



UNIVERSITY OF
KWAZULU-NATAL
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**DEVELOPMENT OF AN AUTOMATION MODEL FOR
LEAKAGE REDUCTION AND ENERGY HARNESSING
THROUGH OPTIMISED PLACEMENT AND SETTING
OF PRESSURE REDUCING VALVES AND PUMP AS
TURBINE PLACEMENT IN WATER DISTRIBUTION
NETWORKS**

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DECLARATION

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.....

26 November 2021

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Date

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ABSTRACT

Water leakage is of paramount interest in South Africa. Due to the increasing population density access to drinking water will be scarcer, as much of the water produced is lost through leakages. South Africa's non-revenue water (NRW) accounts for approximately 30% of the total water supply, with leakages accounting for more than 70% of NRW in a network. Water leakage losses are defined as water lost during transportation to the consumer from the water source. Reducing leakage losses in existing networks is a major task for engineers, as replacing pipes is costly. There is a direct relationship between the pressure in a water distribution network (WDN) and the network's leakage losses. Network pressure is affected by many factors such as consumer demand, nodal elevation differences and network characteristics. The easiest and most cost-efficient method of pressure reduction in existing WDNs is through efficient pressure management. Developing methods to reduce the excess network pressure will reduce the leakage losses in the network.

There is currently little research that incorporates optimising pressure-reducing valve (PRV) placement to regulate network pressure and reduce leakage losses. Furthermore, the use of pumps operating as turbines (PATs) to harness energy in WDNs has not been fully explored. Literature gaps encompass optimising and automating these processes and creating an algorithm applicable to complex WDNs.

This dissertation presents a new optimisation model aimed at minimising network leakage losses within a WDN by determining the optimal placement and setting of additional PRVs. Energy generation from excess pressure is a secondary benefit and by-product of pressure reduction and can be harnessed by replacing PRVs with PATs. Replacing PRVs with PATs to harness renewable energy from the WDN is also incorporated into the new optimisation model. Automation of the model has been achieved using MATLAB and EPANET. The objectives of this study are to create a mathematical model to optimise the placement and setting of additional PRVs within a WDN, following all hydraulic, mathematical, and linear constraints. The model must determine which PATs can feasibly replace PRVs within a WDN to generate electricity and the PAT's potential power output and potential gross margin. The mathematical model must be automated using MATLAB and EPANET. The newly created objective function is made up of two stages to account for the multiple objectives.

The model has been applied to two real-world networks: the Cornubia Integrated Human Settlement Development Phase 2A- Zone 1 network and the Pat Marshal Housing Project. The proposed methodology's ability to reduce network pressures, reduce associated leakage losses, and generate energy has been demonstrated. The network leakage losses minimisation accounts for the hydraulic characteristics and constraints of each WDN in the form of mass continuity

equation constraints at the nodes, momentum balance constraints along the pipes, network constraints, and pressure reducing equipment constraints.

Five successful additional PRVs have been optimally placed and set within the Cornubia WDN, achieving a 12.8011% leakage rate reduction. Two successful additional PRVs have been optimally placed and set within the Pat Marshal WDN, achieving a 27.907% leakage rate reduction. The model has determined that nine of the 36 PRVs in the Cornubia WDN can be feasibly replaced by PATs to harness 135.48 kW of energy, equivalent to a Mini-hydropower plant, with a 948.67 MWh per annum output. One PAT can feasibly replace a PRV in the Pat Marshal WDN to harness 24.55 kW of energy, equivalent to a Micro-hydropower plant, with a 131.6 MWh per annum output. The energy produced could be sold to realise gross margins of approximately R920 211.17 and R127 662.30 per annum for the Cornubia and Pat Marshal WDNs, respectively.

The results obtained from the newly proposed method are positive, significantly reducing the leakage rate in both networks. The excess pressure from the networks can be efficiently harnessed to generate renewable energy to be utilised or sold.

Keywords: Leakage Reduction, Pressure Regulation, Optimum Pressure Reducing Valve Placement and Setting, Energy Harnessing, Pump as Turbine.

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ABBREVIATIONS

| | |
|------|----------------------------------|
| AF | Annual Financial Savings |
| ALCC | Annual Life Cycle Cost |
| AYEP | Average Yearly Energy Production |
| AZNP | Average Night Zone Pressure |
| BEP | Best Efficiency Point |
| CPP | Capital Payback Period |
| CW | Civil Works |
| DDA | Demand-Driven Analysis |
| DLL | Dynamic Link Library |
| DN | Nominal Diameter |
| DMA | District Metered Area |
| EGE | Energy Generation Equipment |
| EPA | Environmental Protection Agency |
| GA | Genetic Algorithm |
| GUI | Graphic User Interface |
| HDPE | High-Density Polyethylene |
| LPS | Litres Per Second |
| LI | Leakage Index |
| MC | Maintenance Cost |
| MNF | Minimum Night Flow |
| MSL | Mean Sea Level |
| NRW | Non-Revenue Water |
| OF | Objective Function |
| PAT | Pump as Turbine |

| | |
|-------|---------------------------------|
| PCF | Pressure Correction Factor |
| PDA | Pressure Driven Analysis |
| PDD | Pressure Driven Demand |
| PRE | Pressure Regulating Equipment |
| PRV | Pressure Reducing Valve |
| PVC | Poly Vinyl Chloride |
| REFIT | Renewable Energy Feed-In Tariff |
| SIV | System Input Volume |
| WDN | Water Distribution Network |

NOMENCLATURE

| | |
|------------------|--|
| α | Leakage exponent constant |
| ρ | Density of fluid |
| c | Conversion of PAT from a pump at BEP |
| $c_d(t)$ | Coefficient of Variable demand pattern at time (t) |
| $C_{L,i}$ | Coefficient of leakage constant |
| d, Act | Actual demand |
| $d, Base$ | Base demand |
| d, L | Leakage demand |
| D_k | Diameter of the k th pipe |
| E^{Total} | Total energy output |
| f_k | Darcy-Weisbach friction factor |
| g | Gravitational acceleration |
| H_i | Pressure head in pipe at node i |
| (ΔH_k) | Headloss along the k th pipe |
| H_k^{PATmin} | Pressure head minimum of PAT at BEP along the k th pipe |
| H_k^{PATmax} | Pressure head maximum of PAT at BEP along the k th pipe |
| $H_k^{PRV}(t)$ | Headloss due to the PRV along the k th pipe |
| i | Start node along the k th pipe |
| j | End nodes along the k th pipe |
| I_{max}^{Pmin} | Maximum number of nodes allowable below the minimum pressure |
| k | Pipe in the network |
| K | Total number of pipes in the network |
| L | Leakage |

| | |
|------------------------------|---|
| $\Delta L_{rate\ reduction}$ | Leakage rate reduction in the network due to PRV implementation |
| N | Water Distribution Network |
| η_{PAT} | PAT efficiency at BEP |
| $\eta_{p,BEP}$ | Efficiency of the pump at BEP |
| n_t | Number of timesteps |
| P | Power |
| $q_i^d(t)$ | Demand for each node |
| $\overline{q_i^d}$ | Average demand at the i th node |
| q_i^L | Leakage flow rate from the orifice at node i |
| Q_k | Discharge flowing through the k th link |
| Q_k^{PATmin} | Discharge minimum of PAT at BEP along the k th pipe |
| Q_k^{PATmax} | Discharge maximum of PAT at BEP along the k th pipe |
| Δs_k | Distance along the flow direction |
| T | Total operational time per day |
| v_k | Mean flow velocity |
| z_i | Elevation of the i th node |

CHAPTER 1

1. INTRODUCTION

1.1 Background Information

The world's population is increasing at an exponential rate (Cohen, 1995). One of the most challenging problems in South Africa is to fulfil water demand in urban areas with increasing population density and a deteriorating water distribution infrastructure.

Old and deteriorated water distribution networks (WDNs) have high instances of water leakages associated with high pressures in the network (Kanakoudis & Gonelas, 2014; Patelis, et al., 2017). These high pressures result in excessive water wastage, increasing non-revenue water (NRW) and consumer dissatisfaction (Berardi, et al., 2014; Kanakoudis & Gonelas, 2014; Gencoglu & Merzib, 2017). NRW is referred to as water that has been lost or unaccounted for in a network. Within all WDNs, between the point of supply and the consumer, some proportion of drinking water will be lost (Gencoglu & Merzib, 2017). These adverse effects decrease the operational life of the WDN. South Africa currently loses an average of R7.2 billion annually due to water leaks (Qodashe, 2020). Leakage in a network is directly proportional to hydraulic pressures, thus decreasing nodal pressures is an appropriate method for leakage minimisation (Gencoglu & Merzib, 2017). Pressure management options need to be implemented within WDNs to reduce the leakage rate, and thus water losses, within the network and extend its operational life. An increase in water demand puts a significant strain on the WDN in the area. A high leakage rate will thus increase the cost of water accordingly.

Pressure management is made possible by the use of pressure reducing valves (PRVs) that control the pressure downstream. PRVs have various control settings and may be set to open, partially open, or closed to control the pressures downstream and regulate excess pressure. A pressure regulation strategy aims to minimise excessive pressure as far as possible while ensuring sufficient pressure is maintained throughout the network to satisfy consumer demand at any time (Vairavamoorthy & Lumbers, 1998). The PRVs' placement and settings need to be optimised to maximise its effectiveness.

Recovering energy through pressure gradients available in existing WDNs is an efficient and sustainable method of renewable energy generation (Rossi, et al., 2016). Approximately 16% of the world's electricity is generated from the flow of water (Rossi, et al., 2016). New methods are being adopted to assist in the generation of a sustainable energy supply through the use of renewable energy sources such as hydropower and solar power plants (Rossi, et al., 2016).

According to Marchis et al. (2014), energy can be recovered by incorporating mini- and micro-hydropower turbines into WDNs. This technique requires expensive machinery, making it an

unfavourable energy harnessing alternative. According to Marchis et al. (2014), utilising a pump in reverse as a turbine (PAT) is a more cost-effective alternative to a conventional turbine. According to Motwani (2013), when compared to normal hydraulic turbines, PATs have a reduced equipment cost in the order of 10 to 1, or even more. The usage of a PAT is a long-term solution for pressure regulation that also generates electricity (Patelis, et al., 2017).

PRVs are typically placed in locations in the pipe network based on trial and error, based on hand calculations, or industry experience (McKenzie, 2021). The placement and setting of a PRV based on computer automation to achieve the maximum leakage rate reduction will significantly benefit the WDN and the community. Pressure, and subsequently leakage reduction, can reduce equipment costs and pipe maintenance costs for the system by reducing the number, and size, of pressure reducing equipment, required. A reduced pressure will also result in less wear on the pipes, requiring less frequent maintenance.

This report focuses on creating a computer program that automates the optimisation of PRV placement and setting in WDNs to reduce the excess pressure within the network at the nodes to acceptable pressures. The report has a secondary focus to feasibly determine which PRVs can be replaced with PATs to have the added benefit of renewable energy generation from excess network pressure. MATLAB is used to create the algorithm. EPANET is used as the hydraulic solver. The EPANET MATLAB Toolkit provides a library of functions that interfaces between MATLAB and EPANET.

The computer program will remove the ‘guesswork’ when implementing these devices. The automation software will run various scenarios of PRV placement and setting, checking every possible PRV location. The optimal location and setting reduce excess pressure to minimise the network leakage rate and maintain the required downstream pressures at all nodes. This process will be repeated until the optimum configuration (number, position in the network, and setting) of PRVs is found. The replacement of PRVs with a feasible configuration of PATs is based on an acceptable capital payback period (CPP). The energy produced can be used by the WDN or sold.

1.2 Motivation

The expense of treating, storing, and transporting fresh water that has been lost due to WDN leakage represents a significant financial loss. In South Africa, the cost of water is constantly rising, and its availability is becoming increasingly scarce. Water is a fundamental human need, and as access to fresh, clean drinking water becomes more difficult, it is critical that water is not squandered through leakages (Colvin, et al., 2016). Leakage in WDNs accounts for a large portion of the total water transported. Leakage rates can attribute as much as 70% of a network’s total NRW in some circumstances (Samir, et al., 2017). NRW in South Africa is approximately 30%

of total water in the system, which is about normal for developing countries (McKenzie & Wegelin, 2008; Babic, et al., 2014).

Access to fresh water is supplied to consumers via vast networks of pipelines, collectively called a WDN. Excessive pressure in the WDN can impair pipes and joints as well as damage consumer appliances (Shammas & Al-Dhowalia, 1993). Excessive pressure also increases the leakage rate within the network, which is costly to the municipality (Greyvenstein & Van Zyl, 2007; Gencoglu & Merzib, 2017). Hence, the water pressure within the pipes needs to be regulated.

There are obvious gaps in current literature for an optimisation algorithm that optimises both the placement and setting of PRVs within a WDN (Germanopoulos & Jowitt, 1989; Vairavamoorthy & Lumbers, 1998; Gencoglu & Merzib, 2017). The use of computer software to automate the placement and setting process of PRVs within the WDN will minimise leakage losses in the network. By automating the selection process of where to place pressure reducing equipment, fewer valves would be needed in a WDN to regulate pressure (Vairavamoorthy & Lumbers, 1998). This would result in lower equipment costs. Optimal pressure reduction directly impacts pipeline lifespan, where reducing the pressure will result in longer lasting networks, further reducing costs. Reducing the pressure within the WDN reduces the leakage rate in the network, reducing NRW (Van Zyl, 2004). Saving water is of paramount interest, as fresh drinking water is scarce, and any attempt to save water must be made.

In South Africa, there is overwhelming demand for electricity, generated by the principal power utility ESKOM, to power households and businesses. Eskom has been unable to generate enough electricity to fulfil this demand in recent years, resulting in Load shedding (Eskom, 2020). Alternative energy generation methods must be developed and implemented to reduce the public's reliance on ESKOM.

PAT devices for energy extraction can be integrated into current WDNs (Fecarotta & McNabola, 2017). PATs regulate pressure within the WDN by serving as a PRV and a 'turbine' generating electricity from the excess pressure (Patelis, et al., 2017). PATs need to be optimally placed to work efficiently, be cost-effective, and reduce the most pressure, thus producing the most energy. Fecarotta & McNabola (2017) found the optimum location to place a PAT is by replacing an existing PRV in the network after the placement of PRVs has been optimised. By optimising the placement and setting of pressure reducing equipment within the WDN, the highest amounts of water can be saved through a reduction in the leakage rate, as well as the most electricity can be generated as a secondary benefit (Germanopoulos & Jowitt, 1989; Vairavamoorthy & Lumbers, 1998; Araujo, et al., 2006; Gencoglu & Merzib, 2017; Samir, et al., 2017).

1.3 Research Questions, Aims and Objectives

This research aims to develop a mathematical model that optimally places and sets PRVs within a WDN to maximise the reduction in the network leakage rate (minimising network leakage losses) and determine a feasible PAT configuration within the WDN for energy generation. The mathematical model must be used to create a computer algorithm that automates this three-part process (PRV location optimisation; PRV setting optimisation; feasible PAT implementation). The hydraulic properties of WDNs are very complex and are time-consuming to analyse (Fecarotta & McNabola, 2017). Creating a computer program to analyse a WDN will greatly reduce analysis time and improve the accuracy of results. The computer program will have to work for a wide variety of WDNs and work within various hydraulic, mathematical, and linear constraints that govern the flow of fluid in a network.

Several mathematical models have been created for specific idealised theoretical WDNs, such as by Germanopoulos & Jowitt (1989), Fontana (2012), Gencoglua & Merzib (2017) and Fecarotta & McNabola (2017). However, the available models are inadequate due to their limitations in operation and strict criteria, often neglecting or ignoring real-world conditions. These idealised theoretical networks are often small and not as complex as real-world networks (Germanopoulos & Jowitt, 1989; Fontana, et al., 2012; Gencoglu & Merzib, 2017; Fecarotta & McNabola, 2017). This research aims to develop a new optimisation model that not only accurately and efficiently simulates the addition and setting of PRVs within any WDN, but also simplifies the analyse of the results, is more accurate, reliable for use with more extensive networks with many thousands of nodes and pipes, and time efficient.

The research sets out to answer the following questions:

1. Can the optimum placement and setting of PRVs be optimised using an computer-automated mathematical model, where the algorithm can be applied to a wide variety of WDNs?
2. Can a computer program be created to feasibly replace PRVs with PATs to harness energy from excess pressure within the WDN?

Aims:

1. To develop a mathematical model that optimally places and sets additional PRVs within a WDN to maximise the reduction in the network leakage rate.
2. To develop a mathematical model that feasibly determines which PATs can replace PRVs to harness energy from excess pressure within the WDN.
3. To create a computer algorithm that automates the processes described in Aims 1 and 2.

Objectives:

1. Create a mathematical model to optimise the placement of additional PRVs within a WDN, following all hydraulic, mathematical, and linear constraints.
2. Create a mathematical model to optimise the setting of the additional PRVs within a WDN, following all hydraulic, mathematical, and linear constraints.
3. Develop a mathematical model to determine which PATs can feasibly replace PRVs within a WDN to generate electricity.
4. Determine the potential power output of a WDN containing PATs as well as potential gross margin expected.
5. Automate the process described in objectives 1 through to 4 using MATLAB and EPANET.

1.4 Desired Outcomes of the Study

1. The primary outcome of this study is to optimally place and set PRVs to reduce and regulate the pressure at the nodes within the WDN to acceptable levels, proportionally decreasing the leakage rate in the WDN, with the aid of a computer algorithm created for this purpose using MATLAB and EPANET.
2. The secondary outcome of this study is to feasibly harness energy using the excess pressure in the WDN. The harnessed energy output will be compared to an equivalent hydropower plant for comparative purposes.

1.5 Structural Outline of the Thesis

The thesis is made up of six chapters, references, and appendices.

Chapter 1

Chapter one outlines the introduction to the thesis and the background of the study. This chapter also includes the motivation, aims, objectives, and desired outcomes of the research.

Chapter 2

Chapter two contains the review of literature on current pressure management techniques. This chapter includes information about PAT technology and factors affecting WDNs, such as variable demand patterns.

Chapter 3

Chapter three describes the water distribution networks that will be used for the thesis. There are two WDNs of different sizes and complexities: the larger and more complex Cornubia Integrated Human Settlement Development Phase 2A – Zone 1 and the smaller and less complex Pat Marshal Housing Project.

Chapter 4

Chapter four presents the methodology used to develop the mathematical models for optimal PRV placement and setting. The mathematical model developed for the analysis and replacement of PRVs with PATs is also shown in this chapter. The constraints and limitations are set out, as well as the factors affecting the network are considered.

Chapter 5

Chapter five presents the results and discussions of the current thesis. The models developed in chapter four are used to analyse the networks described in chapter three. The study's results emphasise the need for pressure management within WDNs as the reduction in leakage achieved is significant.

Chapter 6

Chapter six concludes and summarises the findings and the contributions in the present work. This chapter also deals with the environmental impact of the work and presents the scope for further research.

Appendix A

Appendix A contains the script created in MATLAB to automate the new methodology found in Chapter 4. The program was created in MATLAB using the EPANET MATLAB Toolkit.

CHAPTER 2

2. LITERATURE REVIEW

It is vital to decrease the amount of water lost in water distribution networks through leakages by minimising network pressures, as new water sources suitable for consumption are tough to source. Even where water is abundant, these sources may be expensive to transport, treat, and supply. Adequate management of existing water sources and infrastructure is thus essential (Germanopoulos & Jowitt, 1989). This chapter provides a detailed literature review regarding the factors affecting leakage reduction and energy harnessing techniques in WDNs. The various considerations for PRV and PAT implementation are considered. This chapter also describes the pressure leakage relationship in a pipe. South Africa loses approximately 1.1 million litres of water per year due to leakages from pipelines and reservoirs (Felix, 2020), amounting to approximately R7.2 billion annually (Qodashe, 2020), which needs to be reduced.

2.1 Introduction

A fundamental human right is an access to fresh and clean water. With the availability of water becoming ever scarcer, water must be conserved at all costs. However, the cost of conserving water is of significant importance to municipalities as money is also finite (Germanopoulos & Jowitt, 1989). There is a direct relationship between the pressure in a pipe network and its effect on the networks' maintenance costs and leakage rate (Van Zyl, 2004). There is thus a need to optimise the efficiency of saving water in water distribution networks by reducing pressure within the system to reduce the leakage rate and maintenance costs. With the aid of computer software, the automation of optimising the placement of pressure regulating equipment within the network can be made simpler and more accurate.

2.2 Characteristics of Water Distribution Networks

As population sizes grow exponentially, the strain put on transporting resources also increases. A water distribution network (WDN) is a complex arrangement of interconnected hydraulic elements used to transport water from a source, or multiple sources, to consumers (Ostfeld, 2015). The minimum and maximum generally accepted nodal pressure in the WDN are 24m and 90m, respectively (CSIR Building and Construction Technology, 2005; Jacobs & Strijdom, 2009).

WDNs depend on factors such as the elevations of the site, consumer demands at the nodes, the physical characteristics of the pipe network such as pipe roughness, length, pipe material and pipe diameter, and the sources of water into the system (Ostfeld, 2015). WDNs can be either gravity,

storage, or pumped systems. The consumer water demand affects the pressure within the network, as the higher the demand, the lower the pressure, such as during peak flow periods (McKenzie & Wegelin, 2008).

Pressure Reducing Valves (PRV) can be strategically implemented into the WDN to reduce the pressure within the network, which directly reduces the amount of water leaking out of the system (Carravetta, et al., 2012; Kanakoudis & Gonelas, 2014; Gencoglu & Merzib, 2017). PRVs increase network lifespan, allowing for the rehabilitation of the network to happen at a later stage, reducing future maintenance costs. Implementing a device that reduces excess network pressure and generates renewable energy from the excess pressure is seen as an alternate solution. Pump operating as Turbines (PATs) can be implemented in the pipeline but require a consistent flow to operate efficiently. The PAT is often the most cost-effective solution for energy harnessing in WDNs (Carravetta, et al., 2012).

