Specifically focussing on water supply infrastructure, the most important is certainly the Water Services Act requiring every municipality to have an Asset Management Plan (AMP), structured into three categories: technical assessment, financial assessment and asset management practices (Bonthuys, et al., 2018) (Table 3).

Table 3 - Main structure of an Asset Management Plan

Asset management Plan		
Technical assessment	1.Asset register	i. Asset register
	2.Condition Assessment	ii. Condition Assessment
		iii. Remaining Useful Life
Financial assessment	3.Current & future needs	iv. Levels of service & demand
	4.Costing analysis	v. Valuation & Life cycle cost
		vi. Business risk exposure
Asset management practices	5.Operational plan	vii. Operation & Maintenance plans
		viii. Capital investment validation
	6.Maintenance plan	ix. Future expenditure model & Funding
		x. AMP to suit budget

Central to the AMP is a database (Asset Register) that contains all the relevant data or attributes of all infrastructure assets owned by the municipality within different asset classes, e.g. Water Supply Infrastructure. According to Boshoff and Pretorius (2010), modern-day componentised Asset Registers (AR) not only satisfies accounting requirements but provide data on the physical characteristics and capacity, failure mode status, criticality rating and remaining useful life of assets. As an example, the Asset register of the Water supply system of the City of Polokwane (South Africa), consists out of approximately 32500 components (pipes, reservoirs, valves, etc.) described across approximately 140 data columns.

Energy recovery, and its subsequent benefits of leakage reduction, has the potential to lighten the impact of both the energy and water crises in South Africa. Considering the global drive towards greater sustainability and more self-sufficient systems (Van Dijk et al., 2018), energy recovery could improve service delivery whilst increasing the sustainability of municipal infrastructure, but there exists a lack of knowledge as to the extent as well as the location of this potential (Bonthuys et al., 2018). This paper demonstrates how a water infrastructure Asset Register can be leveraged to overcome this lack of knowledge and to identify this hidden potential for energy recovery and leakage reduction within a municipal environment in order to potentially increase the sustainability and resilience of cities.

2. Material and Methods

All water distribution systems (WDS) have limits for operating pressure fixed based on leakage control and consumers satisfaction. Leakage is directly proportional to pressure in a system (Gupta, et al., 2016) and therefore the higher the operating pressure in a system, the higher the leakage would be (Gaius-obaseki, 2010). In addition, too low pressures influence the flow rate at consumers and may cause unsatisfactory levels of service (McNabola, et al., 2011). For guaranteeing proper service levels of WDS, in 2005, the South African Council for Scientific and Industrial Research reprinted and published the Guidelines for Human Settlement Planning and Design, indicating limits for residual pressures (Table 4) in South African municipalities (CSIR, 2005).

Table 4 - Guidelines for residual pressure in South Africa (CSIR, 2005)

TYPES OF DEVELOPMENT: DWELLING HOUSES	**MINIMUM HEAD UNDER INSTANTANEOUS PEAK DEMAND (m)**	**MAXIMUM HEAD UNDER ZERO FLOW CONDITIONS (m)**
House connections	24	90
Yard taps + yard tanks	10	90

Any pressure over and above the minimum operating pressure of a specific system is potentially excess pressure which can be converted into energy through energy recovery that can be preliminarily calculated by:

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

where P = power output (watt), ρ = density of fluid (kg/m^3), g = gravitational acceleration (m/s^2), Q = flow rate (m^3/s), H = head (m) and η = turbine system efficiency.

Leakage reduction through pressure management is a well-established method to control water losses in water supply and distribution systems (Table 5).

Table 5 - Leakage reduction through pressure management - examples

COUNTRY	AREA	LEAKAGE REDUCTION	REFERENCE
South Africa	Khayelitsha	40 %	(McKenzie, 2014)
Bulgaria	Burgas	20 %	(Dimitrov, et al., 2011)
Macedonia	Skopje	33 %	(Ristovski, 2011)
Zimbabwe	Mutare	25 %	(Marunga, et al., 2006)
USA	Pittsburgh	27 %	(Levine, et al., 2005)

Energy recovery as a form of pressure management in water supply and distribution systems is rapidly gaining popularity and several water authorities worldwide have realized the potential of and implemented energy recovery or conduit hydropower (Santolin et al., 2017). The added value of leakage reduction through energy recovery is still a fairly new idea with the concept of leveraging asset management data to identify the potential for both, being completely novel.

2.1 Leakage Model

To evaluate the efficiency of a WDS, the most detailed performance indicator for non-revenue water and real operational losses, suggested by the International Water Association and the

American Water Works Association, is the Infrastructure Leakage Index (ILI), which is the dimensionless ratio between the current annual real losses (CARL) and the unavoidable annual real losses (UARL) within a system:

$$UARL = (18L_m + 0.8N_c + 25L_P) \times P \tag{2}$$

where L_m = mains length (km); N_c = number of service connections; L_p = the total length of underground pipe between the edge of the street and customer meters (km); P = average operating pressure (m).

As regards the leakage model, following observations made by May (1994), it was postulated that leakage can be represented by a two-part equation. The first part representing flows from leakage paths which do not change with a change in pressure (Fixed Area, i.e. major bursts or substantive unaccounted for large users), and the second part representing flows from an expanding area (Variable Area, no major leaks). This led to the development of the well-known and widely accepted equation for the relationship between leakage and pressure, i.e. the Fixed and Variable Area Discharge (FAVAD):

$$Q = C_d\sqrt{2g}(A_0h^{0.5} + mh^{1.5}) \tag{3}$$

where Q = leakage rate (m^3/s); C_d = discharge coefficient; g = gravitational acceleration (m/s^2); A_0 = initial leak opening without any pressure in the pipe (m^2); h = pressure head (m); m = slope of the pressure area line (m).