2.3 Pressure Management in Water Distribution Networks

Pressure management within a WDN will result in users getting a safe outlet pressure when they require water. The leakage in the network is directly proportional to the hydraulic pressures within the network (Germanopoulos & Jowitt, 1989; Van Zyl, 2004; Gencoglu & Merzib, 2017). Pressure management can reduce leakages within a network as there is a direct relationship between increasing pressure and increasing leakages within a pipeline (McKenzie & Wegelin, 2008; Carravetta, et al., 2012; Gencoglu & Merzib, 2017). WDNs often have leaks, which directly impact their efficiency in transporting water to users (Gencoglu & Merzib, 2017). Leaks also increase the cost of water and the cost to transport the water, as higher volumes of water are required in the network (Jowitt & Xu, 1990; Berardi, et al., 2014). Pressure management can also be seen to reduce the average consumption of water by consumers, which will result in longer-lasting pipelines and less reduced maintenance costs (McKenzie & Wegelin, 2008).

Pressure management is the most widely used method implemented to reduce leakage and water wastage in a network (Germanopoulos & Jowitt, 1989; Gencoglu & Merzib, 2017). Pressure minimization may be accomplished by using several types of valves, such as pressure reducing valves, flow control valves, general purpose valves or pressure sustaining valves (Gencoglu & Merzib, 2017). Valves may be set to open, partially open, or closed positions. The optimal setting of a pressure control valve will minimise the excess pressures within a WDN (Germanopoulos & Jowitt, 1989; Vairavamoorthy & Lumbers, 1998).

WDNs are designed to cater for fire-flow that might occur at a peak-flow period, which usually occurs at some time of the day during a specified month but does not last a very long time

(McKenzie & Wegelin, 2008). Throughout the rest of the year, the pressure within the system is thus higher than necessary. Germanopoulos (1989) identifies numerous factors that affect leakage from a WDN; these include: the pipe pressure, the elevation difference between the nodes of the pipe, the movement and characteristics of the soil the pipe is laid in, the quality of the pipes, materials, and fittings, the degree and rate of deterioration of the water mains and pipes, as well as the possible affects that traffic loading has on the buried pipelines.

The downside to high pressures is high leakage rates. A reduction in network pressure will benefit the WDN and the municipality resulting in fewer leakages and less money wasted in water treatment, storage, and transportation costs (Germanopoulos & Jowitt, 1989; Fecarotta & McNabola, 2017). PRVs are used to regulate and lower the pressure in the WDN. This lower pressure results in fewer leakages (Vairavamoorthy & Lumbers, 1998). Leakages can make up the majority of non-revenue water (NRW), which increases the cost of water supplied to consumers due to their being less supply (Berardi, et al., 2014; Gencoglu & Merzib, 2017). By decreasing leakages in the network, the amount of NRW is also decreased, making water transportation more efficient and environmentally friendly.

According to Patelis et al. (2017), a case study in Kozani city, Greece, found that the per capita daily water usage ranged from 370 to 455 litres. They also mentioned that this is very high and possibly due to high levels of NRW. The average per capita daily water usage in KwaZulu Natal, South Africa, was 225 litres in 2015/2016 (Africa Check, 2018). South Africa's NRW leakage is around 30% of total water in the system, around the average amount for developing countries (McKenzie & Wegelin, 2008; Babic, et al., 2014).

Germanopoulos and Jowitt (1989) tested an algorithm to optimize control valve settings on two sample networks. They compared the effects of adding the control valves to the corresponding nodal pressures and leakage losses to the same networks when the valves were fully open, i.e., no pressure control. The calculations were done using pipe lengths in meters and flow in litres per second. The head losses within a network are at their maximum during peak flow periods (Germanopoulos & Jowitt, 1989; McKenzie & Wegelin, 2008). This equates to higher excess pressures, and thus higher corresponding leakage losses, during the low night-time demand periods. Germanopoulos and Jowitt (1989) state that the pressure control valves will be set to open more often during the period of peak demand than the period of low night-time demands. During the period of night-time demands, the number of PRVs set to open will be reduced to account for the increasing pressures in the network.

It is essential to look at the daily demand fluctuations and set the PRVs accordingly instead of only determining the PRV setting based on peak flows (Germanopoulos & Jowitt, 1989). Germanopoulos and Jowitt (1989) conclude that the simplest and most immediate way of

reducing the leakage losses within a WDN is through leakage reduction by pressure control. Germanopoulos and Jowitt (1989) also mention that further research is needed to develop a systematic procedure identifying the ‘best’ location and setting for pressure control devices within WDNs.

2.4 The relationship between network Pressure and Leakage Rate

Pipes can leak due to the pipe breaking, joint failures and excessive pressures, internally or externally applied, on the pipe, causing the pipe to crack. The pressure within a pipe is directly proportionate to the pipe’s leakage rate (Germanopoulos & Jowitt, 1989; Van Zyl, 2004; Fontana, et al., 2012; Piller & Van Zyl, 2014; Kanakoudis & Gonelas, 2014). Excessive pressures within a pipeline can increase the occurrence of pipe failures (Shammas & Al-Dhowalia, 1993). The reduction in pressure in the network leads to a reduction in leakages and decreases the frequency of pipe bursts (Germanopoulos & Jowitt, 1989). The pressures within a pipe are the easiest to control to reduce the leakage losses (Vairavamoorthy & Lumbers, 1998). Water losses directly relate to energy-wasting (Berardi, et al., 2014; De Marchis, et al., 2016). Some WDNs rely on pumping to transport the water within the network. Leakages lower water pressure within a pipe, requiring more energy for pumping, costing more to run the WDN.

Pipe leakages can be reduced by installing PRVs to control the pressure within the pipes (Germanopoulos & Jowitt, 1989; Shammas & Al-Dhowalia, 1993; Piller & Van Zyl, 2014). The replacement of PRVs with PATs gives rise to the added benefit of energy production within the pipeline as a by-product of reducing pressure in the network (Fontana, et al., 2012).

Pipes leak through holes or cracks. The flow through the hole can be calculated as (Van Zyl, 2004):

$$q = C \times H^{\alpha} \quad (1)$$

Where q = the flowrate from the hole or crack (leakage flowrate) (l/h), H = pressure head in the pipe (m), C = the leakage coefficient constant, and α = leakage exponent constant. The leakage coefficient constant is based on the hole’s diameter, the material of the pipe, and the effect of the contraction of the flow path downstream of the hole in the pipe (Van Zyl, 2004). The relationship between the pressure in the pipe and the leakage in the pipe is shown in Figure 2-1. Figure 2-1 shows that as the pipes’ pressure increases, so too does the leakage rate. This relationship is based on a 1mm hole in the pipe. The leakage coefficient (C) of 0.614 can be assumed for a circular hole in the pipe (Ferraiuolo, et al., 2020). The Leakage exponent (α) can be assumed as 0.5 (Van Zyl, 2004).

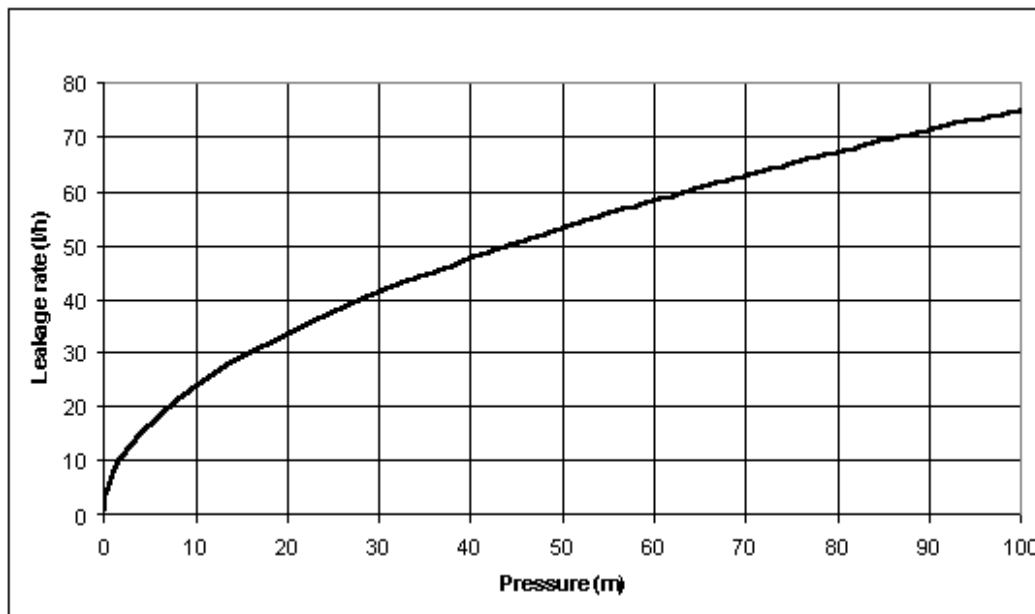


Figure 2-1: Pressure- Leakage rate relationship through a 1mm hole with a leakage exponent of 0.5 (Van Zyl, 2004).

2.5 Leakage determination

The WDN's primary purpose is to supply water to the consumer from the source. The efficiency of the WDN system is measured based upon the water entering the system and the water reaching the end-user. The difference between the input and output water volumes is called NRW (Babic, et al., 2014; Berardi, et al., 2014). NRW is made up of water losses and authorised unbilled consumptions. Water losses are made up of real and apparent losses. Authorised unbilled consumptions occur during cases of pipeline flushing and firefighting. Real water losses consist of water leakages within the WDN. Apparent water losses consist of unauthorised water consumption due to illegal use and inaccurate meter readings (McKenzie & Lambert, 2002; Babic, et al., 2014).

Real water losses are the focus of this thesis. Leakage control methods such as regular sounding of pipes, district metering and waste metering can be applied to locate leaks (Germanopoulos & Jowitt, 1989). Leakages are most commonly analysed by the Minimum Night Flow (MNF) method, as it is seen as the most accurate method of leak detection (Babic, et al., 2014). The MNF is the lowest flow that is supplied to an isolated supply zone within the WDN. The lower the water use in the network, the higher the pressure in the system. Higher pressures should result in higher leakages within the system (Germanopoulos & Jowitt, 1989; Jowitt & Xu, 1990).

According to Babic (2014), the average MNF water usage is 10 litres per person per hour, based upon the capacity of a standard toilet tank. The population considered active during the MNF can

be approximated at 6% of the total WDN population (Babic, et al., 2014). The WDN can be split into smaller metered zones, referred to as District Metered Areas (DMA).

Through experimental data, the relationship between the dimensionless Leakage Index (LI) parameter and the Average Night Zone Pressure (AZNP), measured in meters, in a DMA is as follows (Babic, et al., 2014):

$$LI = 0.5 \times AZNP + 0.0042 \times AZNP^2 \quad (2)$$

The LI enables the prediction of the night flow and leakage rates in the DMA due to pressure changes in the system (Babic, et al., 2014). The leakage index, or infrastructure leakage index (ILI), is a reasonably new performance indicator that measures real water losses within WDN's. Real water losses represent the actual water losses from the WDN (Taylor, n.d.). The minimum LI usually achieved is 1, as a value below one would imply that the actual leakage is less than the theoretical leakage minimum (Seago, et al., 2005). The higher the LI value, the greater the need for leakage reduction interventions, as shown in Table 2-1. Table 2-1 shows Liemberger's (2005) proposal to classify leakage levels into four categories: A represents Excellent, requiring no intervention; B represents 'good' leakage levels where no urgent action is required, but the system should be monitored closely; C represents 'poor' leakage levels that require corrective action; and D represents 'very bad' leakage values that require immediate interventions to reduce the water losses. In South Africa, the average LI value is estimated to be 6 (Seago, et al., 2005).

Table 2-1: Leakage Index in developing and developed countries (Seago, et al., 2005).

| Technical Performance Category | | ILI | Litres/ connection/ day (when the system is pressurised) at an average pressure of: | | | | |
|--------------------------------|---|--------|--|---------|---------|---------|----------|
| | | | 10 m | 20 m | 30 m | 40 m | 50 m |
| Developed Countries | A | 1 - 2 | | < 50 | < 75 | < 100 | < 125 |
| | B | 2 - 4 | | 50-100 | 75-150 | 100-200 | 125-250 |
| | C | 4 - 8 | | 100-200 | 150-300 | 200-400 | 250-500 |
| | D | > 8 | | > 200 | > 300 | > 400 | > 500 |
| Developing Countries | A | 1 - 4 | < 50 | < 100 | < 150 | < 200 | < 250 |
| | B | 4 - 8 | 50-100 | 100-200 | 150-300 | 200-400 | 250-500 |
| | C | 8 - 16 | 100-200 | 200-400 | 300-600 | 400-800 | 500-1000 |
| | D | > 16 | > 200 | > 400 | > 600 | > 800 | > 1000 |

The Background Night Leakage, measured in litres per hour, is calculated as follows (Babic, et al., 2014):

$$BL_N = (C_1 \times L + (C_2 + C_3) \times N) \times PCF \quad (3)$$

Where BL_N = background night leakage (litres per day), C_1, C_2 , and C_3 are leakage constants, shown in Table 2-3, L = the length of the pipeline (km), N = the number of service connections, and PCF = the pressure correction factor related to the AZNP, shown in Table 2-2. This formula assumes no bursts within the network. The period for analysis is 24 hours to get the daily water loss in the system.

Table 2-2: Pressure Correction Coefficient used for Leakage Calculation, (Babic, et al., 2014)

| Pressure Correction Factor (PCF) for variable AZNP | | | | | | | | | |
|--|------|------|------|------|------|------|------|------|------|
| AZNP (m) | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| PCF | 0.33 | 0.53 | 0.75 | 1.00 | 1.27 | 1.57 | 1.88 | 2.23 | 2.59 |

Table 2-3: Background Night Leakage Component used for Leakage Calculation, (Babic, et al., 2014)

| Background night leakage components at standard AZNP = 50m | | | | |
|--|-------------------|--------------------------|---------|------|
| Leakage Components | Unit | Infrastructure Condition | | |
| | | Good | Average | Poor |
| C_1 : Distribution Mains | litres/(km × h) | 20 | 40 | 60 |
| C_2 : Communication Pipes | litres/(conn × h) | 1.5 | 3.0 | 4.5 |
| C_3 : Underground Supply Pipes | litres/(conn × h) | 0.5 | 1.0 | 1.5 |

2.6 Bursts and Background Leaks

In South Africa, leaks are classified based on whether they require immediate attention or not. Large leaks warrant attention and are regarded as bursts. Small leaks are regarded as background leaks (McKenzie & Lambert, 2002). In South Africa, bursts can be regarded as leaks greater than $25 \text{ m}^3/\text{h}$ whereas background leaks are leaks less than $25 \text{ m}^3/\text{h}$.

Leakage Rates for different Pipes:

- Transmission Mains: $30 \text{ m}^3/\text{h}$
- Distribution Mains bursts: $12 \text{ m}^3/\text{h}$

- Distribution Mains background leaks: $6 \text{ m}^3/\text{h}$
- Connection and Service pipes bursts: $1.6 \text{ m}^3/\text{h}$
- Connection and Service pipes background leaks: $1.6 \text{ m}^3/\text{h}$

Connection background leaks are commonly unreported and contribute the majority of the leakage within a WDN (McKenzie & Lambert, 2002).

2.7 Cost of Leakages

NRW has a direct effect on the cost of water. Increasing water demand in urban areas results in progressively increasing energy consumption needed for treating and pumping the increasing volumes of water (Vairavamoorthy & Lumbers, 1998; Berardi, et al., 2014; Gencoglu & Merzib, 2017). A reduction in NRW, and consequently leakage losses, will reduce the cost of water. Table 2-4 shows the water tariffs for South Africa as of July 2021 (eThekweni Municipality, 2021). The NRW in eThekweni (Durban) is approximately 32%, which amounts to 85000 Ml/annum (Van Zyl, 2004).

Table 2-4: Water Tariffs for the eThekweni Municipality for 2021 (eThekweni Municipality, 2021)

Water Tariffs English

These tariffs came into effect from July 1, 2021

| Type of water supply | Roof tank Semi-pressure system | | Domestic Full pressure for property rateable values less than R250 000 | | Domestic Full pressure for property rateable values greater than R250 000 | | Industrial, commercial and other users | |
|---|--------------------------------------|--------|--|--------|---|--------|---|--------|
| Monthly Consumption | | | | | | | | |
| Prices per kilolitre excluding VAT | old | new | old | new | old | new | old | new |
| 0kl to 6kl * | nil | nil | nil | nil | R23.42 | R27.83 | R36.52 | R39.65 |
| From 6kl to 25kl * | R18.87 | R20.52 | R27.70 | R32.96 | R27.70 | R32.96 | R36.52 | R39.65 |
| From 25kl to 30kl | R25.81 | R28.00 | R36.90 | R43.83 | R36.90 | R43.83 | R36.52 | R39.65 |
| From 30kl to 45kl | R56.98 | R61.74 | R56.91 | R67.65 | R51.91 | R67.65 | R36.52 | R39.65 |
| More than 45kl | R62.58 | R67.91 | R62.58 | R74.35 | R62.58 | R74.35 | R36.52 | R39.65 |

2.8 Optimising Valve Control Settings

PRVs are hydraulically or electrically operated valves that reduce the pressure within a pipeline. A WDN has a desired pressure required for optimal operation, but due to location properties such as steep elevations, the pressures within the pipelines can increase beyond the desired pressure range. Reducing these high pressures with control valves reduces the likelihood of pipe damage and occurrence of leakages (Germanopoulos & Jowitt, 1989; Hydraulics and Pneumatics, 2012).

PRV's reduce the high upstream pressures and thus control the pressures downstream (Bermad, 2020). PRVs can operate in three different modes (Babic, et al., 2014): Fixed outlet PRVs maintain the downstream pressure at a fixed level, referred to as a setting (Kanakoudis & Gonelas, 2014). This mode is based on constant downstream water demand. Time modulated PRVs use the fixed downstream pressure level for certain times of the day. This mode is based on a consistent daily water demand pattern. Flow modulated PRV's are based on hourly demand curves. During low demand (high pressure) periods, the PRVs reduce the pressure to a minimum which reduces the losses and leakages in the system (Germanopoulos & Jowitt, 1989).

The amount of pressure that the valve reduces, referred to as the valve's setting, can be adjusted manually or through computer programs if the valve is electrically operated. The reduction of pressures within the WDN is the most efficient form of leak reduction (Vairavamoorthy & Lumbers, 1998; Babic, et al., 2014; Tricarico, et al., 2014; Gencoglu & Merzib, 2017).

The objective of pressure management should be to minimise excessive network pressures while ensuring sufficient network pressures are maintained to satisfy consumer demand (Vairavamoorthy & Lumbers, 1998). The development of an optimisation method to minimise leakage in WDNs through the most effective setting of flow reduction valves has been proposed by Vairavamoorthy and Lumbers (1998). As the size and complexity of the WDN increases, maintaining the target pressure at all nodes becomes increasingly difficult. The most effective form of pressure reduction in a WDN results from a PRV implemented with a flow meter and a controller. This allows for different pressure reductions within the system at different times of the day, based on the demand pattern of the system (Vairavamoorthy & Lumbers, 1998). Implementation of these variable closure valves can achieve leakage reductions of up to 30% (Germanopoulos & Jowitt, 1989; Vairavamoorthy & Lumbers, 1998). To maximise the effectiveness of a PRV, two separate problems need to be solved, first, their optimum location within the network needs to be found, then their setting needs to be optimised for their locations (Vairavamoorthy & Lumbers, 1998). Vairavamoorthy and Lumbers (1998) state that the computation of determining the optimum valve setting is a difficult task due to networks being non-linear and the high dimensionality of the optimisation problem. Germanopoulos and Jowitt (1989) use an iterative procedure involving the linearisation of the objective function and

constraints about the current point, consequently solving the linear program to find the new solution point. This method is iterated until the termination criteria have been met. Vairavamoorthy and Lumbers (1998) state that the method used by Germanopoulos and Jowitt (1989) is inadequate as it does not include the valve settings from the previous iterations in its calculations, only focusing on pressures. Vairavamoorthy and Lumbers (1998) allowed their target pressures to drop below the minimum acceptable for some nodes to allow for a better-optimised valve setting. They concluded that the only way to control the leakage in an existing network is through pressure management, using optimisation techniques to determine the setting of the pressure reducing valves.

2.9 Variable Demand Patterns

Consumers use water in predictable patterns throughout the day, throughout the week, and varying with the seasons. The water demand is affected by factors such as the population size using the water, the climate in the area, the socio-economic conditions in the area and the various water policies set out by municipalities (Germanopoulos & Jowitt, 1989; Haque, et al., 2018). The average per capita per day water consumption in KwaZulu Natal is 225 litres (Africa Check, 2018).

Water demand forecasting can be used to get models for a systems' water demand pattern based on historical data (Gedefaw, et al., 2018). To accurately supply water to consumers, an accurate demand flow pattern is needed. This demand flow pattern includes the water quality, pressure, and quantity required. Water utilities need to accurately predict the water demand for a network to meet the consumers' demands. When implementing PATs into the WDN to harness energy, the amount of energy that can be harnessed is vital (Giugni, et al., 2014).

The amount of energy available in the system is a function of the pressure in the system, thus directly affected by the demand pattern of the WDN. The most common model used for long-term water demand forecasting is the linear regression model (Gedefaw, et al., 2018). According to Candelieri (2014), the peak water demand is in the morning, at approximately 8 am, and in the evening, at approximately 7 pm to 8 pm.

The peak in the morning for weekends is usually delayed by one hour, compared to weekdays (Candelieri & Archetti, 2014). This generalised water demand pattern can be seen in Figure 2-2.

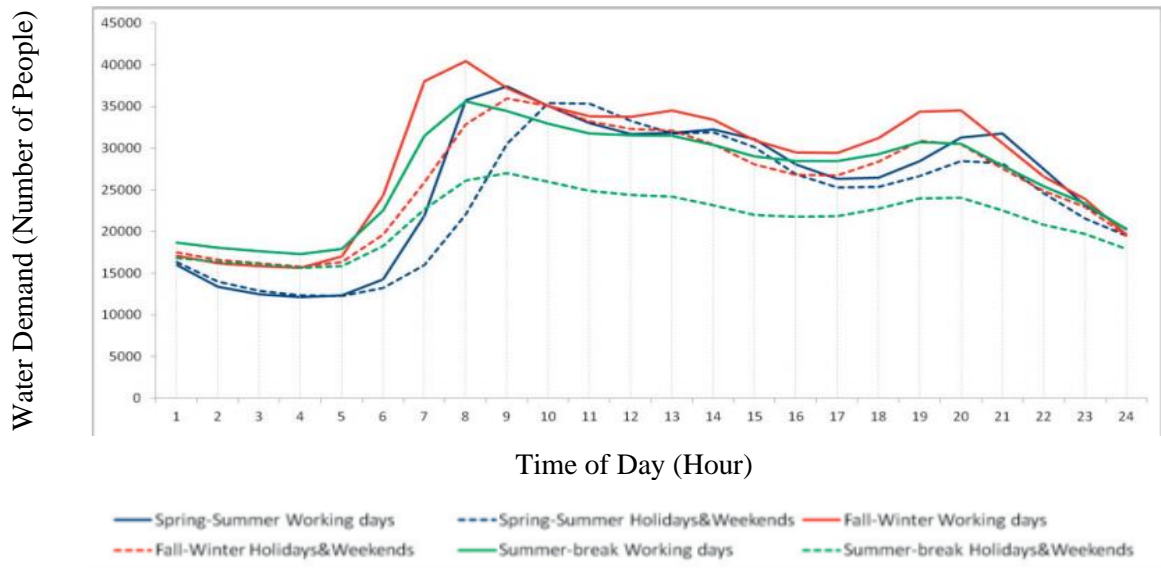


Figure 2-2: Daily Demand Patterns for urban water demand of a WDN (Candelieri & Archetti, 2014)

Consumer demand for water varies throughout the day. The WDN should provide the required minimum head during peak demand periods. As shown in Figure 2-3, when the demand is at its peak, the pressure at the critical point is maintained at acceptable levels. McKenzie (2008) uses a critical pressure of 20m to illustrate this point. When the demand lessens during off-peak

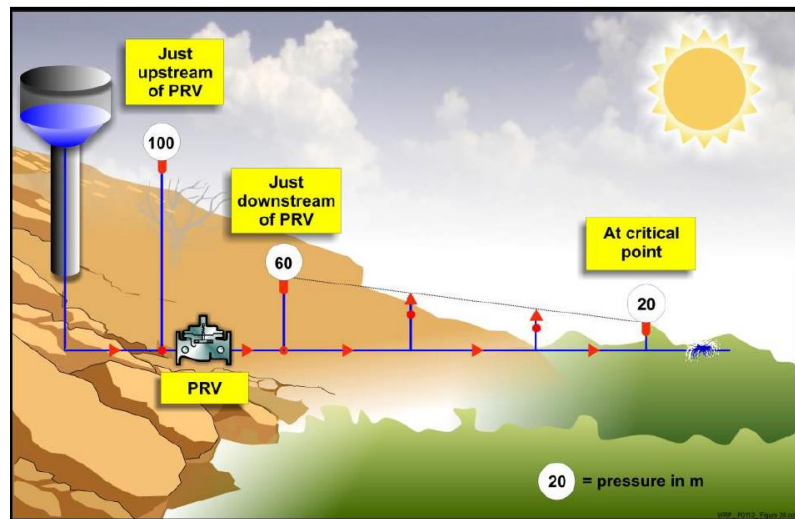


Figure 2-3: Pressure during peak-demand periods showing the minimum pressure at critical points (McKenzie & Wegelin, 2008).

periods, such as when residential consumers are asleep, the water pressure in the network is significantly higher than necessary (McKenzie & Wegelin, 2008; Gencoglu & Merzib, 2017). Figure 2-4 shows this concept and shows that there is a need for further pressure reduction at these times to aid with pressure management in the network.

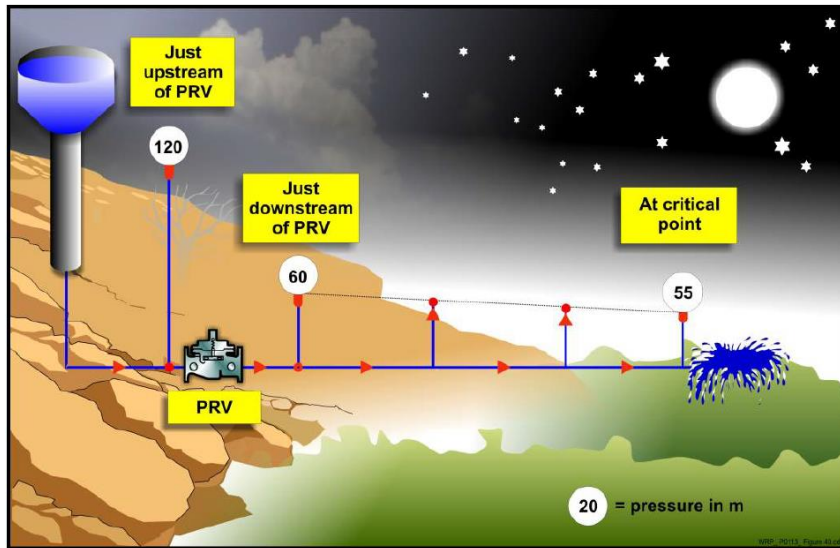


Figure 2-4: Pressure during off-peak periods showing excessive pressure at the critical points (McKenzie & Wegelin, 2008)

2.10 Energy Harnessing using PATs

Pumps are used to increase the pressure of a fluid by using mechanical energy. A pump as turbine (PAT) is a centrifugal pump working in the reverse direction to act as a turbine, generating electricity from excess pressure head in the pipe (Rakibuzzaman, et al., 2019). PATs are implemented within the WDN to not only regulate pressure by reducing the head within the pipe but also provide a stable flow rate to all users (De Marchis, et al., 2014). Satish et al. (2021) state that PATs can replace existing PRVs in WDNs to regulate pressure with the added benefit of energy generation. WDN's have varying flow rates along the pipe network. Varying flow rates and varying pressures can result from changes in pipe properties such as pipe diameter or pipe roughness. The network's location affects the pressures within the pipeline as significant elevation changes will result in varying pressure heads within the system. A PAT can utilise these differences in pressure between junctions to extract energy from the excess network pressure (De Marchis, et al., 2014; De Marchis & Freni, 2015; Rakibuzzaman, et al., 2019). Pumps do not have a direct performance relationship when working as a turbine. This makes it necessary for the pump's characteristic curves to be analysed to accurately predict their performance (De Marchis, et al., 2016). The primary consideration when installing a PAT into the WDN is the position of the PAT. The PAT needs to maximise energy production and maintain the desired downstream water supply pressures at all nodes (De Marchis, et al., 2014; De Marchis, et al., 2016).

Head in a water distribution network refers to the kinetic energy with which the fluid flows. Head measures the height of a column of fluid, in this case, water, that would be achieved due to the energy within the system (James, 2012). Head increases when the velocity of the fluid increases.

A pump in a pipeline system will increase the head of the fluid, so, conversely, a turbine will decrease the head within the system (Rakibuzzaman, et al., 2019).

The power rating of a pump describes the work performed by the pump over a given period. The greater the head reduction, the greater the power generated. The head reduction must be balanced to maintain a downstream pressure above the prescribed minimum head of 24m (CSIR Building and Construction Technology, 2005; Jacobs & Strijdom, 2009). Power harnessed by a PAT is determined by the volumetric flow and the pressure reduction across the PAT (Rakibuzzaman, et al., 2019). The following formula is used to calculate the power generated by the PAT at its best efficiency point (BEP) (Van Vuuren, et al., 2011; Fontana, et al., 2012):

$$P = \rho \times g \times Q \times \Delta h \times \eta \quad (4)$$

Where P = power (W), ρ = the density of fluid (kg/m^3), g = the acceleration due to gravity, taken as 9.81 m/s^2 , Q = the volume flow rate (m^3/s), Δh = the pressure head reduction by the PAT (m), and η = the pump's efficiency. The fluid medium is water, which has a density of 1000 kg/m^3 .

2.11 Pump to PAT Conversion and PAT Characteristics

By reversing the operation of the pump to use the pressure of the water to generate electricity, the pump acts as a turbine. PATs operate in the same way as regular pumps and thus do not need any specialised personnel to maintain them, reducing maintenance costs (Patelis, et al., 2017).

Pump characteristic curves relate the discharge flow rate, head, power, and efficiency of the pump (Carravetta, et al., 2012; James, 2012). These curves represent the physical characteristics of the pump. Pump curves show the head of the pump versus the flow rate of the pump and show the pump curve and the system curve. The system curve represents the characteristics of the whole system and is affected by the factors of the system, such as the length of pipes, diameter of pipes, pipe roughness, valves, and bends in the pipes (James, 2012). The intersection of the pump curve with the system curve will indicate the operating point of the pump. When a pump operates in turbine mode, the flow increases with increasing head. The following relationships can be used between a pump and a PAT at BEP (Fontana, et al., 2012; De Marchis, et al., 2014):

$$Q_{t1} = \frac{Q_{pb}}{\eta_{pb}^{0.8}}, \quad H_{t1} = \frac{H_{pb}}{\eta_{pb}^{1.2}} \quad (5)$$

$$\frac{H_{tb}}{H_{t1}} = \left(\frac{N_t}{N_p}\right)^2, \quad \frac{Q_{tb}}{Q_{t1}} = \frac{N_t}{N_p} \quad (6)$$

Where Q = flow rate (m^3/s), H = head (m), N = rotational speed (rpm), and η = efficiency. The subscripts t , p , and b refer to the turbine, pump, and BEP, respectively. The subscript 1 refers to the PAT and the pump being at the same rotational speed. The BEP of a PAT can be said to coincide with the pump's BEP (Derakhshan & Nourbakhsh, 2008a; Derakhshan & Nourbakhsh, 2008b; Fontana, et al., 2012; De Marchis & Freni, 2015).

To select the optimum PAT for the WDN under consideration, the WDN's characteristics need to be analysed (Carravetta, et al., 2012). The pressure-head and flow rate conditions must be determined (De Marchis, et al., 2014). The available head in the system must then be calculated based on the backpressure required by the system. The backpressure value is the downstream pressure value within the network (Germanopoulos & Jowitt, 1989; Carravetta, et al., 2012). The PAT type should be considered. The centrifugal pump type is best suited for high flow rates of lower viscosity fluids such as water (Budris, 2009; De Marchis, et al., 2014; Rakibuzzaman, et al., 2019). The PATs region of best efficiency must be considered, and a range of PAT characteristic curves must be analysed (De Marchis & Freni, 2015). Derakhshan and Nourbakhsh (2008b) showed that a centrifugal pump could operate as a turbine with varying heads, flow rates, and different rotational speeds without any mechanical problem (De Marchis, et al., 2014). The PAT with the highest efficiency will be selected for use in energy recovery in the WDN. This PAT is the most optimal (De Marchis, et al., 2014).

Figure 2-5, from Carravetta (2012), shows the pump's characteristic curves and compares the head drop and flow rate of a pump. It can be seen that different pumps are used for different network conditions.

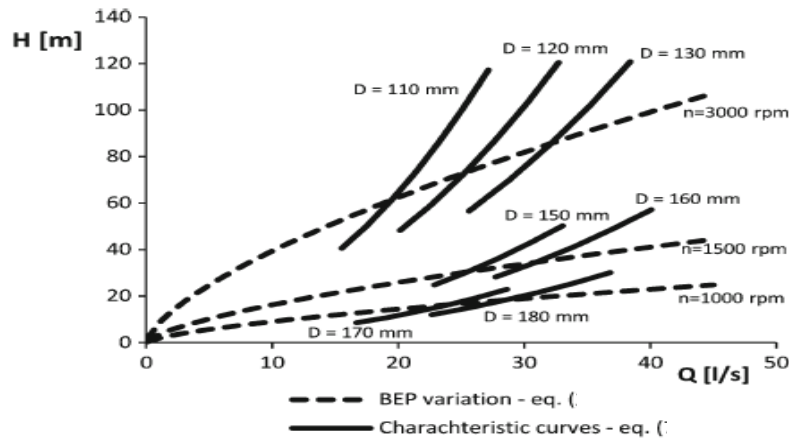


Figure 2-5: PAT Best Efficiency Point and Characteristic curves relating to Flow Rate and Head drop (Carravetta, et al., 2012)

Patelis (2017) states that the electricity produced by the PAT can be either low or high voltage, varying from 1 to 200KW. Energy harnessed from the WDN can be used to offset the costs of running the system, or excess electricity can be sold to increase revenue (Motwani, et al., 2013). This form of energy production produces clean energy, as opposed to the ESKOM alternative, which produces energy through the combustion of fossil fuels.

PATs can be implemented into old WDN's that have recently had newer pipe sections added to them. These new pipes have lower internal roughness and thus higher flow rates than the old, existing pipes (Carravetta, et al., 2012). The PAT can regulate the smoother new pipes' higher flow rates to dissipate the surplus energy head (Carravetta, et al., 2012). Flow rate within the network also depends on user demand, indicating that flow rates, and consequently, the available head, will vary throughout the day (Germanopoulos & Jowitt, 1989). The most important requirement for implementing a PAT into the WDN is that there is a natural energy surplus within the system (Patelis, et al., 2017). This means that the WDN is a gravity network and does not rely on pumping to provide head to the water. WDN's that are only gravity-fed and have high altitude differences between the water source and the water users are ideal for pressure management devices. Consequently, they are best suited to implement energy extraction devices (Patelis, et al., 2017). This makes the use of PATs a viable form of pressure management. Pipes within the system with high energy surpluses must be identified. The PATs must be situated in locations that can benefit from the energy produced. The energy produced must ideally not have to be transferred long distances to be utilised (Patelis, et al., 2017). The construction of transmission lines will further increase the cost of the project and should be avoided.

2.12 Optimising PAT Placement within a Network

From Figure 2-6, it can be seen that the optimal placement of a PAT for energy harnessing would be at sections of the pipeline with the highest available head (Carravetta, et al., 2012; Fontana, et al., 2012; De Marchis, et al., 2014). Available head fluctuates throughout the day. The PAT would have to work only when the available head is above a prescribed minimum value to ensure sufficient power output, making the PAT's implementation feasible and economical (Fontana, et al., 2012). The larger the pipe diameter and the longer the pipe, the greater the pressure difference within the pipe's ends, allowing for greater energy extraction (Patelis, et al., 2017).

Carravetta et al. (2012) mention that a series-parallel combination for PATs can be used. This includes placing a PAT control and isolation valve in series before the PAT and a bypass regulating valve in parallel with the PAT, as shown in Figure 2-7. This will prevent the PAT from being damaged during surge flow periods as the control valve will dissipate some of the excess pressure. The bypass regulating valve will bypass the PAT during periods of high discharge when

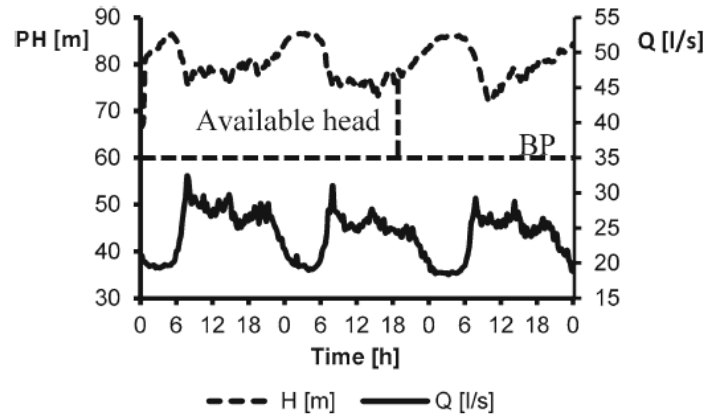


Figure 2-6: The hourly fluctuation of Pressure Head, Backpressure and Flow rate within a section of a WDN (Carravetta, et al., 2012)

the head drop required by the PAT is greater than the available inflow head. Patelis (2017) proposes that a PRV can be placed before a PAT to maintain a constant flow rate entering the PAT. This will also protect the PAT from any irregular flows or pressures in the network. This is also beneficial as PATs function best when exposed to a steady flow rate.

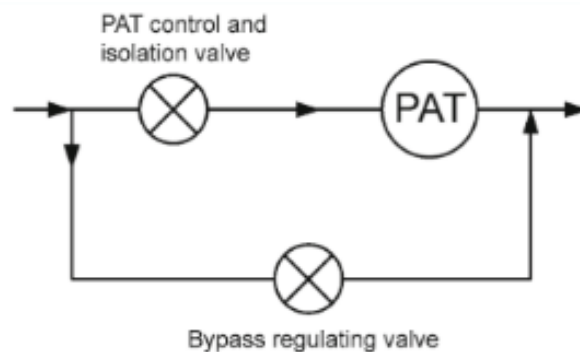


Figure 2-7: PAT implementation within a Pipeline making use of a bypass regulating valve (Carravetta, et al., 2012).

When installing PATs within the WDN, it must be noted that a PAT upstream can control and regulate the pressure downstream, reducing the need for placing additional PRVs and PATs in many locations downstream. This is done by either adequately reducing the downstream pressure or making the downstream pressure unsuitable for implementing another PAT (Patelis, et al., 2017). Some PATs placed downstream would have to be temporarily switched off due to insufficient pressure, which is uneconomical. The network may experience flow rates lower than what the PAT requires to operate. This could be due to factors such as a pipe leak or excessive use of water by consumers from the network (De Marchis & Freni, 2015).

The minimum required nodal pressure in South African WDNs is 24m (CSIR Building and Construction Technology, 2005; Jacobs & Strijdom, 2009). The Department of Housing, South

Africa, has limited the maximum head within a system junction that supplies water to households to be 90m (CSIR Building and Construction Technology, 2005). Household appliances can require pressures as low as 10m (Jacobs & Strijdom, 2009). The South African civil engineering fraternity has mentioned that the theoretical peak demand makes the minimum nodal pressure of 24m too low, but peak flow conditions are rare in a system (Jacobs & Strijdom, 2009). It can be seen that there are WDNs in South Africa that have minimum nodal pressures of as low as 14m (Jacobs & Strijdom, 2009). The pressure in the WDN is lowest when there is maximum demand during peak periods. The minimum head value in the system occurs under these peak conditions and at the most critical node in the system (McKenzie & Wegelin, 2008; Jacobs & Strijdom, 2009).

The optimal placement of a PAT must consider the PATs initial cost, maintenance cost, amount of energy recovered, amount of pressure reduced, the value of the energy recovered, and the water volume being saved (Patelis, et al., 2017). PAT technology has new developments that allow PATs to measure downstream pressure conditions and adjust their pressure-reducing capabilities to suit these conditions. The aim of maintaining a minimum pressure within the system is to ensure that there are no negative pressures that arise within the system which damages pipes and to ensure customer satisfaction in terms of delivered water pressure.

2.13 Feasibility and Cost analysis of PAT implementation

An annual life cycle cost (ALCC) must be analysed to determine the feasibility of implementing a PAT into the WDN (Motwani, et al., 2013). The ALCC includes factors such as the initial cost of implementation, maintenance costs, water-saving factors, capital recovery factors resulting from selling the generated electricity and other expenses related to the project (Motwani, et al., 2013).

The cost of a PAT is significantly less than that of a hydro turbine, and pumps are readily available and are less complex and mass-produced (De Marchis, et al., 2014; Satish, et al., 2021). Motwani et al. (2013) state that the payback period of a hydropower plant can be in the range of 15-20 years. A Pico hydro-power plant produces electricity under 20kW. A Micro hydro-power plant can produce between 20kW and 100kW of Power. A Mini-hydro-power plant produces energy from 100kW to 1MW (Sustainable Energy Africa, 2017). Hydropower plants that produce less than 1MW of power usually do not need to tie into the power grid, whereas hydropower plants generating more than 1MW of power usually feed into the grid (Aidhen & Gaikwad, 2016). Hydropower plants producing less than 1MW of electricity usually find it uneconomical to connect to the electricity grid as the construction of additional infrastructure is required.

Marchis et al. (2015) conclude in their study that a capital payback period of approximately 2.5 years can be achieved when the PATs are located close to the water supply node. This low payback period makes the installation of PATs very favourable. The PATs have their highest efficiency when installed in the main pipes. This, however, has the highest maintenance and installation costs, justifying the use of the PAT operating at BEP for efficient energy production. The feasibility of implementing a PAT into the WDN must also consider all the WDNs requirements. The installation of a PAT must not produce any negative pressures within the network. The system must also still meet the minimum consumer demand pressures (Tricarico, et al., 2014). The more PATs installed into a WDN, the more income they will generate, but the more costly the setup and maintenance costs will be for the system (Tricarico, et al., 2014). The more PATs installed in the system will also reduce the efficiency of each PAT, as the total available head is distributed amongst more PAT's. This makes installing too many PATs in the WDN uneconomical.

The capital payback period (CPP) is the period required for the PAT to pay back the initial capital investment. The CPP depends on the power output and placement of the PAT. The PAT cost is calculated based on the BEP of the power produced by the PAT. Energy Generation Equipment (EGE) cost is the cost price for the required equipment. The civil works (CW) cost must be added to the total costs of the project. According to Fontana et al. (2012), civil works can be estimated as being 30% of the EGE cost. The maintenance cost (MC) can be assumed to be between 10-15% of the total cost per year. The total cost is made up of the EGE and CW costs. An MC of 15% will be chosen for this dissertation analysis. Annual financial saving is the product of the energy cost and the Average Yearly Energy Production (AYEP) subtracting the MC (De Marchis, et al., 2014). The AYEPP is the power generated per year by each PAT. AF represents the annual financial savings achieved. These calculations are shown in equation (7) to (12) (De Marchis, et al., 2014):

$$EGE = \text{Cost in Rands} \times 1.3 \quad (7)$$

$$CW = 30\% \times EGE \quad (8)$$

$$MC = 15\% \times (EGE + CW) \quad (9)$$

$$AYEP = \text{Power output of Turbine} \times \text{Runtime per day} \times \text{Runtime per year} \quad (10)$$

$$AF = R2,03 \times AYEPP - MC \quad (11)$$

$$CPP = \frac{EGE + CW}{AF} \quad (12)$$

2.14 Benefits of using PATs in WDNs

The primary benefit of using a PAT to generate electricity in the WDN is that most of the infrastructure is already built (Satish, et al., 2021). Other benefits of PAT implementation include:

- There are short project payback times due to little work needed to implement the PAT into the WDN compared to large-scale hydroelectric power generation projects (Van Dijk, et al., 2016; Satish, et al., 2021).
- Low operation and maintenance costs, compared to using a conventional turbine as pumps, are more accessible and easier to use, requiring little to no expert technical knowledge.
- Pump technology has been researched in detail, and the technology is well known (De Marchis, et al., 2016).
- The electricity generated is from a renewable resource and can thus be regarded as “green energy” generation.
- PATs require low-cost equipment and are sustainable solutions to renewable power generation (De Marchis, et al., 2016; Satish, et al., 2021).