The potential leakage reduction achievable with pressure management within the WDS can be estimated by comparing the CARL to leakage calculated with the FAVAD equation, utilizing the flow and head available from the hydraulic model after energy recovery. This method can only be used where the parameters of the FAVAD equation can be calibrated using measured data from the system. Alternatively, in a WDS where leakage is assumed to be governed by variable area leaks, the percentage reduction in the CARL of a system can be calculated from the percentage reduction in the operating pressure of the WDS. Thirdly, the calculated UARL using pressure before and after energy recovery can be compared to indicate potential leakage reduction.

2.2 Leveraging asset management data

Water infrastructure asset management data contained within both the AMP and AR of a municipality can be leveraged to identify the hidden potential for energy recovery and leakage reduction within a municipal environment. The process of identifying the energy recovery and leakage reduction potential from the asset management data is simplified in Figure-1.

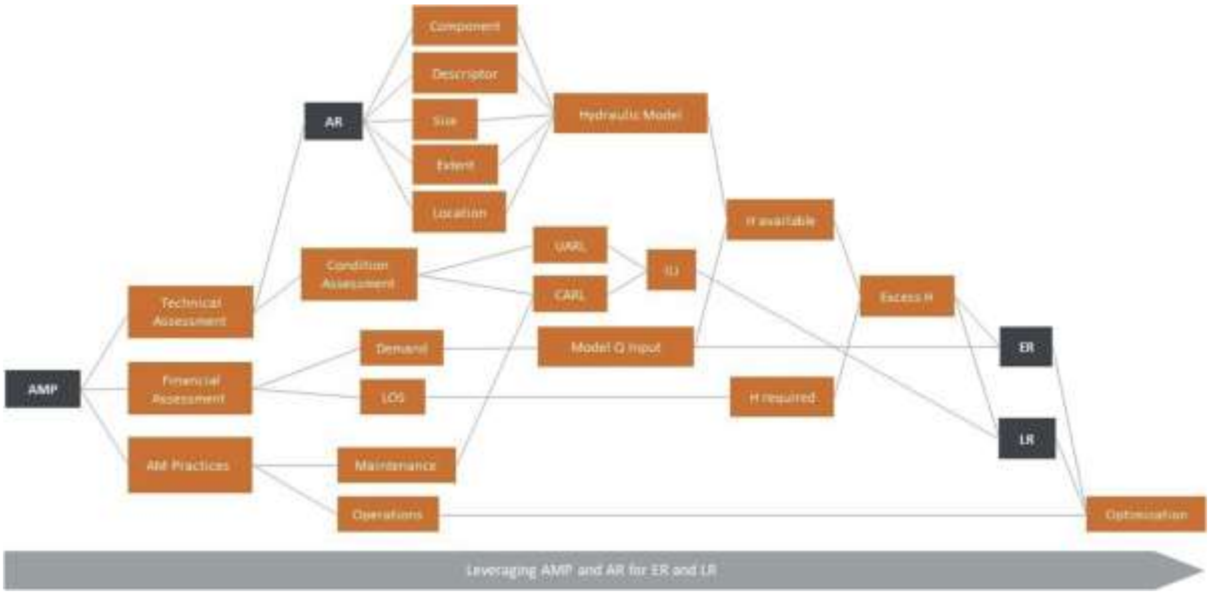

Figure-1 - Energy recovery and leakage reduction potential from water supply infrastructure asset management data (Bonthuys, et al., 2018)

The AR database, which forms part of the technical assessment of the AMP, contains data which can be used within a hydraulic model of the WDS to analyse (Figure-2). The hydraulic model can then be used to perform a preliminary calculation to estimate the excess pressure in the water distribution system available for energy recovery and leakage reduction.

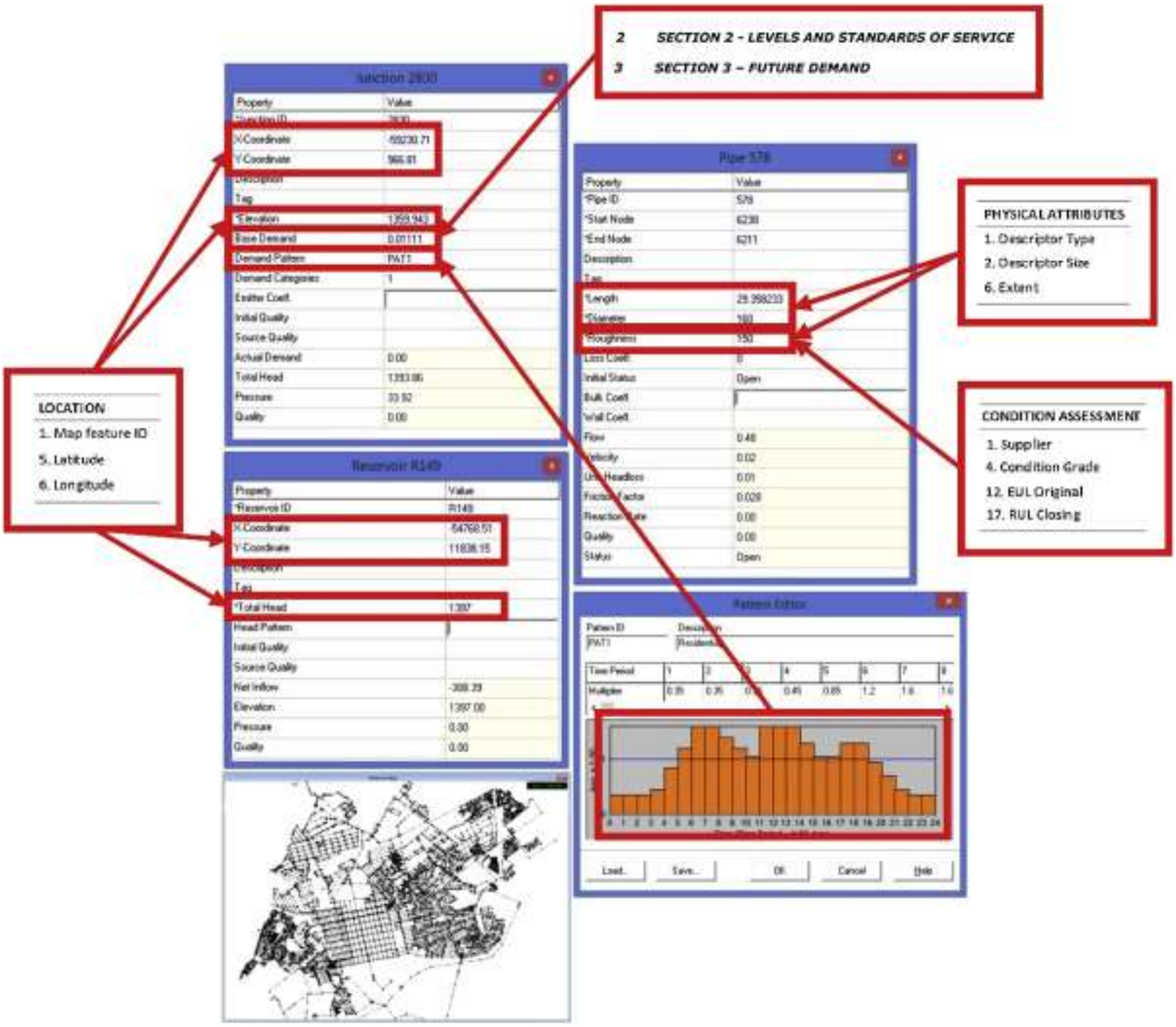

Figure-2 - Populating the EPANET hydraulic model from the AMP and AR

2.3 Hydraulic Model of the City of Polokwane (South Africa)

For the purpose of this paper, the AMP of the City of Polokwane (South Africa), along with the corresponding AR (developed to comply with regulatory requirements in South Africa) was used to apply the proposed methodology and analyse findings.

The City of Polokwane (CoP) is a local municipality within the Limpopo Province in South Africa. The CoP municipal surface area covers over 5000 square kilometres and serves around 280 000 customer units, inclusive of residential and non-residential customers. The water asset portfolio comprises approximately 6 000 km of pipelines and around 1 000 facilities such as dams, water treatment works, reservoirs and pump stations that are configured into 14 regional water schemes managed in seven operational clusters. Within the Polokwane Local Municipality, a section of the Polokwane/Seshego regional segment was isolated as a District Metered Area (DMA) and used for the hydraulic model.

The EPANET hydraulic modelling software was used for the development and analysis of the hydraulic model of the Polokwane Central DMA. There are two predominant modelling techniques for WDS. The classical demand-driven modelling (DDM) approach, as used by EPANET, was first presented by Cross (1936). Wagner et al. (1988) first presented the hypothesis that outflow at demand nodes is not a fixed but rather a pressure-dependent boundary condition leading to the school of thought on pressure-driven modelling (PDM). Several authors followed by developing pressure-outflow relationships. Piller and Van Zyl (2007) in turn presented a mathematical formulation of the pressure-driven model that uses a modified mass-balance constraint at consumptive nodes to allow reduced demands in case the pressure is insufficient (Braun, et al., 2017).

Both schools of thought still have limitations and may in certain instances produce deficient networks where the model presents a unique solution, but it is physically incorrect. Due to the pressure-dependent nature of leakage or pipe rupture, demand-driven modelling is not able to adequately handle such a problem and leads to a deficient network solution. In contrast, a pressure-driven demand model is suitable to solve leakage and water loss problems in the PDM framework. Both current demand and pressure-driven models does not consider low, zero or negative pressure zones (Braun, et al., 2017).

In the case of zero or negative pressure, EPANET produces a warning that pressure is below zero in the network, but the hydraulic connection remains intact and the consumptive node is supplied with the specified demand resulting in a deficient network (Braun, et al., 2017). Within the PDM framework a simple solution to this problem is to iteratively analyse the pressure at every node and delete all links connected to deficient nodes. Piller and Van Zyl (2009) proposed an approach were an additional constraint is introduced to the PDM that reduces flow in deficient pipes to zero (Braun, et al., 2017).

This research does not model the actual leakage from the system but only models the flow associated with the demand on the system, the pressure profile of the system and the excess pressure available. Excess pressure is recovered using the proposed algorithm by Samora et al. (2016). Within the algorithm any potential energy recovery location which causes a pressure drop below zero at any node or below the defined minimum operating pressure at any consumptive node is rejected, causing no negative of low-pressure zones which cannot be modelled adequately by a demand-driven model such as EPANET. With this constraint on the algorithm EPANET remains a suitable model for the preliminary identification of energy recovery potential using the algorithm proposed by Samora et al. (2016).

It is important to note that some assumptions were made in the calculation of the excess pressure. Reservoir levels were assumed at full supply level for the duration of the analysis; existing pressure reducing stations were omitted from the analysis in order to obtain the full energy recovery potential; only nodes classified as consumptive nodes were held to the minimum operating pressure requirements and several links to adjacent parts of greater Polokwane/Seshego regional segment were modelled as closed to obtain the isolated District Metered Area (DMA). Lastly, roughness coefficients were estimated from supplier information and condition and age of the infrastructure as extracted from the condition assessment data of the asset management plan.

There are 3 basic categories which contains the minimum information required to develop a hydraulic model for energy recovery: spatial information, physical attributes (hydraulics) and the demand on the system.

Spatial data for the Polokwane DMA is contained in the AR as point and linear data (Figure-2). Point data for all the reservoirs, valves, PRV's, meters and service connections and linear data for the pipe network. For the purposes of the study the PRV's were negated in order to estimate the total energy recovery potential inclusive of existing energy dissipation. The spatial data for the DMA is obtained from as-built data and verified during the condition assessment and asset verification phase of the AR and AMP development. The spatial data contains unique map feature IDs for each individually recognized component or segment (linear). The map feature IDs are linked to GIS coordinates for the point data and for the start and end points of each linear pipe segment. These GIS coordinates were converted to XY configuration and used as the node input into EPANET to form the basis of the model. The nodes are subsequently connected to represent the WDS which forms the skeleton of the hydraulic model. The City of Polokwane has GIS linked to their AR from which the extent of the linear pipe segments can be obtained. Alternatively, the extent of the pipe network can be extracted from the physical attributes.