2.15 Cost and Selling Price of Renewable Energy generated in South Africa.

In South Africa, the cost of renewable energy is R1.2/kWh using the Least-Cost model (South African Wind Energy Association, 2019). South Africa has a very low GDP per unit energy use compared to other countries, meaning South Africa’s energy use is very inefficient (South African Wind Energy Association, 2019). South Africa utilises mostly coal-burning methods of energy production, while most of the world is moving towards energy production by renewable energy sources, such as wind and hydropower.

The cost of producing electricity through diesel Open Cycle Gas Turbines is approximately R3/kWh (South African Wind Energy Association, 2019). This is 2,5 times more expensive than producing energy through renewable energy methods. The cost to produce electricity using coal-burning power plants in South Africa is R0.87/kWh (Mulongo & Kholopane, 2017). The cost to generate electricity using Solar Photo-Voltaic energy in South Africa is R3.05/kWh (Mulongo & Kholopane, 2017). The cost to generate electricity using Wind in South Africa is R2.37/kWh. It can be seen that the cost of electricity generation is lowest when utilising coal. The cost of purchasing electricity for the household consumer in South Africa is R2.17 as of March 2021 (Global Petrol Prices, 2021).

According to the South African Department of Energy (2010), the Renewable Energy Feed-In Tariff (REFIT) for Small Hydropower (Less than 10MW) is R0.94/kWh as of 2010,

approximately R2.17/kWh in 2021, which coincides with the cost of purchasing for the household consumer. These values have been summarised in Table 2-5.

Table 2-5: Summary of the Cost and Selling Price of Different forms of Energy in South Africa

| <u>Energy Source</u> | <u>Price (R/kWh)</u> |
|--------------------------------|----------------------|
| Cost | |
| Open Cycle Gas Turbines | 3 |
| Coal | 0.87 |
| Solar Photo-Voltaic | 3.05 |
| Wind | 2.37 |
| Selling | |
| Cost of Purchasing Electricity | 2.17 |
| REFIT (2021) | 2.17 |

2.16 EPANET

EPANET is a hydraulic modelling and analysis software developed by the United States Environmental Protection Agency's (EPA) Water Supply and Water Research Division (United States Environmental Protection Agency, 2022). EPANET can be used to interface with other programming software and is open source. EPANET is used to solve the hydraulic equations necessary to analyse the flow of water within a WDN. EPANET can also carry out extended-period simulations to determine the behaviour of water in pressurised pipe networks (Nino, et al., 2018). EPANET is a research tool that enables the user to understand the movement of drinking water and its constituents within a WDN. EPANET can be used to analyse the hydraulic network characteristics of the WDN, aiding with locating possible problems in the network, such as bottlenecks, and assisting with technical decision making for water utilities (Nino, et al., 2018).

EPANET 2, launched in 2000, introduced the EPANET Programmer's Toolkit, which allows for the modification of network data to analyse the behaviour of the WDN (Iglesias-Rey, et al., 2017). The EPANET Programmer's toolkit ("the Toolkit") is a library of functions that allows the execution of a simulation from an external program to run, provided that the network characteristics have been defined. The Toolkit is a dynamic link library (DLL) which is a library containing code that can be used by other programs simultaneously (Rossman, 2000). The EPANET Toolkit DLL contains additional functions allowing anyone to modify and customize EPANET's capabilities. The Toolkit can be integrated into any native programming environment or licensed software programs (Nino, et al., 2018). The EPANET Toolkit is open-source software that can be downloaded from the MATLAB website (MathWorks, 2022).

Figure 2-8 shows EPANET's standalone operation model and how third-party tools or add-ins modify the program using the Toolkit. Information in EPANET is modified through the INP file.

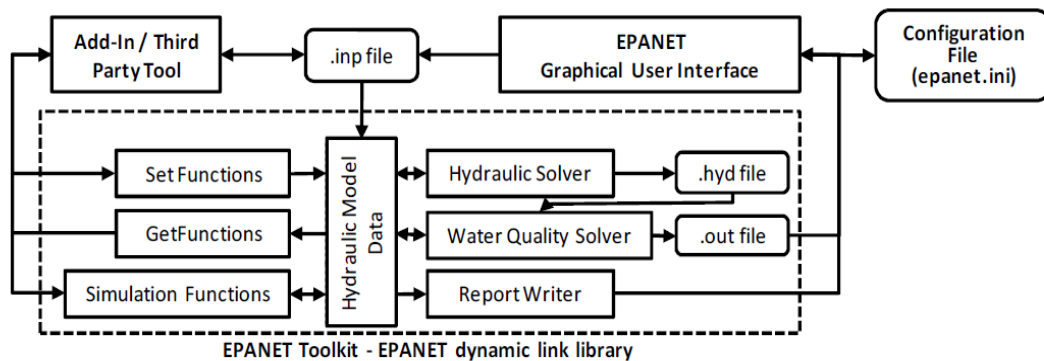


Figure 2-8: EPANET Standalone operation model showing how third-party tools and add-ins interface using the Toolkit (Rossman, 2000).

As the name suggests, add-in tools allow third parties to add applications to EPANET's menu that will run simultaneously with EPANET (Iglesias-Rey, et al., 2017). Figure 2-9 shows the operating diagram for EPANET's relationship between the Toolkit and Add-ins.

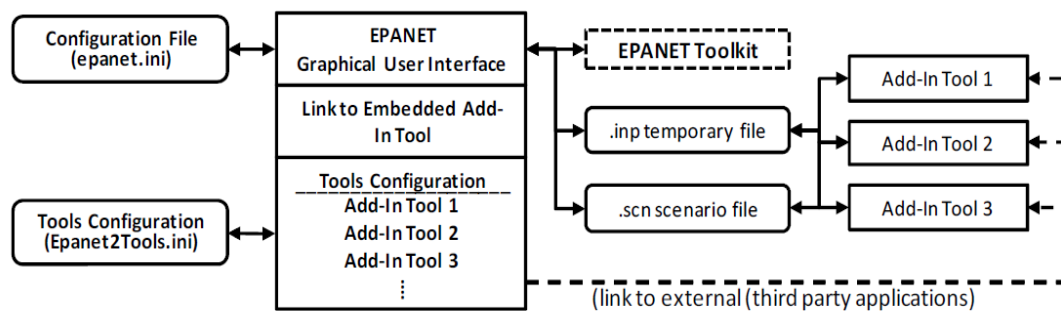


Figure 2-9: EPANET relationship with the Toolkit and Add-ins (Rossman, 2000).

2.17 MATLAB

MATLAB is a mathematical software used for programming and numeric computing (Mathworks, 2022). The latest version of MATLAB, R2021a, makes use of visualization, computation, and programming to solve problems mathematically. MATLAB was originally written in Fortran but is currently written in C.

MATLAB makes use of matrix calculations which save time in processing an answer. The use of the EPANET-MATLAB Toolkit makes connecting the two programs far easier. This program was created by Marios Kyriakou and Demetrios Eliadas. The Toolkit is free to download and can be found in the Open Water Analytics digital repository.

MATLAB offers an Integrated Development Environment using its own programming language, called M. This programming language allows MATLAB to perform operations with matrices, functions, and vectors, allowing it to communicate with programs written in other programming languages (Nino, et al., 2018).

2.18 WDN Objective Function

For WDN's, the objective function (OF) that can be used for optimisation is shown in equation (13):

$$\begin{aligned}
 F = & \sum_{i=1}^{N_P} C_{B,i} + \sum_{i=1}^{N_D} C_{P,i} \\
 & + \lambda_1 \sum_{i=1}^N \delta_i(P_{min,i} - P_i) + \lambda_2 \sum_{i=1}^N \delta_i(V_{min,i} - V_i) \\
 & + \lambda_3 \sum_{i=1}^N \delta_i(V_i - V_{max,i})
 \end{aligned} \tag{13}$$

Where F represents the objective function; $C_{B,i}$ represents the energy cost related to each of the N_P pumping stations; $C_{P,i}$ represents the cost to install each N_D pipeline; λ_1, λ_2 , and λ_3 are penalties for non-compliance of following design constraints: pressure $P_i > P_{min,i}$ and the velocity V_i must be in between the maximum and minimum velocity ($V_{max,i}$ and $V_{min,i}$ respectively). This function will result in the optimal pipe diameter and pressure head at the nodes (Fontana, et al., 2012).

To locate the optimal location and setting for a PRV, the mean square error between the actual and target pressure needs to be minimised, as shown in equation (14).

$$Z_j = \sum_{i=1}^n \gamma \times (P_{i,j} - P_{min})^2 \tag{14}$$

Where Z is the pressure in the WDN, j is the timestep, n = number of nodes, $P_{i,j}$ = pressure calculated at node i at the timestep j , P_{min} = target pressure, and γ = penalty coefficient. To ensure adequate service for consumer demand, the pressure must always be greater than P_{min} at the demand nodes (Fontana, et al., 2012).

2.19 Genetic Algorithm

A genetic algorithm (GA) can be utilised to find the optimal PRV location in a network. A GA is a search method that mathematically simulates natural selection and population genetics (Fontana, et al., 2012; Gencoglu & Merzib, 2017). GAs randomly generate solutions, keeping solutions with a higher OF and discarding solutions with a low OF. GA allows the user to see a range of several possible solutions that can then be chosen instead of only one solution (Fontana, et al., 2012). GA computation requires high computational requirements to reach the optimal solution. Due to most algorithms being created using a ‘hill climbing’ method, they tend to give results which usually fall in a local optimum, thus the results obtained depend on the initial weights and learning parameters (Castillo, et al., ND).

2.20 Case Study – Napoli Est, Italy

The following study was conducted by Fontana et al. (2012). Water losses in Italy range from between 20-65%, averaging around 42%. Managing the leakages within the network required a pressure management strategy. The reduction in pressure reduced leakage losses, while ensuring that the pressure is within acceptable limits in the network (Fontana, et al., 2012). Micro and mini-hydro generators can be implemented into WDNs to regulate the pressure in the system, reduce leakages and produce energy.

Fontana (2012) found that when operating the PAT in the WDN, finding the pump’s best efficiency point is important and usually varies between 40 to 80%. Before the implementation of pressure reducing equipment, the total losses were around 67%. These losses have been attributed to pipe corrosion and high-pressure heads. The network was hydraulically analysed using EPANET 2.0. Physical losses were distributed among all the nodes in the system.

The leakage flow rate at a generic node j at time t is given by equation (15):

$$\text{leakage node (emitters): } q_{lj} = C \times p_{tj}^{\alpha} \quad (15)$$

Where C = the emitter coefficient, and α = the emitter exponent (Fontana, et al., 2012). The emitter exponent assumed was $\alpha = 0.80$, and the emitter coefficient of $C = 0.02$ was determined after calibration. The optimal PRV location was determined by minimising the mean square error equation (Equation 14) between the target and actual pressure. The OF assumed a $\gamma = 10000$ for $P_{i,j} < P_{min}$ to force the equation to be invalid for any result where the nodal pressure is less than the minimum target pressure, shown in the following equation:

$$P_{min} = 25\text{m} \quad (16)$$

Due to the high flow rates and head drop over the valves, the use of PATs was a very suitable solution for pressure reduction and energy generation in this WDN. Due to this, the existing PRVs within the WDN were replaced with PATs to bring the added benefit of energy generation (Satish, et al., 2021). The leakages in the system dropped by approximately 30% due to pressure reduction (Fontana, et al., 2012).

The results showed an increase of real losses when replacing PRVs with PATs as some of the pressure dropped below the minimum target pressure of 25m. This was due to PATs not being able to accurately regulate their head loss ability like PRVs. The solutions were still accepted, as the pressure head did not drop below 20m. The optimal location for a PRV focuses on reducing pressure to reduce losses, not to maximise energy production, which is an added benefit (Fontana, et al., 2012). Water loss reduction is dependent on the head reduction across the valve, whereas energy production also depends on the flow rate in the pipe. The objective function used for PRV placement was one to minimise losses, not to maximise energy production. The coupling of reducing water losses with energy production within WDNs can provide water agencies with a way towards sustainable development. A favourable capital payback period was achieved between 2.5 and 3 years for the various scenarios (Fontana, et al., 2012).

2.21 Case Study – Kos and Kozani WDN, Greece

The following study was conducted by Kanakoudis and Gonelas (2014) on two WDNs in Greece, namely Kos and Kozani. Watergems V8i was used as the hydraulic analysis software. By managing the pressure within a WDN, the occurrence and magnitude of leaks and bursts can be reduced (Kanakoudis & Gonelas, 2014). Kanakoudis and Gonelas (2014) state that the optimal allocation of PRVs in DMAs using various scenarios should be tested for the WDN. The demand pattern is applied at the nodes of the model, as is commonly the case. The hydraulic model of Kos consists of 694 nodes, three water tanks, and 122.64km of pipes and water mains. The hydraulic model of Kozani consists of 1817 nodes, eight water tanks, and 211.86km of pipes and water mains. Fixed outlet PRVs were used and virtually installed into the WDNs, which regulated the downstream pressure to a fixed value irrespective of the upstream water pressure. Multi-point control modulated PRVs were also used, which can change their setting based on an internal timer.

As a result of the pressure management study within the two WDNs, the two networks achieved a reduced system input volume (SIV) ranging from 12.22% to 25.54%. The SIV reduction in the DMAs for the Kos ranged from 16% to 20%. The SIV reduction in the DMAs for the Kozani WDN ranged from 24% to 26%. The local authorities placed two PRVs within Kozani's WDN, resulting in higher-than-expected real-world water savings of up to 60%.

2.22 Summary

WDNs are used to transport water from a source to the consumer. WDNs in South Africa suffer from high leakage rates, which is a major contributor to NRW, increasing the cost of water. The NRW in Durban is approximately 32% which is in line with other developing countries. Pressure within the network directly affects leakage losses; thus, reducing network pressure will reduce the leakage rate in the network. PRVs can be strategically implemented into the WDN to reduce network pressure, consequently reducing the network leakage rate. There is a gap in research to create a methodology that optimises the placement and setting of pressure reducing valves within a network to minimise the network pressure and network leakage rate. By optimising the placement and setting of PRVs, the network leakage losses can be minimised. WDNs have variable demand patterns which affect the flow rate and pressure in the network throughout the day, further complicating the optimisation problem. Peak water demand is in the morning, approximately at 8 am, and in the evening, at approximately 7-8 pm. Excessive network pressures occur during periods of low demand, requiring pressure regulation.

Municipalities can reduce the costs involved with operating and maintaining WDN's by installing PAT's which generate electricity from excess head within the network. PATs can also regulate pressure downstream within the network, allowing users to receive consistent pressure. Pumps are generally easier to purchase and install and require less technical experience than conventional turbines to operate and maintain, thus making it more favourable and generally cheaper to use a pump as a turbine instead of using a conventional turbine. There is a gap in research to determine where to place PATs and how to set them to coincide with the variable demand pattern of WDNs. PATs need to undergo a feasibility analysis to determine their viability as short capital payback periods are favourable. PATs, if correctly positioned, can harness substantial amounts of renewable energy from existing WDNs.

EPANET can be used to analyse the hydraulic properties of WDNs and assist with technical decision making for water utilities. The use of the EPANET Toolkit allows EPANET to integrate with other programs, such as MATLAB, expanding its capabilities.

CHAPTER 3

3. CASE STUDY

Chapter 3 outlines the two hydraulic networks used in my study: The Cornubia Integrated Human Settlement Development Phase 2A and the PAT Marshal Housing Project. These two WDNs have been used in my thesis as a basis for optimising the placement and setting of PRVs to reduce nodal pressure and network leakage rates, in addition to harnessing energy from the WDNs using PATs.

3.1 Case Study 1: Cornubia Integrated Human Settlement Development Phase 2A

3.1.1 Title of Case Study:

Cornubia Integrated Human Settlement Development Phase 2A – Gravity Network Hydraulic Modelling Report.

J36250A – Revision 2

Case Study created: March 2019

3.1.2 Site Location

The proposed site is located in Cornubia, a mixed-use development situated North of Durban and South of King Shaka International Airport. Cornubia is accessible via the N2 Freeway. Figure 3-1 shows the approximate location of the proposed development at Cornubia. Cornubia is approximately 1200 hectares with approximately 80 hectares for industrial use (Business Tech, 2016). Cornubia Phase 2A is the site under consideration, situated between two proposed arterial roads, Dube East and Dube West. Phase 2A lies North of the proposed Cornubia Boulevard.

Cornubia is a very steep location with gradients exceeding 25% in certain locations (Nyirenda, 2019). The site location is to be uniformly graded in the future, which will assist and even out supply pressures in the pipeline. The Blackburn Reservoir feeds water into the pipe network via the Nominal Diameter (DN) 400mm bulk water pipeline to the Cornubia Retail Park. DN400mm is a temporary pipeline, which ties into the existing network and Phoenix 1 Reservoir.

3.1.3 Cornubia Water Distribution Network Description

The hydraulic analysis and results for the bulk water services and the reticulation services for Cornubia are to be analysed. Cornubia Phase 2A is split into three phases: Zone 1A, Zone 1B,

and Zone 2. Zone 1A is a low-lying area, Zone 1B is a higher-lying area, while Zone 2 is situated further north. The number of dwellings in each zone is shown in Table 3-1.

Description of Zones:

Table 3-1: Cornubia Phase 2A - Zone Make-up (Nyirenda, 2019).

| Supply/ Pressure Area Zone | Number of Dwellings | Population |
|-----------------------------------|----------------------------|-------------------|
| Zone 1A | 876 | 4380 |
| Zone 1B | 401 | 2005 |
| Zone 2 | 1184 | 5920 |
| Total | 2461 | 12305 |

3.1.4 Serviceable Area

The network under consideration services 2461 government subsidy houses of $40m^2$ in size. Each house has a 300-litre yard tank with a 6m top water level above the ground level. Yard tanks are utilised to supplement water flow to households during peak flow times where desired flow rates could drop. Roughly $5900m^2$ are for proposed community facilities.

There are two pressure zones within the area under consideration:

- Zone 1 is to be supplied from two metered network connection points.
- Zone 2 is to be supplied by one metered network connection point.

The connection points are located west of the development and are provided by the eThekwin Municipality. The two zones receive water directly from the bulk water pipelines.



Figure 3-1: Approximate location of Phase 2 of the Cornubia Integrated Human Settlement Development (Google Earth Pro, 2020)

3.1.5 Scope of Works

This report will focus on a portion of the Cornubia Development, specifically Zone 1 of Phase 2A. Phase 2A is approximately 31 hectares in size. Figure 3-2 shows where Cornubia's Phase 2A is situated in relation to the surrounding areas.



Figure 3-2: Cornubia - Phase 2A Location (Nyirenda, 2019)

3.1.6 Properties of the Pipeline

The head supplied to the connection points from the bulk pipeline are to be taken as a minimum of 30m. Zone 1 makes use of the DN400 bulk water supply pipeline as its primary water supply.

17m is the minimum head to be supplied during all flow conditions: average, peak, and fire flow rates (Nyirenda, 2019). These are measured heads at the critical nodes and connection points within the network.

3.1.7 Design Methodology for Phase 2A

Proposed Infrastructure

eThekwini Municipality is responsible for constructing the second stage of the Blackburn Reservoir, making its top water level a height of 146m above Mean Sea level (MSL). Due to the location's steep topography, an elevated storage tank at Blackburn Reservoir will be required to service high altitude zones within the northern development.

The assumed constant supply pressure head at the two inlet connection points from Blackburn Reservoir is 30m. The invert levels of the two connection points from the DN400 pipeline are 103.84m and 94.67m above MSL.

There are to be two major pressure management zones, namely: Zone 1 and Zone 2.

- Zone 1 is the southern portion of the site. Zone 1 also incorporates portions of the site below the 121m contour line. Zone 1 is further broken down into Zone 1A and Zone 1B. Zone 1A is the lower-lying area, and Zone 1B is the higher lying area. Zone 1 will be completed before Zone 2 and before the construction of the elevated tank situated at Blackburn Reservoir. Zone 1 will be supplied by the temporary DN400 bulk supply pipeline. Zone 1 will be supplied by two metered connection points directly from bulk pipelines located west of the development.
- Zone 2 is the northern portion of the site. Zone 2 also consists of portions above the 121m contour line, as well as some portions between the 91m and 121m contour lines. Zone 2 is to be supplied by the proposed elevated storage tank situated at Blackburn Reservoir, as it is at higher elevations. This consists of only one metered connection point to the WDN.

Figure 3-3 from the GIBB Report (J36250A-Revision 2) (Nyirenda, 2019) shows how Phase 2A is subdivided into Zones 1A, 1B, and 2. Only Zone 1 will be analysed in my report as only data for Zone 1 has been hydraulically modelled.