The physical attributes of the point and linear components inform the hydraulics of the system (Figure-2). These attributes are obtained from as-built data and verified during the condition assessment and asset verification phase of the AR and AMP development, and include extent, size, material, supplier, condition, estimated useful life (EUL) and remaining useful life (RUL). The critical attributes for the linear components are extend (length), internal diameter and roughness, whereas the critical attribute for the point components such as the reservoirs is the total head available.

The extent of the pipe network (linear components) for the model was either sourced directly from the AR for the individual map feature IDs or extracted from the GIS database. For the internal diameter of the pipe, the pipe diameter data in the AR is cross referenced with supplier information, also contained in the AR, and pipe class to obtain the wall thickness and calculate the internal diameter of the pipe. The supplier information is also used to establish the roughness coefficient of the new pipe equivalent of every individually recognized pipe segment. From the EUL and RUL of the pipe segments within the AR, the hydraulic age of the pipe can be calculated in order to estimate the current roughness coefficient from developed pipe deterioration and roughness curves for the specific pipe material. EPANET uses the roughness coefficients to calculate the friction losses of the system. Secondary losses were omitted from the model for the purposes of the study as these would in most cases be small compared to the friction losses.

For the reservoirs, the total available head is calculated as sum of the Natural Ground Level (NGL), obtained by geo-referencing the GIS location of the reservoir to obtain the elevation (through either specialized GIS software or Google Earth), and of the full supply level of the reservoir, evaluated as the reservoir height obtained from the AR minus an assumed freeboard value. Alternatively, and conservatively you could assess the system using solely the NGL as the total available head.

These physical attributes govern the hydraulics of the spatially referenced and modelled components of the system and determines how the model will react to the demand placed on it. Table 6 provides a summary of the main components of the hydraulic model used in the analysis of the Polokwane Central DMA.

Table 6 - Hydraulic model component summary - Polokwane Central DMA

COMPONENT	UNIT	QUANTITY
Nodes	No.	6 225
Pipes	No.	7 133
Pipes	km	592
Pump Stations	No.	2
Reservoirs	No.	13

The demand on the system can be either calculated from measured flow data within the system or by modelling the demand from the end users in the system. Modelling the end user demand can be done by either analysing historic municipal services accounts for each end user in the system or by modelling users per classification. The end user average annual daily demand (AADD) for the study was done by classifying the end users (service connections) per land-use, size and level of service as contained in the customer profile and levels of service sections of the Polokwane Local Municipality Water and Sanitation AMP and aligning this classification to the classification of water demand for developed areas in South African municipalities as per the Guidelines for Human Settlement Planning and Design in South African municipalities (CSIR, 2005). Standard demand patterns for the applicable levels of service were used for the extended period simulation of the model (Figure - 3). The extended period simulation was done for 24 hours using the demand patterns for residential and industrial water users in Polokwane as shown in Figure - 3. The demand pattern in Figure-3 was multiplied with the AADD of each consumptive node as classified and calculated. A graphical representation of the developed EPANET model to evaluate the excess pressure within the Polokwane DMA for energy recovery is shown in Figure-4.

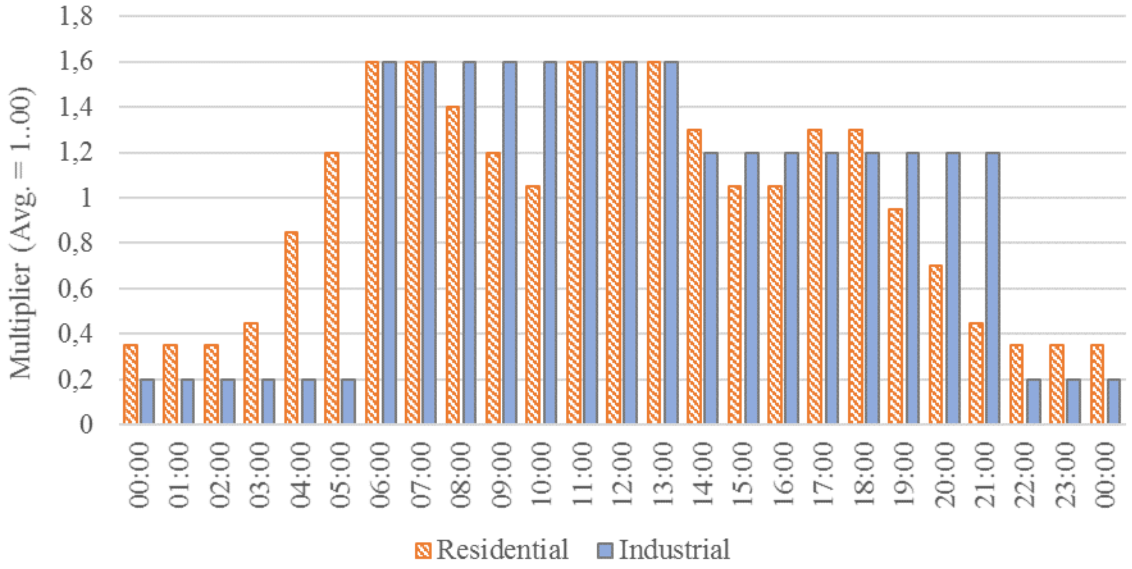

Figure - 3 - Demand pattern for the extended period simulation

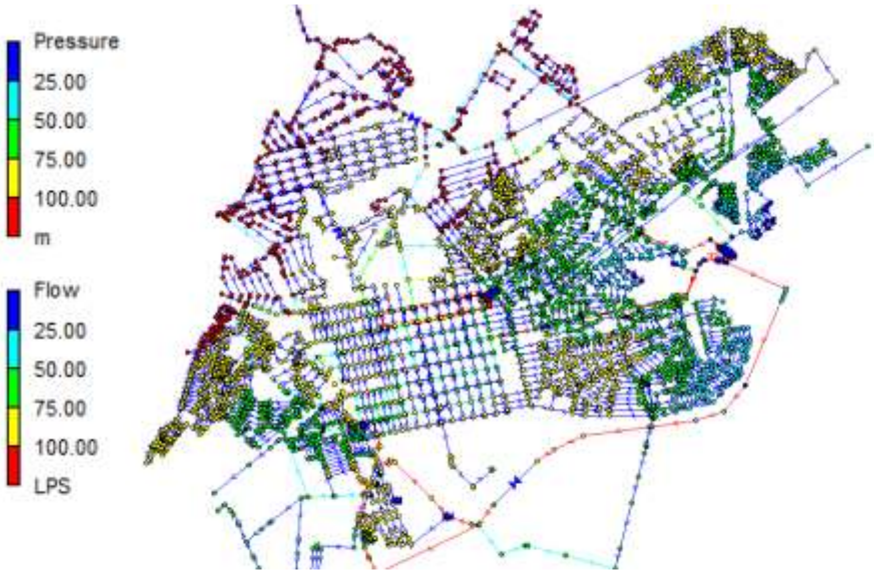

Figure-4 – Polokwane DMA – EPANET model

The excess pressure within the WDS will differ at any given point in time due to the varying nature of the demand on the system (Figure - 3). The minimum potential for energy recovery will occur at the lowest combination of excess pressure and operation flow, as evident from eq. 1. However, the minimum potential for leakage reduction will occur at the lowest excess pressure within the system. Therefore, the time step with the lowest accumulative excess pressure within extended period EPANET model simulation of the Polokwane DMA was taken as the steady state to base energy recovery and leakage reduction potential on. For the extended period simulation of the research the time step is defined as the time from each specific demand until the time a new demand period begins. According to Samora et al. (2016) considering the steady state condition with the minimum head is an effective way to immediately estimate available energy within a WDS. Samora et al. (2016) also developed an algorithm to calculate the cumulative excess energy within a WDS which is discussed in Section 3.2.

2.4 Energy recovery optimizing algorithm

Samora et al. (2016) defines critical points within a WDS were the available energy is not allowed to drop under a predetermined value such as the values defined by the CSIR (2005) in Table 4, for South African municipal WDS. Nodes within the WDS that does not have to adhere to said restrictions are defined as non-consumptive nodes and only have the requirement of positive pressure to avoid cavitation (Samora et al., 2016). As can be seen from Figure-5, the energy recovery potential algorithm sorts all the nodes (excluding non-consumptive nodes) from highest to lowest available head using the pressure data obtained from the hydraulic model. Since energy recovery depends on head available and flow rate, flow rate from the hydraulic model along with the available head is used to estimate potential energy recovery at specific points, and the algorithm again ranks these values from high to low. A head loss equal to the potential energy recovery is applied at the point with the highest potential energy. This changes the energetic equilibrium in the WDS, and the hydraulic model is run again to obtain a new pressure state at all the nodes. If the minimum operating pressure is obtained at every consumptive node the potential energy recovery is added to the total potential energy recovery within the WDS, otherwise the point with the second largest potential is investigated and the algorithm is run again (Samora et al., 2016).

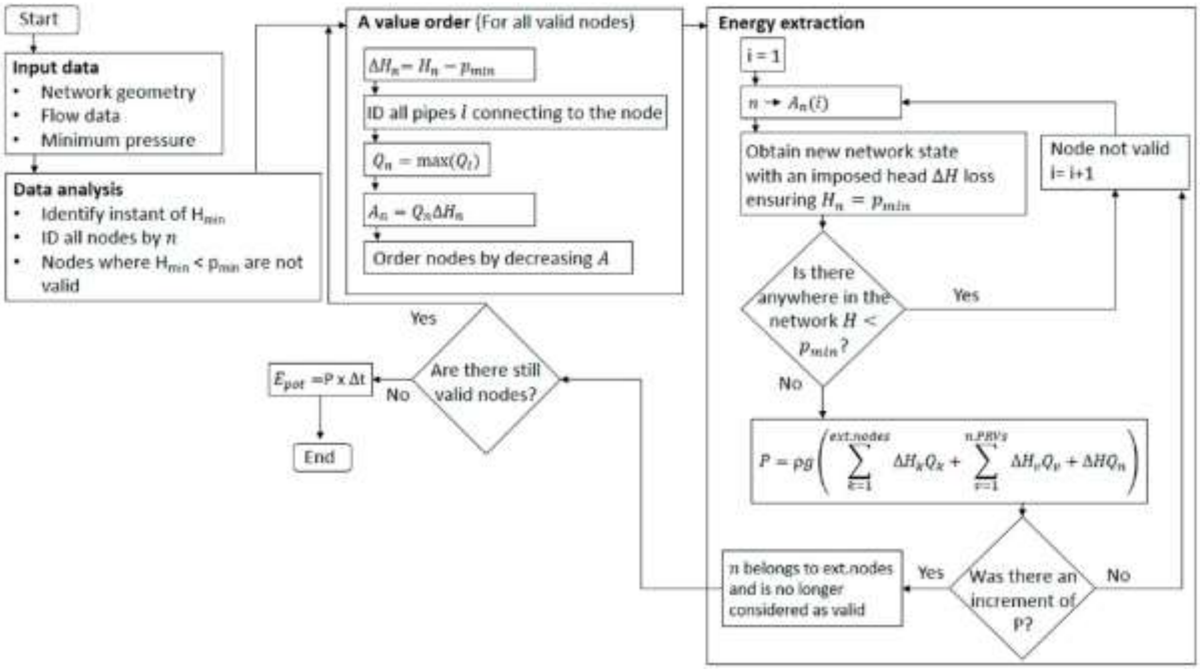

Figure-5 - Energy recovery potential algorithm (Samora et al., 2016)