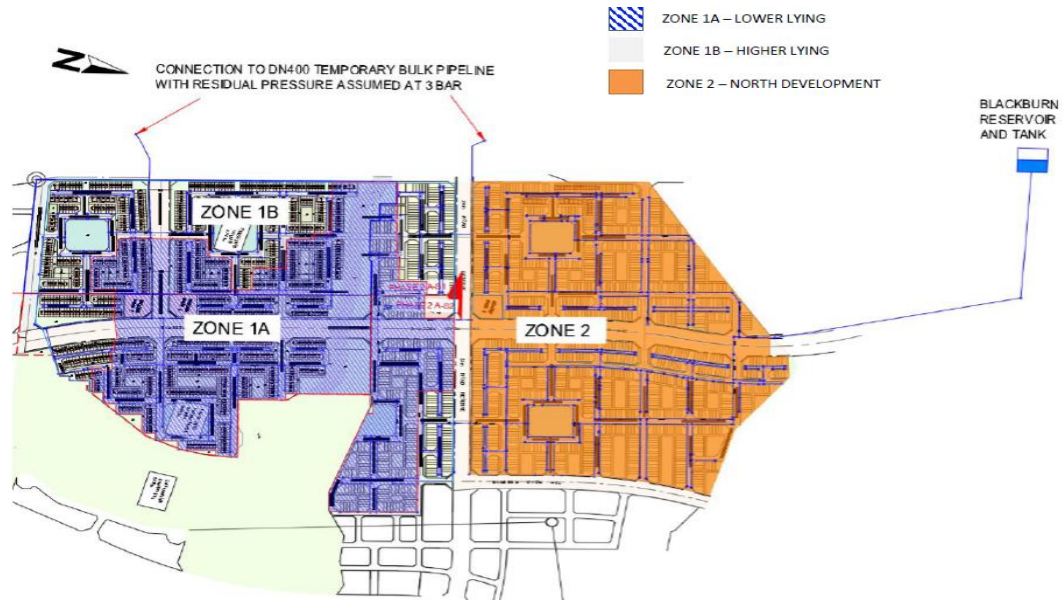


Figure 3-3: Subdivision of Cornubia Phase 2A into Zones (Zone 1A, Zone 1B, and Zone 2) (Nyirenda, 2019)

3.1.8 Hydraulic Model Creation for EPANET from GIBB (Nyirenda, 2019)

GIBB has assumed the following Design Considerations to create the Hydraulic Model for Zone 1 of the Cornubia Development. This model is based on standard guidelines from the “Guidelines for Human Settlements Planning and Design – The Red Book (CSIR Building and Construction Technology, 2005)”.

Blackburn Reservoir was assumed to provide a constant head of 30m to Zone 1 via two connection points to the temporary DN400 bulk supply pipeline. The bulk water supply points were considered to be DN300 steel pipes. These pipes have a roughness of 0.1mm when utilising the Darcy-Weisbach equation (Nyirenda, 2019). The internal network pipes were modelled as DN110 and DN75 uPVC SANS 966-1 pipes. The DN110 and the DN75 uPVC pipes have a Darcy-Weisbach roughness of 0.03mm (Nyirenda, 2019). Pipeline elevations were used from Google Earth Pro. The network consists of seventy-five fire hydrants located along the DN110 and DN75 pipelines. Low-risk category three fire hydrant characteristics were assumed (CSIR Building and Construction Technology, 2005).

3.1.9 GIBB Hydraulic Model Results

- When analysing the Average Daily Flow:
 - Four nodes were found to be below the minimum recommended pressure of 24m. Of these four nodes, the minimum pressure was 21.5m, which can be regarded as acceptable. A minimum pressure head of 5m is required for supply to roof tanks during these flow periods.
 - No nodes experienced a pressure head above the maximum pressure head of 90m (CSIR Building and Construction Technology, 2005).
- When analysing Peak Daily Flow:
 - Five nodes had pressures below the recommended minimum pressure head of 24m. The lowest pressure was 21.3m. No nodes had pressures exceeding 90m.
 - Lower pressures can be expected as the demand is increased during peak flow conditions.
 - As mentioned above, these minimum pressures can be accepted.
- When analysing Average Flow and Fire Flow Combined:
 - Nine nodes had pressures below the recommended minimum pressure head of 24. The lowest pressure head was 17m. No nodes experienced a pressure head above 90m.
 - As mentioned above, these minimum pressures can be accepted.
 - The fire flows are assumed to be for 1-hour periods according to the Red Book Volume 2 as the fire risk category is seen as Low-Risk (CSIR Building and Construction Technology, 2005).
 - This flow condition has the highest flow velocity of 1.96m/s. This is a result of the excess demand due to the fire hydrant being active in the distribution network.

3.2 Case Study 2: Pat Marshal Housing Project

3.2.1 Title of Case Study:

Pat Marshal Housing Project

Water Preliminary Design Report – Rev B

Case Study created: September 2018

The case study report containing the information of the proposed Pat Marshal Housing Project has been produced by the eThekweni Municipality Human Settlements, Engineering and Transport division.

3.2.2 Site Location

The Pat Marshal housing project is approximately 3km west of the Phoenix suburb and 2km northwest of the Phoenix Industrial Area in Inanda. The site is surrounded by informal and formal settlements, as shown in Figure 3-4.

The proposed land use for the project is shown in Table 3-2. The total area of the development is 8.32 Ha.

Table 3-2: PAT Marshal - Proposed Land use (Xozwa, 2020)

| Land use | Number of Sites | Area (Ha) |
|-----------------|------------------------|------------------|
| Residential | 479 | 4.3548 |
| Roads | 1 | 1.5683 |
| Commercial | 1 | 0.0196 |
| Creche | 1 | 0.5531 |
| Park | 1 | 0.1839 |
| Undeveloped | 1 | 1.7145 |
| Total | | 8.3942 |



Figure 3-4: Pat Marshal site location situated in Bhambayi (Google Maps, 2021).

3.2.3 Pat Marshal Housing Project Network Description

The Pat Marshal development aims to provide houses to residents from the Bhambayi Informal Settlement on 8.4ha of undeveloped land, on Erf 315 and Erf 259, within the eThekweni Municipality. The site is proposed to provide 478 low-cost semi-detached houses, a creche, a park, and a commercial area. The houses are between 80 m^2 and 110 m^2 . The proposed development will require approximately 0.539ML/day (inclusive of 25% losses and excluding fire flows) under peak summer demand and a 1.078ML storage capacity (Xozwa, 2020).

The proposed development will be supplied via the Phoenix 4 Reservoir, operating at 170.22m top water level (Xozwa, 2020). Water flow logging tests have indicated a 62,12% leakage factor on reservoir flows. The pressure for the proposed development is expected to range from 45.6m to 61.9m (at tie-in).

3.2.4 Properties of the Pipeline and Site details

The proposed pipeline has been designed according to the eThekweni Municipality Guidelines and Specifications and other accepted service guidelines, standards, and specifications. Two DN400mm water trunk mains centrally traverse the proposed site. These two pipes feed Phoenix 4 Reservoir Umgeni Water Works in Reservoir Hills. The site chosen has a gentle slope from north to southwestern, with gradients ranging from 3.5% to 10%.

3.2.5 Design Methodology for PAT Marshal Housing Project

Phoenix 4 Reservoir has an average flow of 962kl/hr and 1664kl/hr peak flow from its two tanks. There is a 62.12% water leakage rate during peak demand flow. The Pat Marshal Housing Project is designed considering the average water demand, peak water demand, and the average water demand + fire hydrant. The following design criteria were used to model the network (Xozwa, 2020):

- Low-cost residential flows: 600l/erf/day
- Summer peak factor: 1.5
- Instantaneous daily peak: 4.2
- Losses: 25%
- Fire category: 12000l/day
- Minimum residential head: 25m
- Maximum head: 60m
- Roughness coefficient for mPVC and Asbestos cement pipe: 0.0015
- 15mm diameter HDPE Class 16 will be used for Single House connections
- 25mm diameter HDPE Class 16 branching into two 20mm diameters for Double House connections.
- 75-100mm diameter UPVC Class 12 SS pipe sizes will be used for the distribution mains.
- 160mm diameter UPVC Class 12 SS will be the maximum pipe size for the distribution mains.
- Each branch will have an isolation valve to allow for maintenance.
- 3 Fire hydrants will be provided at different locations.

3.2.6 Vuv'amu Hydraulic Model Results

The Phoenix 4 Reservoir is a 35ML Reservoir with an operating capacity of between 30% and 35% of its total capacity. Thus, the reservoir does not have the required storage of 1.078ML for 48 hours. This results from the high leakage rate of approximately 62% downstream of the reservoir leading to high water demand (Xozwa, 2020). A high leakage rate will lead to greater demand on the reservoir. A reduction in leakage will increase the potential for the reservoir to be filled up without an additional water supply. The bulk pipeline infrastructure comprises DN400mm and DN600mm pipes from the reservoir to the proposed Pat Marshal development. The flow capacity at 1m/s is 452kl/hr and 1017.87kl/hr, respectively (Xozwa, 2020). There has been no provision for future expansion. Xozwa (2020) mentions that methods to reduce the leakage rate should be of paramount importance.

CHAPTER 4

4. METHODOLOGY

4.1 Introduction

This chapter outlines the methodological approach to optimise the location and setting of pressure reducing valves within a WDN. A new algorithm for optimization is proposed, which uses linear programming and an iterative linearization of the problem constraints, based on the linear theory method of network analysis. The objective function (OF) will prioritise network leakage reduction when choosing the PRV location and setting and determine PAT placement as a secondary benefit. This new OF is split into two stages. Stage 1 determines the optimal location and setting of a PRV to minimise network leakage rates. Once the PRV has been optimally placed, stage 2 of the OF will be implemented. Stage 2 determines the economic viability of replacing a PRV with a PAT to harness energy from excess pressure. Stage 2 will determine the optimum configuration of PRVs and PATs within the network.

EPANET and MATLAB were used to create the optimisation program that is used to solve the two-stage OF. The mathematical formulation for minimising leakage rate within a WDN and feasible PAT implementation will now be described.

4.2 Experimental Apparatus

The experimental apparatus used for creating the optimisation program are the following:

- Network Data
- EPANET version 2.2
- MATLAB R2018b
- EPANET-MATLAB Toolkit v2.2

4.3 New Optimisation Model

4.3.1 Variables

A WDN is made up of n nodes and l links. A computer program has been created using MATLAB R2018b and EPANET 2.2 to determine the optimal number, location, and setting of a combination of PRVs and PATs. The PRVs and PATs will reduce pressure, consequently reducing leakage losses and generating renewable energy. Every pipe k in the network will be checked for possible PRV placement. The k th pipe of the network at time t will thus produce a headloss $H_k^{PRV}(t)$ due to the PRV (Fecarotta & McNabola, 2017).

Fecarotta (2017) suggests the use of a binary variable that indicates the presence of a PRV be used for each link in the network: PRV_k . The program will first determine if a link already contains, or is adjacent to, an existing PRV and exclude that link from possible selection. A PRV cannot be replaced with a PRV, nor can a PRV be connected adjacent to another PRV. $PRV_k = 1$ represents PRV placement is possible, $PRV_k = 0$ represents PRV placement is impossible.

The total number of PRVs can be checked using this function to determine PAT feasibility. The implementation of a PRV affects the network's flow $Q_k(t)$ through the k th pipe as well as the head $H_i(t)$ at the i th node. If a node is a reservoir or tank, all connected links will be excluded from selection.

The program has been created in MATLAB and uses EPANET 2.2 as the hydraulic solver. This is achieved with the EPANET-MATLAB Toolkit v2.2. The water demand pattern changes throughout the day and is modelled at the nodes. The demand for each node $q_i^d(t)$ is thus time-dependent and calculated as:

$$q_i^d(t) = c_d(t) \times \overline{q_i^d} \quad (17)$$

Where $\overline{q_i^d}$ is the average demand of the i th node and $c_d(t)$ is the variable demand pattern coefficient. The variable demand pattern is input directly into EPANET. It is time dependent as water use changes hourly, shown in Figure 4-2. Due to the nature of water-use patterns, the variable demand pattern coefficient can be the same at multiple time steps.

Fecarotta (2017) states that the daily demand pattern can be divided into n_t timesteps of Δt_i hours, thus the number of variables are:

$$\left\{ \begin{array}{ll} PRV_k & l \\ H_k^{PRV}(t) & l \times n_t \\ Q_k(t) & l \times n_t \\ H_i(t) & n \times n_t \end{array} \right. \quad (18)$$

4.3.2 Variable Demand Pattern

The water consumption used by residential consumers is not constant throughout the day; it varies hourly. There are usually two peaks during the day, one in the morning and one in the evening (Muya, 1996). The morning peak for high-density houses is at 6 am, while it is at approximately 8 am for low-density houses. The evening peak occurs at approximately 7 pm for high-density houses and 9 pm for low-density households, as shown in Figure 4-1.

The peaks coincide with when household members leave for work or school and get back home from work or school. The evening peak for high-density South African households is early because they have to wake up earlier to travel for work (Muya, 1996). Muya (1996) observed that people staying in high-density households generally have a greater distance to travel to get to work than people staying in low-density households. The earlier water use peak times could also be attributed to more people using the points of water, such as the bathrooms, to use the available hot water efficiently. The analysis for summer will be used as summer generates the greatest water usage, resulting in a ‘worst-case’ water usage case.

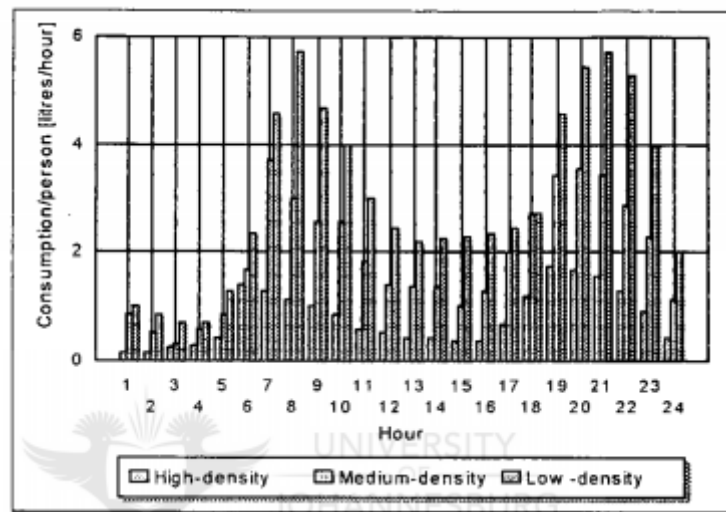


Figure 4-1: The hourly variation of water usage per person per day during summer (Muya, 1996).

The water usage period used in this study will be an average of low-density and high-density household characteristics. The peak morning usage will be at 7 am, and the peak evening water usage will be at 8 pm.

The variable demand pattern used for my study is shown in Table 4-1 and in Figure 4-2.

Table 4-1: Variable Daily Demand pattern for the Cornubia and Pat Marshal WDNs.

| Variable Daily Demand pattern used for the Cornubia and Pat Marshal WDN | | | | | | | | | | | | |
|---|------|------|-----|-----|-----|------|-----|-----|------|-----|------|-----|
| Time Period (Hour) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Multiplier | 0.1 | 0.1 | 0.1 | 0.2 | 0.4 | 0.8 | 1 | 0.8 | 0.6 | 0.5 | 0.45 | 0.4 |
| Time Period (Hour) | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| Multiplier | 0.35 | 0.35 | 0.4 | 0.4 | 0.4 | 0.45 | 0.8 | 1 | 0.75 | 0.4 | 0.2 | 0.1 |

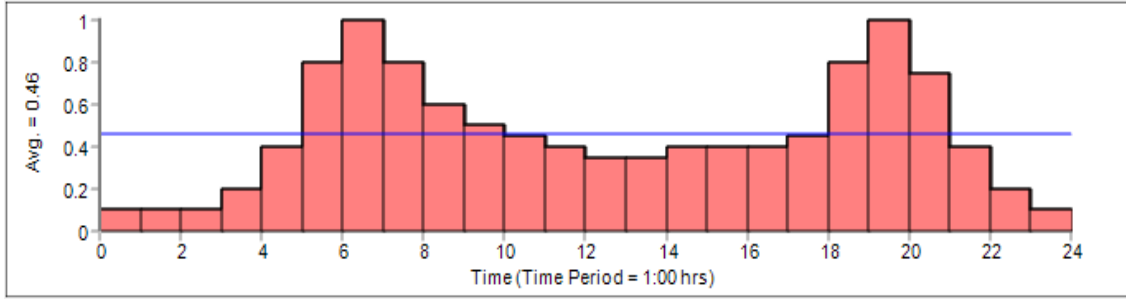


Figure 4-2: Variable Daily water demand pattern for the Cornubia and Pat Marshal WDNs shown graphically.

4.4 Objective Function

There is a two-stage OF that will be used.

- Stage 1: Is further broken down into two substages, namely:
 - Stage 1a: Will determine the optimum location to place a PRV to maximise the network leakage rate (minimise network leakage losses) within the network.
 - Stage 1b: Will determine the optimum setting for the PRV being added to the network.
- Stage 2: occurs after Stage 1 and determines the feasibility of replacing a PRV with a PAT for energy generation.

4.5 Stage 1: Determine the Optimal Location and Setting of a PRV

4.5.1 Stage 1a: Determine PRV location to Maximise Network Leakage Rate Reduction

According to Araujo (2006), the leakage in the system can be allocated to the nodes of the network as a pressure-driven demand (PDD). The leakage flow rate of a fluid through an orifice can be calculated by (Van Zyl, 2004; Araujo, et al., 2006) equation 19 :

$$q_i^L = C_{L,i} \times (H_i)^\alpha \quad (19)$$

Where q_i^L = flow rate from the orifice (L/h), L represents leakage, $C_{L,i}$ represents the leakage coefficient constant, H_i = pressure head in the pipe (m), and α = leakage exponent. Based on current literature (Van Zyl, 2004; Greyvenstein & Van Zyl, 2007), the leakage exponent of $\alpha = 0.5$ can be generally used and will be utilised in this analysis. The leakage coefficient chosen will be negligible as the leakage reduction in the system is to be determined and not the actual leakage amount, using equation 19. A leakage coefficient of 0.001 has been used (Fecarotta & McNabola, 2017). This was done to minimise the leakage's effect on the network's analysis to theoretically determine the change in leakage rate.

Leakage in the system affects the demand at the nodes, as higher leakage rates increase demand. The actual demand at a node is thus the summation of the base demand and the leakage demand, as shown:

$$q_{i,bp}^{d,Act}(t) = q_{i,bp}^{d,Base}(t) + q_{i,bp}^{d,L}(t) \quad (20a)$$

$$q_{i,ap}^{d,Act}(t) = q_{i,ap}^{d,Base}(t) + q_{i,ap}^{d,L}(t) \quad (20b)$$

Where d,Act represents the actual demand, $d,Base$ represents the base demand, and d,L represents the leakage demand. The subscripts bp and ap represent before the addition of the PRV and after the addition of the PRV, respectively.

Rearranging this equation, we make the leakage rate the subject of the formula, as follows:

$$q_{i,bp}^{d,L}(t) = q_{i,bp}^{d,Act}(t) - q_{i,bp}^{d,Base}(t) \quad (21a)$$

$$q_{i,ap}^{d,L}(t) = q_{i,ap}^{d,Act}(t) - q_{i,ap}^{d,Base}(t) \quad (21b)$$

The summation of all the nodes' leakages is taken for each PRV placement. This will give the total leakage for the network before and after PRV installation as follows:

$$Q_{N,bp}^{d,L} = \sum_{i=1}^I \sum_{t=0}^T q_{i,bp}^{d,L}(t) \quad (22a)$$

$$Q_{N,ap}^{d,L} = \sum_{i=1}^I \sum_{t=0}^T q_{i,ap}^{d,L}(t) \quad (22b)$$

Where N represents the WDN, I is the total number of i nodes, and T represents the total time for hydraulic simulation.

The percentage change in leakage rate for the WDN can be given by:

$$\Delta L_{rate\ reduction} = \left[\frac{Q_{N,bp}^{d,L} - Q_{N,ap}^{d,L}}{Q_{N,bp}^{d,L}} \right] \times 100 \quad (23)$$

Where $\Delta L_{rate\ reduction}$ represents the leakage rate reduction in the network due to PRV implementation. Introducing a PRV reduces the pressure in the pipeline and downstream pipes, and thus the whole WDN. Equation 23 was checked for every PRV installation to determine the leakage rate reduction in the network after hydraulic simulation.

The OF for Stage 1 has been chosen as the PRV placement that maximises the leakage rate reduction to the WDN as a whole. This is equivalent to minimising the network leakage losses in the network, proposed by Gencoglua and Merzib (2017), as follows:

$$\text{Maximise } (\Delta L_{\text{rate reduction}} = \left[\frac{Q_{N,bp}^{d,L} - Q_{N,ap}^{d,L}}{Q_{N,bp}^{d,L}} \right] \times 100) \quad (24)$$

To maximise the leakage rate reduction, the PRV needs to be optimally placed within the network. PRVs can only be placed in pipes that meet strict criteria.

4.5.1.1 Constraints

The optimised placement of any pressure regulating equipment (PRE) is subject to several constraints. There are also technical limitations of the variables related to the behaviour and structure of the network.

4.5.1.1.1 Hydraulic constraints

Two factors need to be considered: the pipes and the nodes. These two factors have hydraulic constraints: the mass continuity equation constraints at the nodes and the momentum balance constraint along the pipes. The continuity equation is:

$$q_i^d = \sum_{k \in K_i} Q_k^{in} - \sum_{k \in K_i} Q_k^{out} - C_{L,i} \times (H_i)^\alpha \quad (25)$$

Where Q_k is the discharge flowing through the k th link contained in the set K_i of links connected to the i th node (Fecarotta & McNabola, 2017). The superscripts *in* and *out* indicate whether the discharge flows into or out of the node, respectively.

A continuity equation can be written for each node. The momentum balance equation can be described as:

$$H_i - H_j - \Delta H_k - PRV_k \times H_k^{PRV} \times (\text{sign of } Q_k) = 0 \quad (26)$$

Where i and j are the start and end nodes, respectively, of pipe k , and ΔH_k is the headloss along the k th pipe. The headloss due to the PRV is always positive. The headloss term is multiplied by the sign of the flow, (*sign of* Q_k), to account for the direction of flow through the pipe.

The headloss (ΔH_k) along the k th pipe has been calculated using the Darcy-Weisbach friction factor equation:

$$\Delta H_k = f_k \times \frac{\Delta s_k \times (v_k)^2}{D_k \times 2 \times g} \quad (27)$$

Where f_k is the Darcy friction factor, Δs_k is the distance (along the flow direction) that the headloss is being considered for, v_k is the mean flow velocity, and D_k is the diameter of the k th pipe.