The algorithm from Samora et al. (2016) was adapted and used to evaluate the energy recovery potential within the Polokwane DMA. There are numerous optimisation procedures utilized in the operational optimisation of water distribution systems as described in Mala-Jetmarova, Sultanova and Savic (2017). For the purposes of this paper a simple linear approach along with the energy recovery algortihm as adapted from Samora et al. (2016) was used to illustrate the concept, and it is proposed in following research to use an evolutionary algorithm, such as a genetic algorithm or particle swarm, to optimize energy recovery for both electiricity generation and leakage reduction The results as per the energy recovery potential algortihm are discussed in Section 4. Subsequently the energy recovered from the system was used to estimate the leakage reduction potential in the system.

2.5 Leakage reduction potential

The excess pressure identified during the energy recovery potential calculation, informed by the asset management data contained in both the AMP and AR of a municipal water distribution system, was used as the input to the leakage reduction potential calculation. As described in

Section 2.1 both the FAVAD and the UARL (eqs. 2-3) equations can be used in calculating the leakage reduction potential for the Polokwane DMA:

- From the UARL: since the unavoidable losses (UARL) forms part of the current real losses (CARL) of the system, a reduction in the UARL, achieved by a reduction in the system average pressure P (eq. 2) through energy recovery, will also cause a reduction in the CARL of the system. So, the reduction in the CARL can be determined by comparing the UARL calculated before and after energy recovery.
- from the FAVAD equation: May (1994) demonstrated that if leakage in a system is predominantly governed by variable area leaks (i.e. minimal large leakages or bursts), the initial leak opening term of the FAVAD equation tends to be negligibly small and the equation becomes governed solely by the variable pressure area line term. At this condition, the percentage reduction in the CARL of a system can be calculated from the percentage reduction in the operating system pressure of the WDS through the variable area term of the FAVAD equation, i.e. a 10% reduction in the average operating system pressure will have a 14% leakage reduction in a WDS where no major leaks or illegal connections are present.

The leakage reduction potential for the Polokwane DMA was calculated adopting both the above-mentioned methods.

3. Results and discussion

The methodology outlined above for determining energy recovery potential, leveraging Asset Management data (contained in the AMP), showed that the average operating pressure within the Polokwane Central DMA can be decreased from 74.5m to 64.7m (during the time step with the lowest accumulative excess pressure), after only 10 iterations of the energy recovery algorithm. At this average operating pressure all consumptive nodes have residual pressures within the specified municipal limits (Table 4). The total AADD for all consumptive nodes in the model amounts to 35 ML/day.

Figure-7 shows the operating pressures within the Polokwane Central DMA through 9 iterations. The decreased average operating pressure was achieved by energy recovery at the 10 locations with the highest conduit hydropower potential as per the methodology. The ten locations are highlighted in Figure-8, and have a combined energy recovery potential of 264kW after 10 iterations. The energy recovery potential for the Polokwane Central DMA was calculated assuming a turbine system efficiency of 70%. The energy recovery method proposed is to install a pump-as-turbine (PAT) to minimize capital cost and maintenance and operations in the local South African market. PAT is a widely recognized choice for conduit hydropower or energy recovery method (Kramer, et al., 2018) (Venturini, et al., 2017). The Water Division of the Department of Civil Engineering of the University of Pretoria also installed a PAT at the Queenswood Reservoir in the City of Tshwane as part of a pilot conduit hydropower plant (Loots, et al., 2014). This plant has the potential to recover 960 kWh of energy per day. Rossi et al. (2016) tested the used of PAT in the water distribution system of the City of Merano, Italy. The installation had an annual energy recovery of 338 kWh at 76% efficiency of the PAT. Lima et al. (2017) found that at maximum flow conditions in a system the energy recovered by a PAT high and the reduction in leakage comparable to conventional PRVs. At low flow conditions however, there is no energy production and the headloss through the PAT is insignificant.

Figure-6 – PAT installation – Queenswood Reservoir – City of Tshwane, South Africa (Loots et al., 2014)

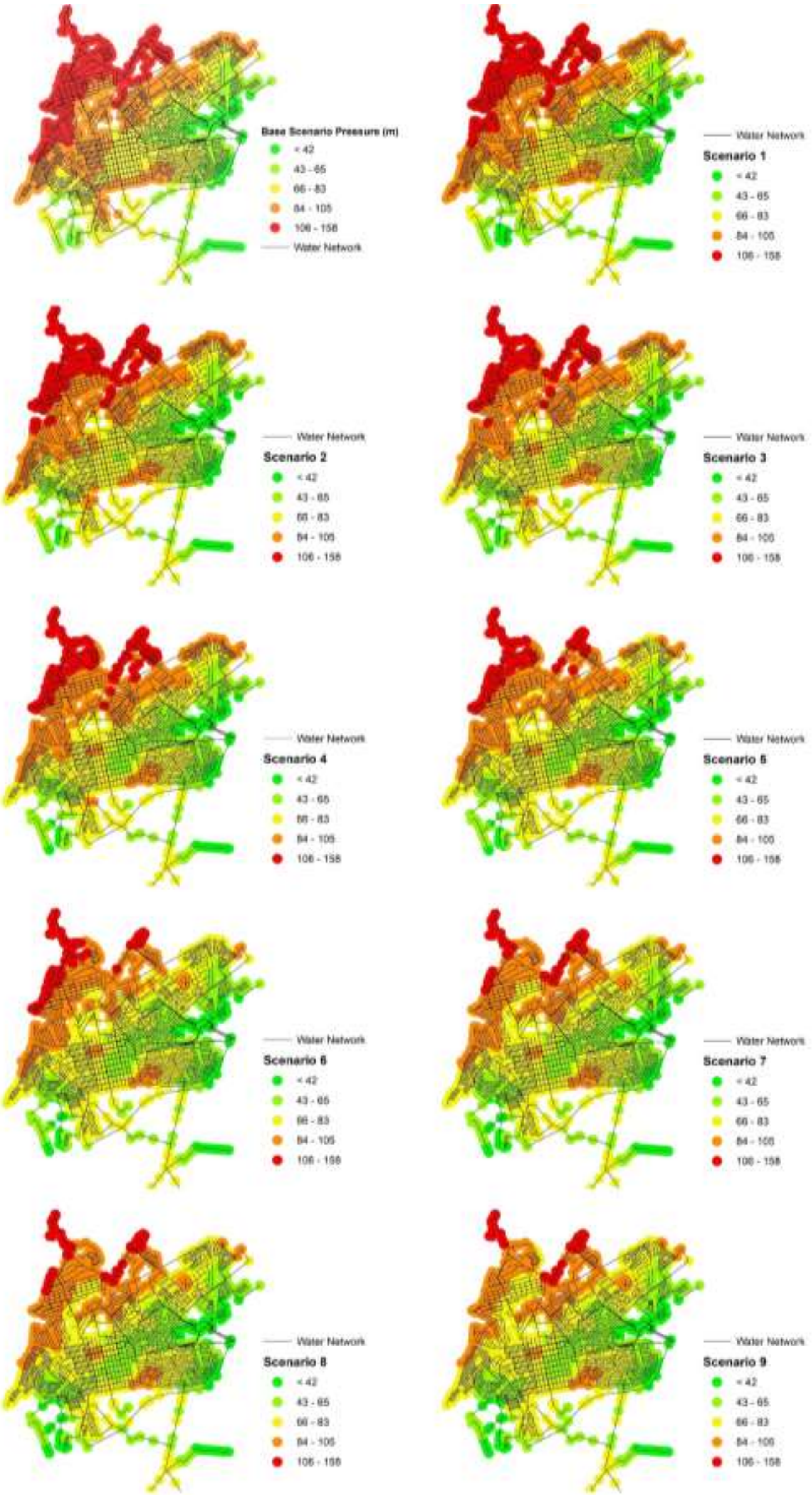

Figure-7 - Polokwane Central DMA operating pressure distribution (9 Iterations)

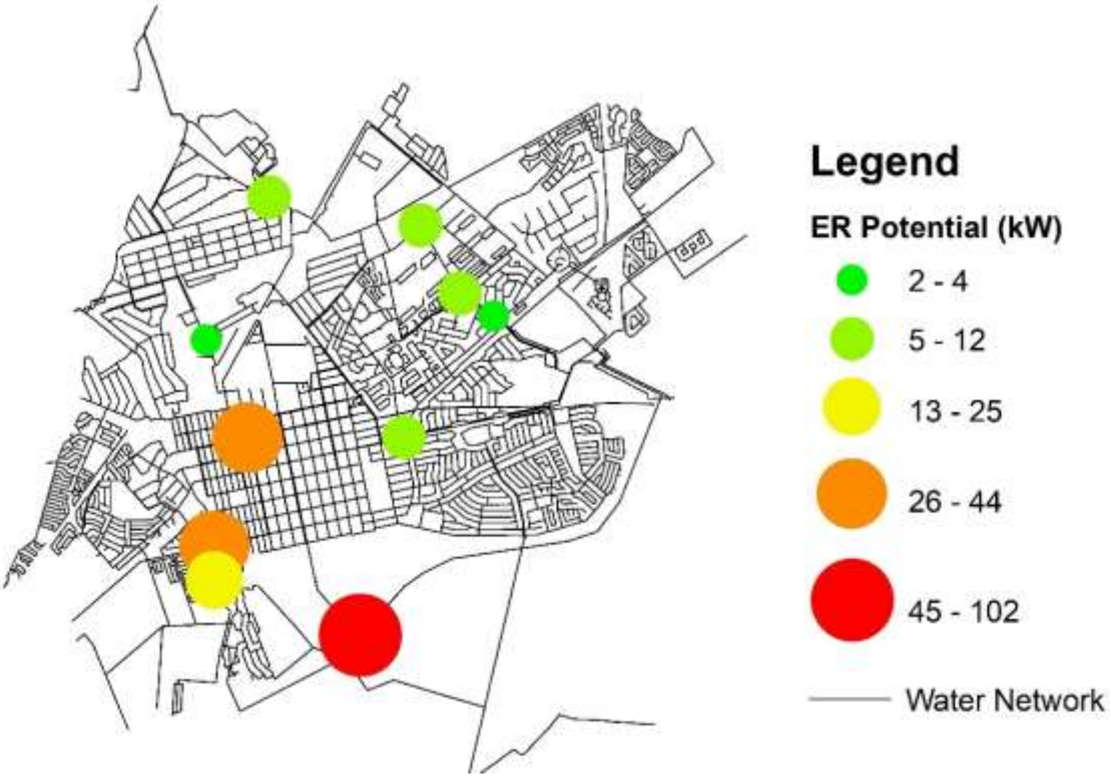

Figure-8 - Energy recovery potential in the Polokwane Central DMA (10 iterations)

The calculation of the UARL (eq. 2) using the hydraulic analysis and results of the base scenario showed a 3.5 ML/day UARL. Comparing this result to a 3.0 ML/day UARL calculated from the hydraulic analysis results after 10 iteration shows a leakage reduction of 15% based on the UARL within the isolated Polokwane Central DMA water distribution system.