4.5.1.1.2 Linear Constraints

The linear constraints are made up of line constraints and boundary conditions. The CSIR Building and Construction Technology (2005) limits the pressures acceptable within a WDN. These are the boundary constraints P_{min} and P_{max} which are 24m and 90m, respectively. These boundary conditions can be written as:

$$P_{min} \leq H_i - Z_i \leq P_{max} \quad (28)$$

Where Z_i is the elevation of the i th node (Fecarotta & McNabola, 2017). All nodes are subject to these constraints except reservoirs and tanks. There must also be no nodes in the network that are subject to negative pressures.

The PRV headloss should always be positive, according to equation 26, thus:

$$H_k^{PRV} \geq 0 \quad (29)$$

Ensuring that the headloss has the same direction as the discharge. This is especially important for PAT implementation as the PAT cannot produce energy if the flow direction changes. To place a PRV, the network must first be checked for existing PRVs, as PRVs cannot be connected adjacent to each other. This can be expressed using the binary function as follows:

$$PRV_k = 0 \quad (PRV_i = 0 \text{ or } PRV_j = 0) \quad (30)$$

This ensures that no PRV can be placed in the k th pipe if the i th or j th node of the pipe contains an existing PRV connection. This expression is extended to ensure PRVs are not connected to any existing reservoirs or tanks either, as shown in equations 31 and 32, respectively:

$$PRV_k = 0 \quad (RES_i = 0 \text{ or } RES_j = 0) \quad (31)$$

$$PRV_k = 0 \quad (TANK_i = 0 \text{ or } TANK_j = 0) \quad (32)$$

Where RES_i and RES_j represent the reservoir connected to the i th and j th node of the k th pipe respectively, and $TANK_i$ and $TANK_j$ represent a tank connected to the i th and j th node of the k th pipe, respectively.

The program will add PRVs into the system until no additional PRVs can be added, as the constraints are violated (Araujo, et al., 2006). This will be the optimal placement and number of additional PRVs that can be added to the network.

4.5.2 Stage 1b: Determine Optimal PRV settings

The addition of a PRV into the network should not reduce the pressure downstream in the network to below P_{min} . A tolerance of 10% has been used, allowing a further $0.1 \times I \leq P_{min}$ to be below the minimum pressure in the network, where I is the total number of nodes in the network. This tolerance has been chosen as a network usually has some nodes below the minimum acceptable pressure, requiring minor violations in the target pressure requirement (Vairavamoorthy & Lumbers, 1998). Setting a tolerance limit to the number of nodes that can violate the minimum pressures allows the network to be better optimised (Vairavamoorthy & Lumbers, 1998).

We use the binary variable $MINP_i$ to determine if a node is below P_{min} , as shown:

$$MINP_i = 1 \quad \left(\left\{ \frac{1}{T} \times \sum_{t=0}^T H_i(t) \right\} \leq P_{min} \right), \quad (i \in I) \quad (33)$$

$$I_{max}^{P_{min}} = \sum_{i=1}^I MINP_i + 0.1 \times I \quad (34)$$

Where $I_{max}^{P_{min}}$ represents the maximum number of nodes allowable below the minimum pressure. After PRV addition, the hydraulic analysis is run to find the number of nodes below the minimum pressure, as follows:

$$I^{P_{min}} = \sum_{i=1}^I MINP_i \quad (35)$$

The setting of the PRV will be increased incrementally to satisfy equation 34, according to:

$$H_k^{PRV}(t) = H_k^{PRV}(t-1) + 1 \quad (I^{P_{min}} \geq I_{max}^{P_{min}}), (t > 1) \quad (36)$$

When, after hydraulic analysis, $I^{P_{min}} \leq I_{max}^{P_{min}}$, the PRV can be said to be optimally set for that location within the WDN, subject to all other constraints mentioned being met.

4.5.3 Determine the Optimum Number of PRVs to be added into the Network

The addition of a PRV must not result in any previously added PRV being set to open or bypassed. This will negate the effects of adding in that PRV and is thus unfavourable. The optimum number of PRVs will thus be the number of PRVs added into the network before this condition has been breached.

4.6 Stage 2: Feasibility analysis of a PAT replacing a PRV

All the PRVs in the network (existing plus additional due to Stage 1) will be checked to see if they can be financially replaced by a PAT. This is done by considering the variable demand pattern in the network, the energy produced by the PAT, and the PATs associated costs to calculate its Capital Payback Period (CPP).

The total number of PRVs in the network can be determined by summing all the binary indicators for PRVs as shown:

$$PRV_k^{Total} = \sum_{k=1}^K PRV_k \quad (37)$$

Where K represents the total number of links.

The variable demand pattern present in the network will change the flow rate and pressure at each link and node, respectively, at any time throughout the day (Germanopoulos & Jowitt, 1989; Vairavamoorthy & Lumbers, 1998; Gencoglu & Merzib, 2017).

A standardised centrifugal pump can be operated in reverse to be used as a turbine without the need to make any design changes or changes to the impeller geometry (KSB, ND). Pumps have a best efficiency point (BEP) when run in turbine mode, allowing an almost shock loss-free fluid flow. The BEP ensures that the pump used in turbine mode runs as smoothly as the pump running in pump mode at its design point. Running the PAT at BEP ensures the least amount of wear on the pump. The flow rate and the turbine head are always greater at BEP in turbine mode than the flow rate and head in pump mode at the same rotational speed (KSB, ND; Fontana, et al., 2012). A PAT should be operated at its BEP to optimise its energy output and minimise costs (Van Vuuren, et al., 2011; Fontana, et al., 2012; De Marchis, et al., 2014). A new binary variable, $PAT_k(t)$, needs to be introduced to account for PATs in the network.

The average headloss and flow rate across the PRV that falls within the PATs operable BEP range has been used for power generation. This allows for the PAT to be bypassed during periods of

low pressure, such as during high demand periods. This is dependent on the variable demand pattern of the network.

The PAT should be installed via a bypass line (Carravetta, et al., 2012). The bypass line includes external control valve limiting flow into the PAT only when required.

For each timestep (t) where the PAT can be operated, the binary PAT function will be true, as follows:

$$PAT_k^H(t) = 1 \quad (H_k^{PATmin} \leq H_k^{PRV}(t) \leq H_k^{PATmax}) \quad (38)$$

where H_k^{PATmin} and H_k^{PATmax} represents the PATs pressure minimum and maximum during BEP, respectively. The headloss across the PRV that falls within the PATs BEP range will be determined using the binary function expressed in equation 38. Equation 39 indexes the headloss that can be utilised for power generation:

$$H_k^{PAT}(t) = H_k^{PRV}(t) \times PAT_k^H(t) \quad (39)$$

The pump's H_k^{PATmax} and H_k^{PATmin} have corresponding flow rate values at BEP: Q_k^{PATmin} and Q_k^{PATmax} , respectively (Derakhshan & Nourbakhsh, 2008a; Derakhshan & Nourbakhsh, 2008b; Patelis, et al., 2017; Caprari, 2021; Grundfos, 2021). The corresponding flow rates across the PAT that coincide with the times when $H_k^{PAT}(t) > 0$, when the PAT is turned on, can be expressed as follows:

$$PAT_k^Q(t) = 1 \quad (Q_k^{PATmin} \leq Q_k^{PRV}(t) \leq Q_k^{PATmax}) \quad (40)$$

$$Q_k^{PAT}(t) = Q_k^{PRV}(t) \times PAT_k^Q(t) \quad (41)$$

The actual time that the PAT is operational per day under BEP conditions needs to be determined using equations 38 to 41. The total PAT operational time can be expressed as:

$$T_{k,Day}^{PAT} = \sum_{t=1}^T [PAT_k^H(t) \times PAT_k^Q(t)] \quad (42)$$

Where T represents the total operational time per day (hours). The average headloss across the PAT, and thus the average flow rate across the PAT, can now be determined as follows:

$$H_k^{PAT} = \frac{\sum_{t=1}^{T^{PAT}} H_k^{PAT}(t)}{T_{k,Day}^{PAT}} \quad (43)$$

$$Q_k^{PAT} = \frac{\sum_{t=1}^{T^{PAT}} Q_k^{PAT}(t)}{T_{k,Day}^{PAT}} \quad (44)$$

4.6.1 PAT-Pump conversion

To convert the pump to a PAT, the following relation has to be used, according to results obtained from experimental analysis (Derakhshan & Nourbakhsh, 2008a; Derakhshan & Nourbakhsh, 2008b; Fontana, et al., 2012; De Marchis, et al., 2014; De Marchis & Freni, 2015):

$$Q_k^{PAT,c} = \frac{Q_k^{PAT}}{\eta_{pump,BEP}^{0.8}}, \quad H_k^{PAT,c} = \frac{H_k^{PAT}}{\eta_{pump,BEP}^{1.2}} \quad (45)$$

Where $\eta_{p,BEP}$ is the efficiency of the pump (*pump*) at BEP. The superscript *c* represents that the PAT has undergone the conversion from a pump at BEP. The BEP of a PAT can be said to coincide with the pump's BEP (Fontana, et al., 2012).

The average headloss due to the proposed PAT, $H_k^{PAT,c}$, and the average flow rate, $Q_k^{PAT,c}$, can be used to determine the PATs theoretical power output as follows:

$$P_k^{PAT} = \rho \times g \times Q_k^{PAT,c} \times H_k^{PAT,c} \times \eta_{PAT} \quad (46)$$

where P is the power in kW, ρ is the density of the fluid, in this case, 1000 kg/m^3 , g is the acceleration due to gravity of 9.81 m/s^2 , and η_{PAT} is the PAT's efficiency, taken at BEP (Fontana, et al., 2012; De Marchis, et al., 2014).

4.6.2 Determine the Feasibility of replacing a PRV with a PAT

The feasibility for each PAT replacement has been calculated using this theoretical power output in the form of the PAT's CPP. The CPP calculation for each PAT is as follows:

$$EGE^{PAT} = R^{PAT} \times 1.3 \quad (47)$$

Where EGE is the energy generation equipment (EGE) cost in Rands and R^{PAT} is the cost of the PAT. The installation of the pump is assumed to be 30% of the cost of the pump. The cost of civil works (CW) is assumed to be 30% of the value of the EGE:

$$CW^{PAT} = EGE^{PAT} \times 30\% \quad (48)$$

The maintenance cost (MC) is assumed to be 15% of the total EGE and CW cost:

$$MC^{PAT} = (EGE^{PAT} + CW^{PAT}) \times 15\% \quad (49)$$

The annual yearly energy production (AYEP) in kWh per annum is calculated as follows:

$$AYEP^{PAT} = P^{PAT} \times T_{k,Day}^{PAT} \times T_{k,Year}^{PAT} \quad (50)$$

Where $T_{k,Year}^{PAT}$ is the operational time for the PAT per year, taken as 335 days to account for PAT maintenance and down-time. The annual financial savings (AF) of the PAT is as follows:

$$AF^{PAT} = [R^{Selling} \times AYE^{PAT}] - MC^{PAT} \quad (51)$$

Where $R^{Selling}$ is the selling price of energy (R/kWh), which is R2.17 per kWh (Global Petrol Prices, 2021). Using equations 47 to 51, the CPP for each PAT can be determined as follows:

$$CPP^{PAT} = \frac{EGE^{PAT} + CW^{PAT}}{AF^{PAT}} \quad (52)$$

A maximum recommended CPP, CPP_{max}^{PAT} , of 2.5 years for PAT implementation has been used (De Marchis & Freni, 2015). A CPP greater than 2.5 years can be regarded as unfeasible for PAT replacement and must thus remain a PRV to optimise leakage reduction, as follows:

$$CPP_{min}^{PAT} \leq CPP^{PAT} \leq CPP_{max}^{PAT} \quad (53)$$

Where CPP_{min}^{PAT} is zero. The zero boundary stops the CPP from being negative, which indicates that the maintenance cost of implementing the PAT is too high, making the AF^{PAT} negative and the PAT unfeasible. A binary function can be implemented using the constraints in equation 53 to isolate all the PRVs that are feasible for PAT replacement:

$$PAT_k^{Feasible} = 1 \quad (CPP_{min}^{PAT} \leq CPP^{PAT} \leq CPP_{max}^{PAT}) \quad (54)$$

Where $PAT_k^{Feasible}$ determines if the PAT is feasible. The number of feasible PATs can be determined by:

$$PAT_k^{Total} = \sum_{k=1}^K [PRV_k \times PAT_k^{Feasible}] \quad (55)$$

4.6.3 Determine the Total Energy output of the PAT Configuration

The total energy output of all the PATs in the system can be determined by:

$$E^{Total} = \sum_{k=1}^K [P_k^{PAT} \times PAT_k^{Feasible}] \quad (56)$$

where E^{Total} represents the total energy output in kW.

Stage 2 of the OF extracts the maximum energy from the system according to the constraints mentioned above, as shown:

$$Maximise (E^{Total} = \sum_{k=1}^K [P_k^{PAT} \times PAT_k^{Feasible}]) \quad (57)$$

4.7 EPANET and EPANET-MATLAB Toolkit

EPANET 2.2 software has been used as the hydraulic modelling and analysis software. EPANET is free, open-source software created by the United States Environmental Protection Agency to model water distribution networks (EPA, 2020). EPANET is Microsoft Windows-based and can be integrated with many programming languages to enhance its capabilities. EPANET has grown in popularity among users due to its intuitive GUI, making the visualisation of data easy to understand (Araujo, et al., 2006).

EPANET contains an accurate hydraulic analysis engine used to solve the hydraulic equations to accurately model the hydraulic network. The EPANET-MATLAB Toolkit allows greater customization of EPANET to suit the user's needs. The Toolkit is a DLL of functions that can be incorporated into programming languages such as C, C++, Microsoft Visual Basic, Java, or any other language capable of calling functions using a Windows DLL (EPA, 2020). The Toolkit is best suited for creating specialised applications, such as automated models and optimization of the hydraulic network, which require running many network analyses. EPANET analyses the PRV by allowing three states of operation (EPANET, 2020):

1. Partially open: The PRV achieves its pressure setting on the downstream side. The upstream side must have a pressure above this setting.
2. Fully open: When the upstream pressure is below the setting allowing flow through the PRV.
3. Closed: When the downstream pressure head exceeds the upstream pressure head. The PRV is closed to inhibit reverse flow within the pipe.

The PRV will be partially open for my analysis, and a downstream pressure will be set based on equation 36.

The EPANET-MATLAB Toolkit was developed by the KIOS Research Center for Intelligent Systems and Networks of the University of Cyprus. The Toolkit operates within the MATLAB environment, which provides a programming interface for the latest version of EPANET. The Toolkit is open-source and serves as a standard programming framework for research and development to create more intelligent water networks (Eliades, et al., 2016).

The two-stage OF (Stage 1 and Stage 2) algorithm will be programmed in MATLAB using the EPANET-MATLAB Toolkit to automate the OF, with EPANET as the hydraulic solver. By automating the algorithm, the methodology can be applied to any network, and the variables can be quickly changed to suit the demands of the network. Automation also increases the accuracy of results and allows for reduced calculation times and improved computational speeds, with many scenarios being run in the same instance. The program code created can be found in Appendix A.

4.8 Hydraulic Models Analysed

The data obtained for the network is known as quantitative data, which forms the input into EPANET. The network could be analysed using the demand-driven analysis mode (DDA) or the pressure-dependent analysis mode (PDA). DDA assumes that nodal flows are satisfied at all demand nodes, irrespective of the available pressure at these nodes. PDA considers the pressure at the demand nodes (Seyoum, et al., 2011). The EPANET model does not analyse pipe bursts. The only water losses considered are as a result of leakage. EPANET will utilise the DDA mode for this analysis.

4.8.1 Cornubia Integrated Human Settlement Development Phase 2A – Zone 1

The first basic hydraulic model analysed is the Cornubia Phase 2A WDN, created by GIBB (Nyirenda, 2019), for the eThekweni Municipality.

Nyirenda (2019) has found nodes in the WDN to have pressures below the recommended minimum pressure of 24m. The actual minimum pressure head in the system was found to be 21.5m during Average Daily Flow, 21.3m during Peak Daily Flow, and 17m under the Average Flow and Fire Flow condition. All of the nodes with pressure heads below the recommended 24m are located in Phase 2A-Zone 1. Zone 1 is the lower laying elevation area compared to Zone 2 (Nyirenda, 2019). Nyirenda (2019) mentions that these lower-than-recommended pressures can be accepted as a minimum residual pressure of 5m should at least be supplied to roof tanks during this period. This has been accounted for in the program, as shown in equations 33 and 34. The pressure head entering the system will be taken as 30m from the temporary DN400 bulk water supply pipeline (Nyirenda, 2019). None of the nodes exceeded the maximum of 90m pressure head. Some pipes were modelled as zero-flows as these pipes have very low flow demand or are situated at end caps. Figure 4-3 shows the pipe and junction layout for the Cornubia WDN.



Figure 4-3: WDN - Pipe and Junction Layout – Cornubia Integrated Human Settlement Development Phase 2A - Zone 1

4.8.2 Pat Marshal Housing Project

The second hydraulic model analysed was the Pat Marshal Housing Project, situated in Bhambayi, near Phoenix. The hydraulic model was created by Vuv'amu (Pty) Ltd for the eThekweni Municipality (Xozwa, 2020).

Figure 4-4 shows the pipe and junction layout for the Pat Marshal WDN.

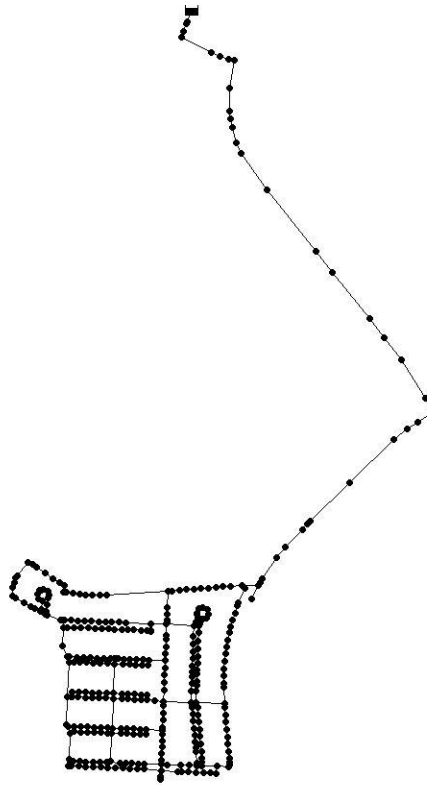


Figure 4-4: WDN - Pipe and Junction Layout - Pat Marshal Housing Project

4.9 PATs used in the analysis

Four pump configurations have been chosen to be implemented as PATs for the second stage of the OF. These pumps have been chosen to fit most head-flow conditions in the networks to harness as much electricity as possible. The chosen pumps are used to create an approximate feasibility study based on the price and operating capabilities of the individual pumps. The data chosen for the pumps are from various pump manufacturers and suppliers, such as Browns Brothers (2019), CAPRARI (2021), and GRUNDFOS (2021). The pumps that have been chosen are end-suction close-coupled centrifugal single-stage pumps. These pumps are common in industrial facilities and water distribution plants worldwide (Grundfos, 2021).

Pump's 1, 2, and 3 represent a power band of approximately 0kW to 85kw. The approximate pricing for each pump is shown in Table 4-2: Pumps chosen for PAT feasibility. Table 4-2. Pump 4 is a combination of two "Pump 3's" in series. The prices and operating limits for pumps are used only as a guide to create a feasibility study to warrant PAT placement for energy extraction for Stage 2 of the OF.

Table 4-2: Pumps chosen for PAT feasibility.

| Pump/ PAT Type | Power (kW) | | Head Range (m) | | Flow Range (m^3/h) | | Price (Rands) | Operating Efficiency (η) |
|----------------------|------------|------|----------------|------|------------------------|------|------------------|---------------------------------------|
| | Min. | Max. | Min. | Max. | Min. | Max. | | |
| 1 | 0 | 5 | 22 | 60 | 1.5 | 40 | 60000 | 89 |
| 2 | 5 | 15 | 25 | 65 | 15 | 130 | 65000 | 93 |
| 3 | 15 | 85 | 35 | 80 | 10 | 600 | 205000 | 93 |
| 4 | 85 | 170 | 35 | 80 | 10 | 600 | 410000 | 93 |

CHAPTER 5

5. RESULTS AND DISCUSSION

5.1 Introduction

Results from the application of the newly proposed method on the two WDNs are presented in this chapter. The optimisation algorithm was programmed in MATLAB, using EPANET as the hydraulic solver using the EPANET MATLAB Toolkit. The results include the optimal placement and setting for additional PRVs within each network to maximise the leakage rate reduction within the network. Every pipe in the network was tested for possible PRV placement. The pipe that maximises the network leakage rate reduction is the optimal location for a PRV in that scenario. Each node's base and actual demand were compared to evaluate the network's leakage reduction due to the added PRV. A feasibility study identifying the optimal configuration of PATs within the network to generate renewable energy was run for each network. Each networks' power generation capabilities are shown.

5.2 Cornubia Integrated Human Settlement Development Phase 2A – Zone 1

5.2.1 Existing Network Conditions

5.2.1.1 The General Site Details

This section will describe the general site location details of the Cornubia Integrated Human Settlement Development Phase 2A – Zone 1 WDN (hereon referred to as 'Cornubia WDN'). The site has gradients ranging from 10% to 25%. Figure 5-1 shows the key used to evaluate Figure 5-2.

The contour lines in Figure 5-2 indicate that the site is very steep, with the highest elevation of 297m being at Tank 2 and Tank 936 and the lowest elevation of 66m at Junction 15090. This results in a total elevation difference of 231m.

The Cornubia WDN is a gravity network with Tank 2 and Tank 936 being the inlet connection points from the DN400 temporary bulk supply pipeline from Blackburn Reservoir. The two inlet connections provide the system with a constant pressure head of 30m.