Table 7 - Polokwane LM - IWA Water Balance

System Input Volume	**Authorised Consumption** 27 899 748 (73%)	**Billed Authorised Consumption** 27 899 748 (73%)	**Recovered Revenue** 27 899 748 (73%)
		Unbilled Authorised Consumption	**Non-Revenue Water** 10 404 091 (27%)
38 303 839 (100%)	**Water Losses** 10 404 091 (27%)	**Apparent Losses** 2 080 818 (5%)	
		Real Losses 8 323 272 (22%)	

***volume in kl/annum, % in brackets**

The CARL for the base scenario before energy recovery was calculated from supply volumes and billing data and reported as 22% (Table 7) by the Polokwane Local Municipality within the city's Water Supply Infrastructure AMP. This equates to a volumetric loss of 3 602 381 kl/annum within the Polokwane Central DMA when applying the percentage to the total modelled AADD. In the absence of measured flow and pressure, both the fixed and variable area terms of the FAVAD equation cannot be calibrated to calculate the CARL of the system. If the CARL of the system is known, it can be used to calibrate either the coefficient of the Fixed or Variable Area term of the FAVAD equation if it is assumed that either the one or the other is solely governing the leakage within the system. This method has its limitations as leakage within a system will be a combination of both Fixed and Variable area leaks.

The methods mentioned in sect. 2.5 have been adopted in the calculation of the leakage reduction from energy recovery. If the assumption is made that the UARL and the CARL of the system follow similar patterns, it can be concluded that the modelled energy recovery after 10 iterations of the algorithm would also decrease the CARL by 15%, similar to the calculated reduction in UARL, from 22% to 18.7% of the Average Annual Daily Demand, i.e. a 3.3% reduction in potable water supply losses.

If it is assumed that the leakage in the Polokwane Central DMA water distribution system is predominantly governed by variable area leaks (i.e. minimal large leakages or bursts), the percentage reduction in the CARL of a system can be also calculated from the percentage reduction in the operating system pressure of the WDS through the variable area term of the FAVAD equation, without calibrating the system. The Variable Area term of the FAVAD equation was calibrated using the calculated CARL and the assumption that the system is predominantly governed by variable area leaks. Using the volumetric CARL of 3 602 381 kl/annum, the average operating system pressure of 74.5m and a discharge coefficient of 0.6 (Van Zyl & Clayton, 2007), the slope of the pressure area line, or the Variable Area term coefficient, m, was calculated as 6.684 x 10^{-5}.

The calculated 13% reduction in the average operating pressure due to energy recovery within the Polokwane Central DMA will result in an 18.9% reduction in the CARL of the system, which in turn results in a 4.2% reduction in potable water supply losses. This result is confirmed by using the calibrated Variable Area terms coefficient if the FAVAD equation.

From the calculation and analysis, it can be concluded that leakage reduction in the Polokwane Central DMA emanating from energy recovery, achieved by leveraging asset management data, is between 3.3% and 4.2% of the potable water supply. Paired with the 264kW potential from energy recovery it amounts to an approximate monetary value of between R 6.1 and R 7.6 million (approximately between € 390k and € 480k) per annum for the Polokwane Local Municipality.

4. Conclusion

The study presented a novel approach to the exploitation of asset management data from Infrastructure Asset Management Plans and Asset Registers for the development of a hydraulic model to analyse energy recovery and leakage potential within a municipal water distribution system. The study showed that adequate information exists within the asset management plans and asset registers of municipal water distribution systems to inform a hydraulic model for the preliminary identification of excess operating pressures within the system. These excess pressures can be converted into electrical energy through the process of energy recovery with hydro turbines, to effectively leverage asset management data for energy recovery.

Similar to the benefits of pressure management in water distribution systems, energy recovery also has the benefit of reducing water losses caused by pipe leakages in the system. Due to the directly proportional relationship of pressure and leakage, reducing the average operating pressure in a water distribution system by converting excess pressures to electricity through energy recovery, reduces the volume of water loss through leakage. Although this method does not reduce the number of leaks or locate the position of leaks, it reduces the volume of leaks through the operational changes caused by the energy recovery in the system.

Leveraging water infrastructure asset management for energy recovery and leakage reduction poses financial benefits in terms of water savings and electricity generated. This represents a solution for creating resilient and self-sustainable cities. Within a country plagued by both energy and water crisis’s this study also has potential social and socio-economic benefits that did not form part of this paper and it is recommended to evaluate this in a separate study. Different methods of energy recovery in terms of technology available needs to be investigated on feasibility, profitability or return on investment and initial capital expenditure as well as environmental impact and total carbon footprint.

Other limitations of the research include the calibration of FAVAD coefficients to the measured and documented pressure and flow data and the optimization of energy recovery using different optimization techniques. In the absence of measured flow and pressure data in the system, the CARL calculated from the IWA Water Balance and received from the Polokwane Local Municipality was used to calibrate the Variable Area Term coefficient of the FAVAD equation. This approach is adequate for preliminary potential studies. Obtaining up to date measured flow and pressure data is proposed for further research and possible implementation of energy recovery within a WDS. It is furthermore proposed that an evolutionary algorithm, such as a genetic algorithm or particle swarm, be used in future research to optimize the energy recovery in terms of both electricity generation and leakage reduction.

The importance of this research emanates from the fact that excess pressure within a municipal WDS that would conventionally be dissipated by primarily using PRVs could be recovered by hydro turbines. This has the benefit of clean, low cost and renewable electricity generation in addition to a reduction in water losses from leakages similar to that of the operation of conventional PRVs. The difficulty is that municipal services managers and water utility managers are not adequately informed of the size and location of such energy recovery potential.

This research shows that asset management data and asset management plans, required by regulations and legislation, contain enough data to investigate energy recovery and leakage potential which adds a major value add to asset management systems. This needs to be backed up by financial and environmental information to complete a full life-cycle analysis of proposed installations.

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6. Disclaimer

The output of the research conducted in this article is generated from hydraulic models developed from the City of Polokwane’s Water Supply Infrastructure Asset Register and Asset Management Plans. These models incorporate assumptions informed by demand modelling and has not been calibrated to any specific time, date or scenario of measured data from the City of Polokwane’s Water Supply Networks. This research does not reflect or constitute the views of the Polokwane LM or any individuals affiliated with the Polokwane LM.

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