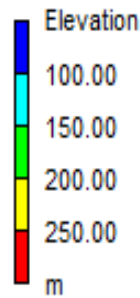


Figure 5-1: Elevation (m) Key
showing elevations of the
Cornubia WDN

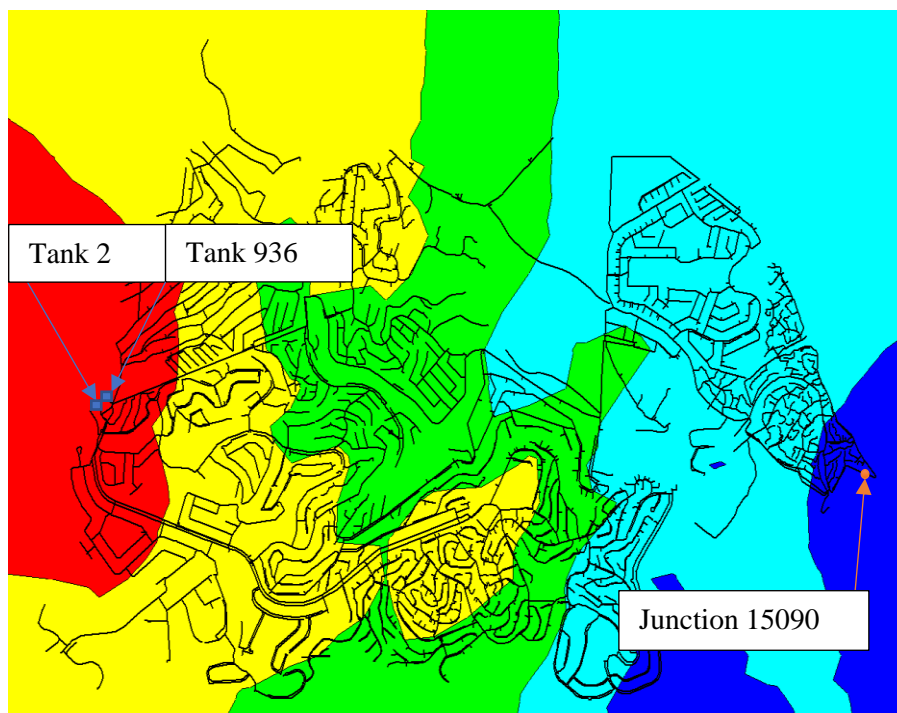


Figure 5-2: Elevations in the Cornubia WDN.

5.2.1.2 The Current Pressure Distribution within the Cornubia WDN

The leakage rate within a pipe is directly proportional to the pressure within that pipe (Germanopoulos & Jowitt, 1989; Van Zyl, 2004). Figure 5-3 shows the pressure contour plot for the Cornubia WDN before any additional PRVs have been placed. The Cornubia WDN has 31 existing PRVs. A minimum pressure of 24m and a maximum pressure of 90m will be used in the key, in line with the requirements in the Guidelines for Human Settlement Planning and Design – Volume 2 (2005). Regions in Figure 5-3 shaded in green, yellow, and red indicate high-pressure

zones within the network, which needs to be regulated to reduce the leakage rate in those areas, and consequently, the entire network.

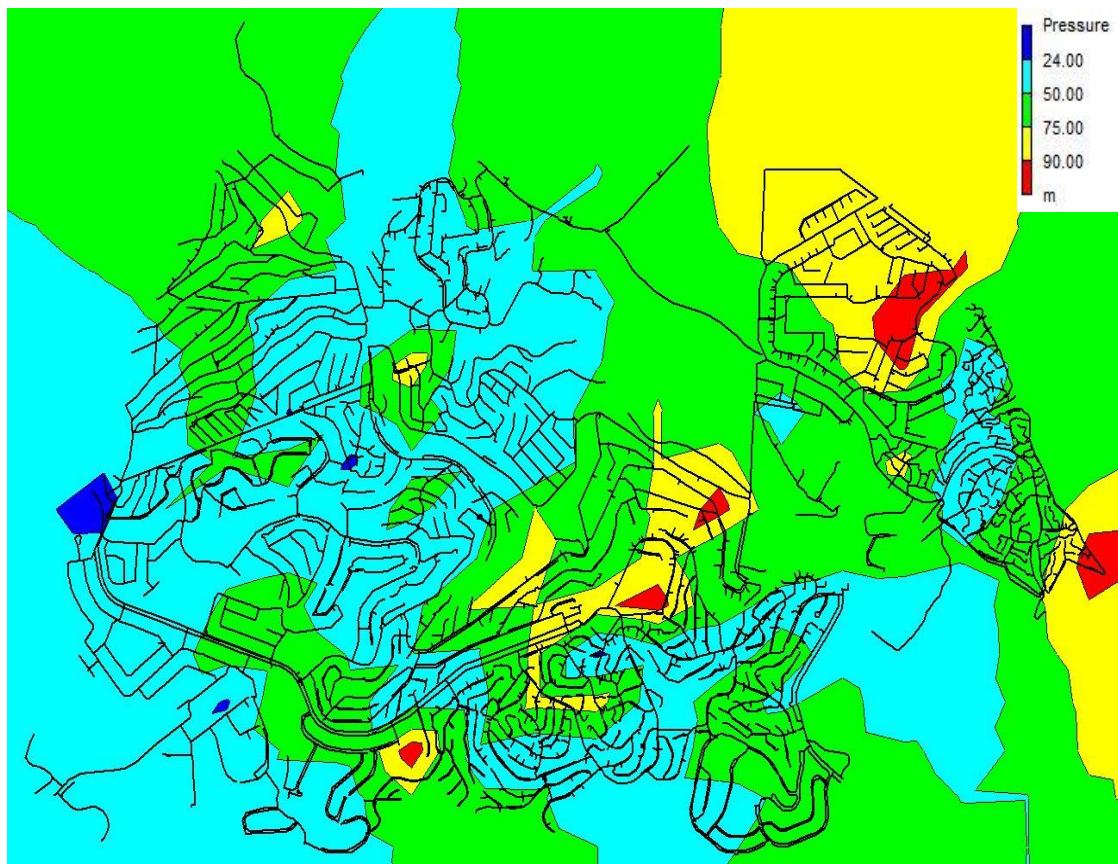


Figure 5-3: Existing Pressure Contour for the Cornubia WDN

5.2.2 Summary of Results: Optimum PRV Location and Configuration for Leakage Reduction

This section of the results deals with Stage 1 of the Objective Function. The Cornubia WDN has 31 existing PRVs.

The optimum location of a PRV is determined by the PRV placement that results in the highest network leakage reduction percentage while maintaining downstream conditions as set out in Chapter 4, Methodology. The optimum configuration of PRVs is the maximum number of PRVs that can be placed before any of these conditions are breached.

Every additional PRV added to the network will be regarded as a new Scenario, as adding a PRV changes the hydraulic characteristics of the entire network. Each subsequent scenario includes all the PRVs placed in the scenarios preceding it.

The optimal number of additional PRVs added to the Cornubia WDN has been determined to be 5 PRVs.

The sixth additional PRV would need to be bypassed (set to open) to maintain downstream conditions in the network after hydraulic analysis, resulting in the optimum number of PRVs to reduce leakage within the network to be five, as shown in Table 5-1.

Table 5-1 summarises the results obtained from the automation program created to optimise the placement of additional PRVs within a WDN to maximise the leakage rate reduction in the network. The flow conditions in the WDN change with each added PRV. Each new Scenario requires a hydraulic analysis to determine the optimum location for that PRV to be added.

The average flow rate and head loss across the PRV is determined using the variable demand pattern shown in Figure 4-2. The PRVs will only be utilized during periods that warrant pressure reduction, such as periods of high pressure when there is less demand on the network. The program considers these times by running a hydraulic analysis over 24 hours (1 day) and averaging the results when the PRV is in use only. This ensures that the pressure downstream is not reduced during high demand periods (during the peak morning usage at 7 am and the peak evening water usage at 8 pm).

The leakage reduction shown in Table 5-1 is calculated by determining the network's nodal base demand and comparing it to the actual nodal demand. Every node in the network was checked before and after PRV implementation, i.e., before and after pressure control, to determine the change in leakage rate. The Cornubia WDN consists of 2941 nodes and 3119 pipes before the addition of additional PRVs. The network has two inlet tanks, 31 existing PRVs, and the network is analysed using a demand-driven analysis.

Table 5-1: Summary of Results for the Optimum Placement of PRVs within the Cornubia WDN

| Table Showing Results for Optimum PRV placement into the Cornubia WDN. | | | | | | |
|---|-------|-------|-------|-------|-------|------|
| Additional PRV Number (Scenario) | 1 | 2 | 3 | 4 | 5 | 6 |
| Pipe being Replaced | 7590 | 10475 | 3531 | 7785 | 10461 | 7736 |
| PRV Optimal Setting (m) | 24 | 30 | 24 | 24 | 24 | 24 |
| Average Flow Rate across PRV (LPS) | 61.46 | 55.22 | 67.27 | 16.10 | 4.04 | 0 |
| Average Head Loss across PRV (m) | 51.97 | 24.36 | 25.58 | 28.15 | 56.73 | 0 |
| Total Network Leakage Reduction (%) | 2.32 | 5.20 | 8.17 | 10.75 | 12.80 | NA |

5.2.2.1 Scenario 1: Addition of Optimally placed PRV 1

The addition of additional PRV 1 into the network results in its optimal placement being in pipe 7590. This PRV is optimally placed and results in a total network leakage reduction of 2.3211%.

PRV 1 has an optimum setting of 24m, reducing the downstream pressure at the outflow of the PRV to 24m. All the downstream and network constraints set out in Stage 1 of the objective function have been met. The flow rate across the PRV is 61.4605 LPS. The PRV has a headloss of 51.9715m. The location of PRV 1 is shown circled in red in Figure 5-4.

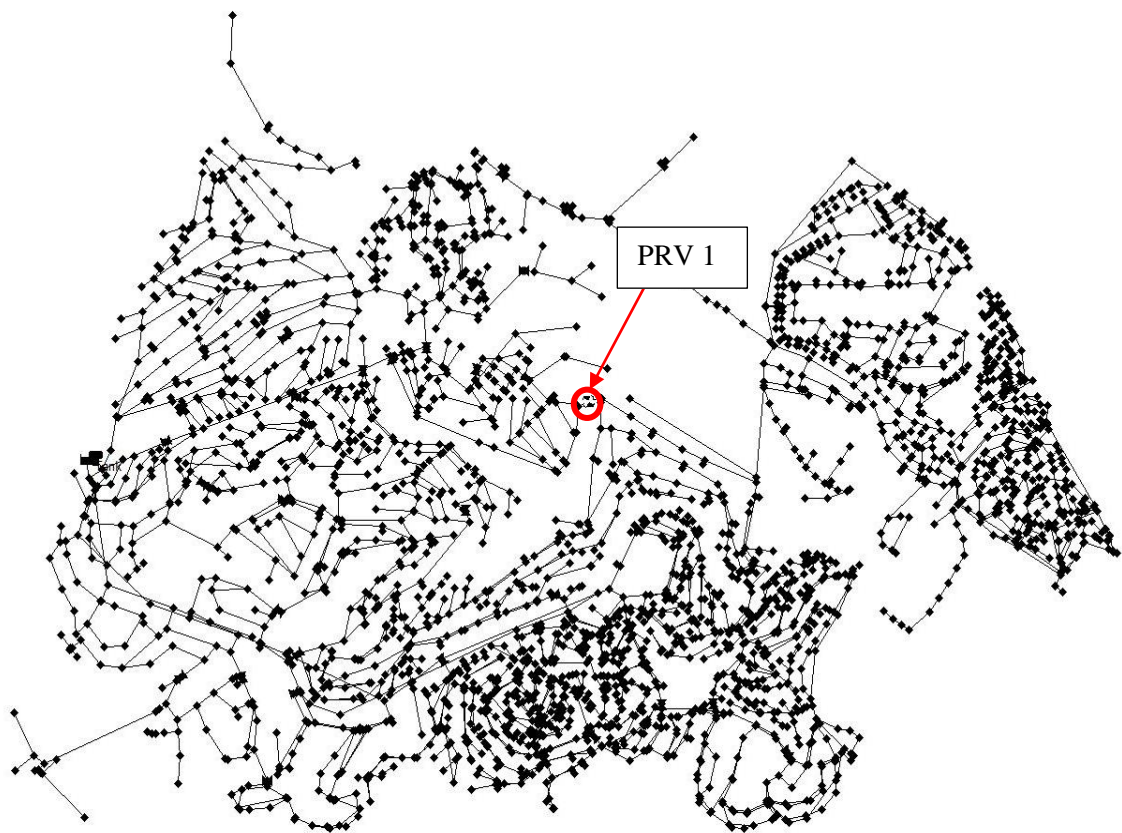


Figure 5-4: Location of PRV 1 in the Cornubia WDN

The addition of PRV 1 has significantly reduced the pressures downstream, as shown in Figure 5-5. This can be seen as the areas in yellow and red have reduced in size in parts of the network. The dark blue region in Figure 5-5 indicates the two inlet connections modelled as tank 2 and tank 936.

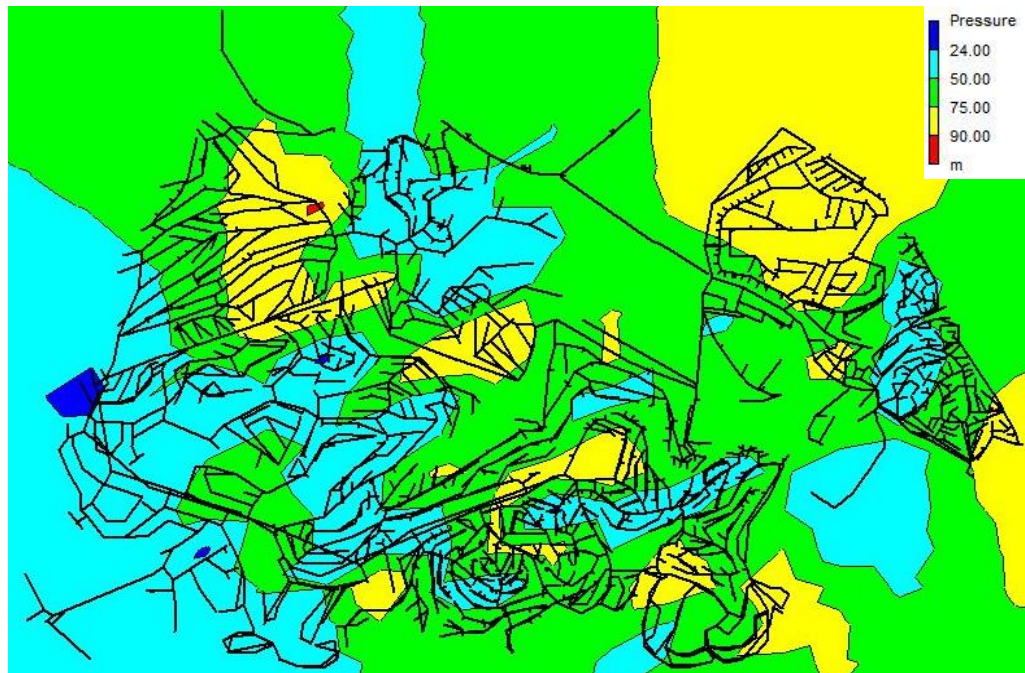


Figure 5-5: Pressure contour plot of the Cornubia WDN with the addition of PRV 1

5.2.2.2 Scenario 2: Addition of Optimally placed PRV 2

The addition of PRV 2 into the network results in its optimal placement being in pipe 10475. This PRV is optimally placed and results in a total network leakage reduction of 5.1997%, increasing the leakage reduction by 2.8786%.

PRV 2 has an optimum setting of 30m while maintaining downstream conditions according to the constraints outlined for the Stage 1 OF, section 4.5.1. The flow rate across the PRV is 55.2199 LPS. The PRV has a headloss of 24.3571m. The location of PRV 2 is shown circled in green in Figure 5-6.

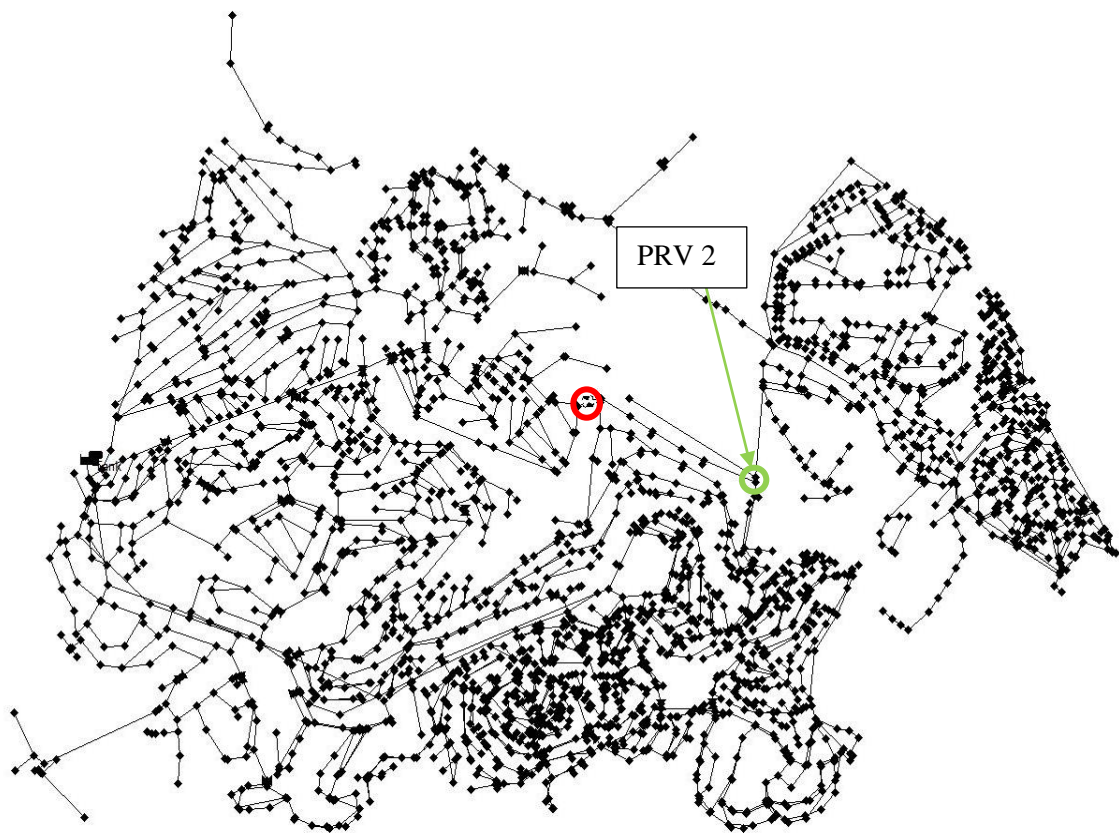


Figure 5-6: Location of PRV 2 in the Cornubia WDN

The addition of PRV 2 has significantly reduced the pressures downstream, as shown in Figure 5-7. This can be seen as the areas in yellow and red have reduced in size in parts of the network. The top right quadrant of Figure 5-7, outlined in red, has changed from green and yellow to light blue and dark blue, indicating the pressure reduction in that quadrant. Zones in dark blue in Figure 5-7 indicate pressures below 24m. The program allows for a 10% tolerance to the total number of nodes allowed to be below 24m, shown in section 4.5.1.3. The number of nodes within the dark blue zones are below the 10% limit. Figure 5-8 has a different pressure minimum (zero)

compared to Figure 5-7, indicating no negative pressures present in the dark blue zone shown in Figure 5-7.

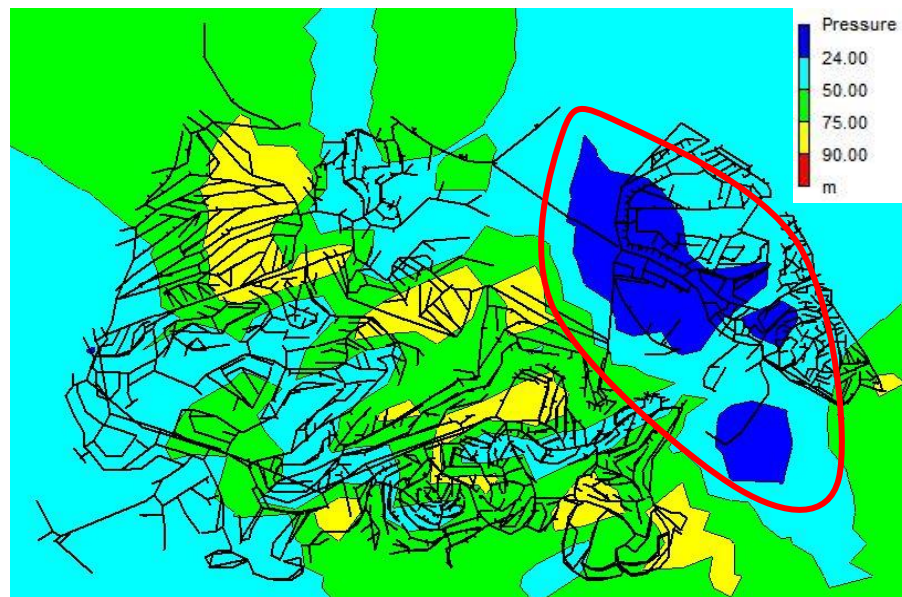


Figure 5-7: Pressure contour plot of the Cornubia WDN with the addition of PRV 2

The pressure range within the dark blue region shown above is between 0m and 24m. The light blue pressure region in Figure 5-8 is thus acceptable.



Figure 5-8: Pressure contour plot of the Cornubia WDN with the addition of PRV 2 showing low pressure range.

5.2.2.3 Scenario 3: Addition of Optimally placed PRV 3

The addition of PRV 3 into the network results in its optimal placement being in pipe 3531. This PRV is optimally placed and results in a total network leakage reduction of 8.1681%, increasing the leakage reduction by 2.9684%.

PRV 3 has an optimum setting of 24m while maintaining downstream conditions according to the constraints outlined for the Stage 1 OF, section 4.5.1. The flow rate across the PRV is 67.2744 LPS. The PRV has a headloss of 25.5766m. The location of PRV 3 is shown circled in orange in Figure 5-9.

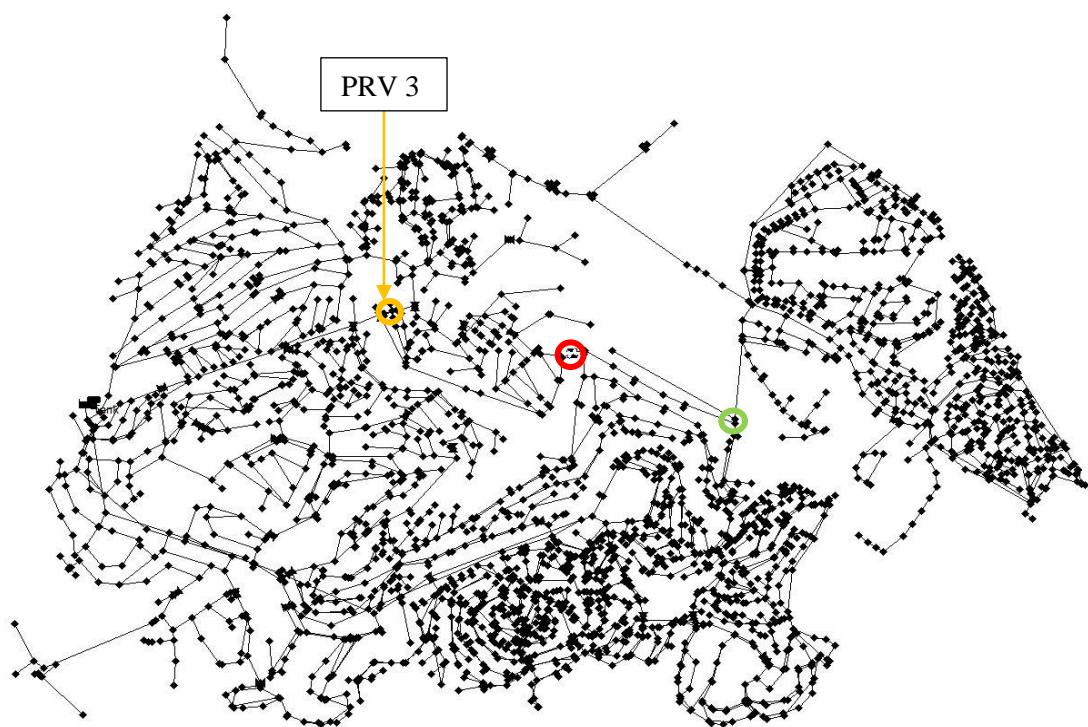


Figure 5-9: Location of PRV 3 in the Cornubia WDN

The addition of PRV 3 has reduced the pressures downstream, as shown in Figure 5-10. This can be seen as the areas in green and yellow have reduced in size in parts of the network. The areas of Figure 5-10 outlined in red have changed from green and yellow to light blue and dark blue, indicating the pressure reduction in that area. Zones in dark blue in Figure 5-10 indicate pressures below 24m. Figure 5-11 has a different pressure minimum (zero) compared to Figure 5-10, indicating no negative pressures present in the dark blue zone shown in Figure 5-10. The number of nodes within the dark blue zones are below the 10% limit.



Figure 5-10: Pressure contour plot of the Cornubia WDN with the addition of PRV 3

The pressure range within the dark blue region shown above is between 0m and 24m. The light blue pressure region in Figure 5-11 is thus acceptable.

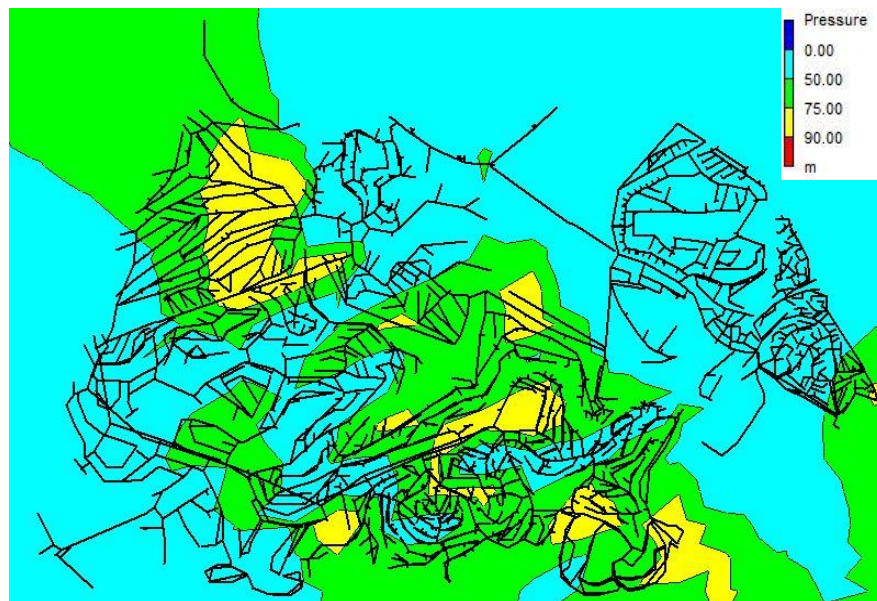


Figure 5-11: Pressure contour plot of the Cornubia WDN with the addition of PRV 3 showing low pressure range.

5.2.2.4 Scenario 4: Addition of Optimally placed PRV 4

The addition of PRV 4 into the network results in its optimal placement being in pipe 7785. This PRV is optimally placed and results in a total network leakage reduction of 10.7511%, increasing the leakage reduction by a further 2.583%.

PRV 4 has an optimum setting of 24m while maintaining downstream conditions according to the constraints outlined for the Stage 1 OF, section 4.5.1. The flow rate across the PRV is 16.1 LPS. The PRV has a headloss of 28.1486m. The location of PRV 4 is shown circled in blue in Figure 5-12.

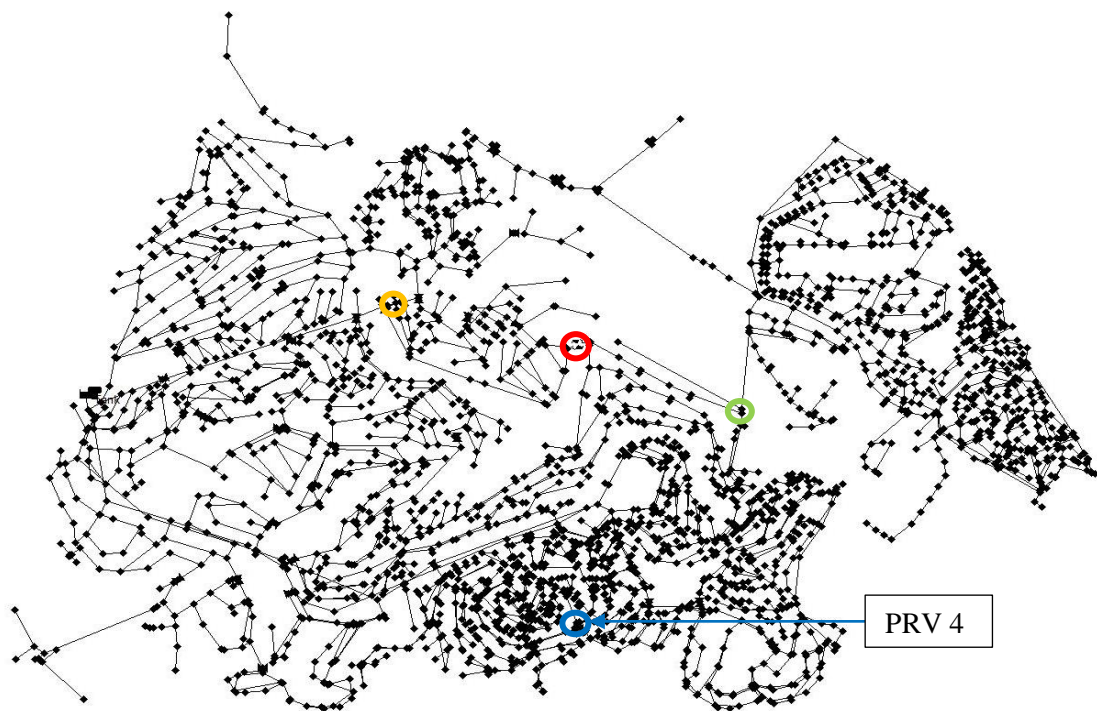


Figure 5-12: Location of PRV 4 in the Cornubia WDN

The addition of PRV 4 has reduced the pressures downstream, as shown in Figure 5-13. This can be seen as the areas in green and yellow have reduced in size in parts of the network, changing to light blue. A small section has changed to dark blue, indicating the pressure reduction below 24m in that area. Figure 5-14 has a different pressure minimum (zero) compared to Figure 5-13, indicating no negative pressures present in the dark blue zone shown in Figure 5-13. The number of nodes within the dark blue zones are below the 10% limit.



Figure 5-13: Pressure contour plot of the Cornubia WDN with the addition of PRV 4

The pressure range within the dark blue region shown above is between 0m and 24m. The light blue pressure region in Figure 5-14 is thus acceptable.

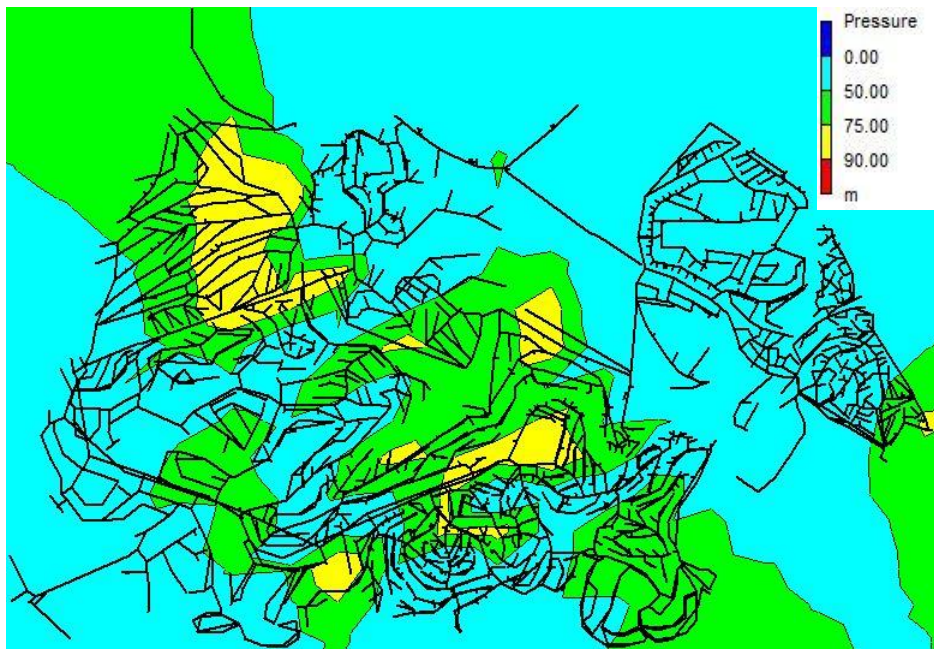


Figure 5-14: Pressure contour plot of the Cornubia WDN with the addition of PRV 4 showing low pressure range.

5.2.2.5 Scenario 5: Addition of Optimally placed PRV 5

The addition of PRV 5 into the network results in its optimal placement being in pipe 10461. This PRV is optimally placed and results in a total network leakage reduction of 12.8011%, increasing the leakage reduction by a further 2.05%.

PRV 5 has an optimum setting of 24m while maintaining downstream conditions according to the constraints outlined for the Stage 1 OF, section 4.5.1. The flow rate across the PRV is 4.0353 LPS. The PRV has a headloss of 56.7253m. The location of PRV 5 is shown circled in purple in Figure 5-15.

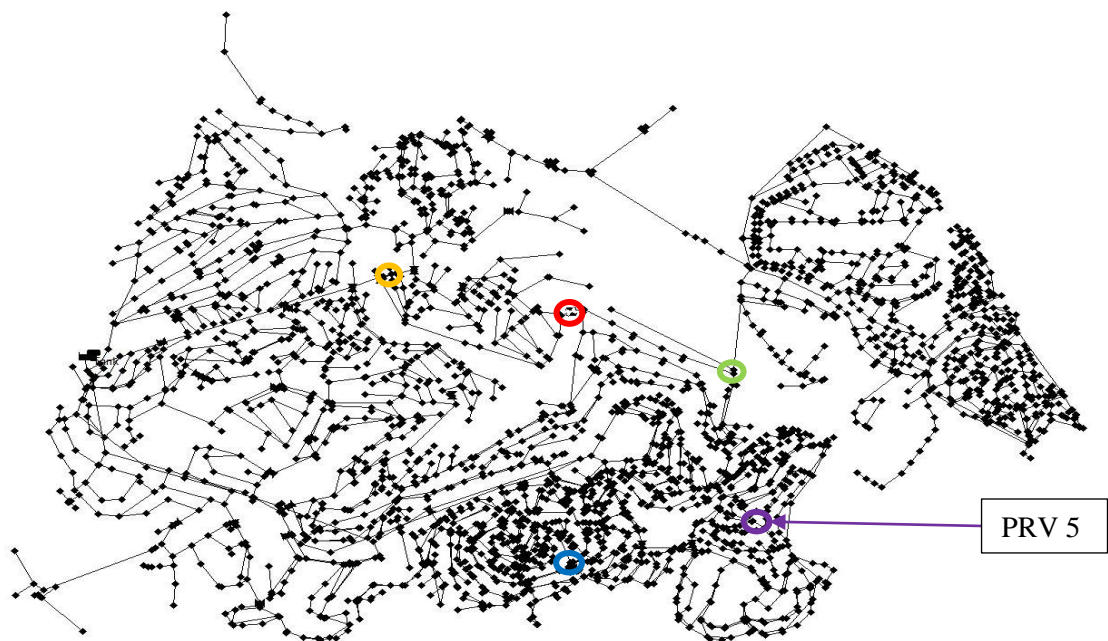


Figure 5-15: Location of PRV 5 in the Cornubia WDN

The addition of PRV 5 has reduced the pressures downstream, as shown in Figure 5-16. This can be seen as the areas in green and yellow have reduced in size in parts of the network, changing to light blue. A small section has changed to dark blue, indicating the pressure reduction below 24m in that area. Figure 5-17 has a different pressure minimum (zero) compared to Figure 5-16, indicating no negative pressures present in the dark blue zone shown in Figure 5-16. The number of nodes within the dark blue zones are below the 10% limit.

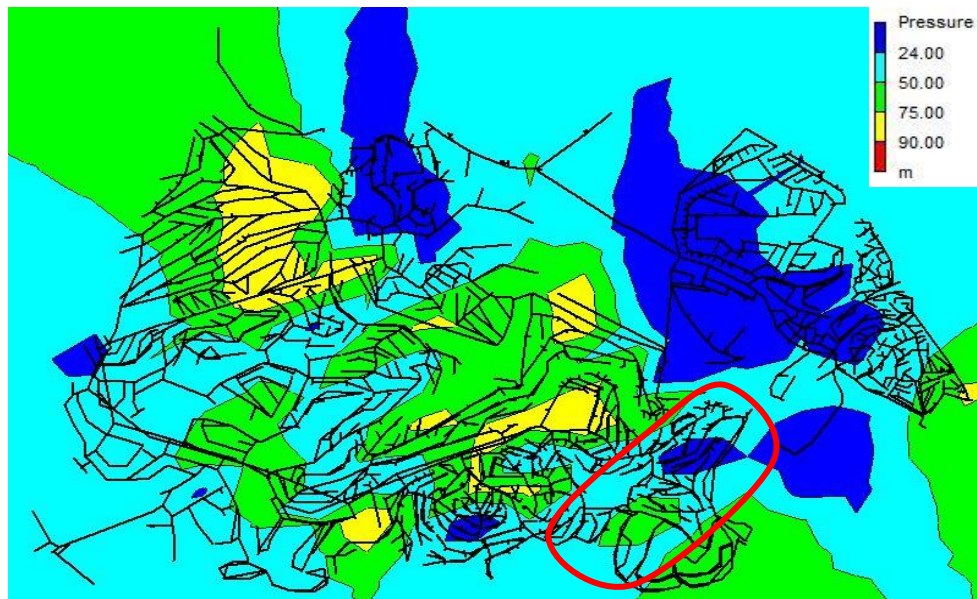


Figure 5-16: Pressure contour plot of the Cornubia WDN with the addition of PRV 5

The pressure range within the dark blue region shown above is between 0m and 24m. The light blue pressure region in Figure 5-17 is thus acceptable.

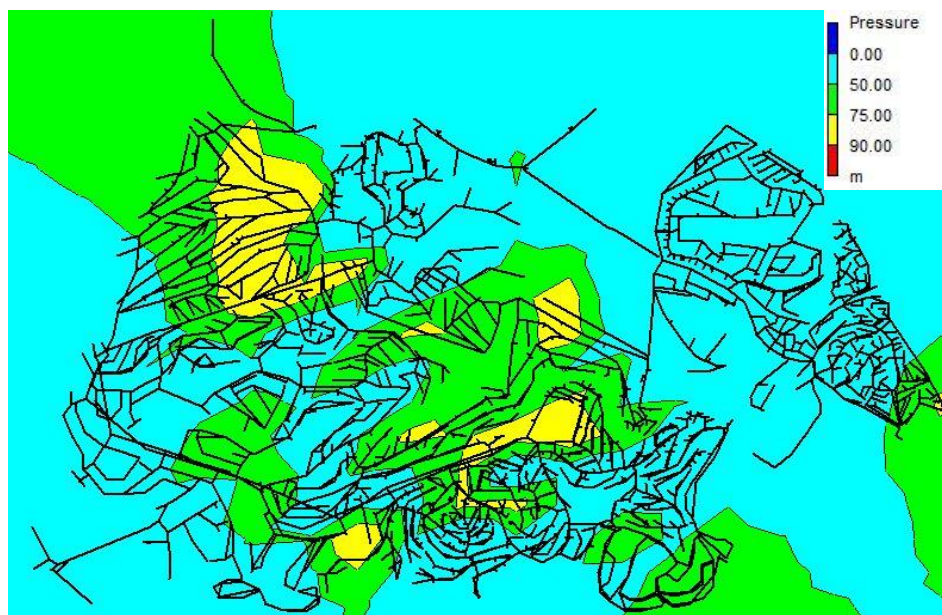


Figure 5-17: Pressure contour plot of the Cornubia WDN with the addition of PRV 5 showing low pressure range.

5.2.2.6 Scenario 6: Addition of Optimally placed PRV 6

There are no additional locations to optimally place a PRV into the Cornubia WDN to reduce the leakage rate within the network further. The program returns an error as it attempts to place PRV 6 but has to set it to open to meet the constraints set out in section 4.5.1. The method has a breached constraint; thus, no additional PRVs can be added to the network.

5.2.2.7 The optimum PRV Configuration

The optimum configuration of additional PRVs to be placed in the Cornubia WDN consists of five PRVs, namely PRV 1, 2, 3, 4, and 5. This configuration of PRVs realises a total network leakage reduction rate of 12.8011%. The five additional PRVs have been optimally located and set for the network.

5.2.3 Summary of Results: Replacement of PRVs with PATs to Harness Energy from the WDN.

This section of the results deals with Stage 2 of the Objective Function. Stage 1 has optimally placed five additional PRVs into the Cornubia WDN, bringing the total PRVs in the network equal to 36.

The program was run analysing the feasibility of replacing each PRV with a PAT. The criteria for PRV replacement is set out in section 4.6, along with the assumptions made. The types of PATs proposed, shown in Table 4-2, gives an approximate costing, as actual PAT prices will vary based on numerous factors. The program determined 9 PRVs that can be feasibly replaced by PATs to generate renewable energy from the excess pressure. The PATs will provide equivalent pressure regulating capabilities as the PRVs they replace, with the added benefit of renewable energy generation. The feasibility study was based on a maximum capital payback period of 2.5 years. The PRVs that can feasibly be replaced with PATs are shown in Table 5-2. The PATs' operational time depends on when the network conditions coincide with the PATs' operational limits to function at BEP. The PAT will only be switched on during certain times of the day when these conditions are met. The PATs are assumed to operate for 335 days a year to account for maintenance. The PATs' operational time affects the average flow rate and average head loss available to the PAT for energy generation, shown in equations 42 - 44. The PAT will be bypassed when there is insufficient head or flow to operate at BEP.

The final PAT configuration consists of replacing nine PRVs with PATs achieving a total power output of 135.48 kW. The power output of the PATs in the Cornubia WDN produces 948.671 MWh per annum. The EGE cost of PAT implementation is R855 000. The PAT configuration would generate a total gross margin of R920 211.17 per year if the Cornubia WDN were to sell the electricity generated to the national power grid. The power output of the Cornubia WDN can be classified as a Mini-hydropower plant, based on its energy output.

Table 5-2: PRVs to be replaced by PATs in the Cornubia WDN

| Additional PRV | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------|--------------|
| PRV to be replaced by a PAT (E = Existing; N = Newly placed) | 451 (E) | 2136 (E) | 3525 (E) | 4635 (E) | 7116 (E) | 7570 (E) | 8831 (E) | PRV 1 (N) | PRV 3 (N) |
| Average Head Loss (m) | 45.27 | 31.04 | 38.97 | 64.52 | 50.15 | 52.47 | 72.90 | 48.36 | 25.00 |
| Average Flow Rate (LPS) | 108.25 | 21.27 | 29.85 | 5.66 | 9.52 | 16.95 | 16.03 | 51.67 | 68.81 |
| PAT Operational Time (Hours) | 19 | 24 | 16 | 24 | 15 | 24 | 24 | 24 | 18 |
| Power Output of the PAT (kW) | 36.26 | 6.96 | 19.70 | 4.02 | 5.69 | 9.38 | 12.32 | 26.36 | 14.78 |
| Power generated Annually (kWh/year) | 230 807 | 58 310 | 105 606 | 33 691 | 28 574 | 78 565 | 103 221 | 220 780 | 89 116 |
| PAT Type (Refer to Table 4-2) | 3 | 2 | 2 | 1 | 1 | 2 | 2 | 3 | 2 |
| CPP (Years) | 0.772 | 0.998 | 0.516 | 1.751 | 2.167 | 0.713 | 0.529 | 0.811 | 0.621 |
| Gross Margin generated per Year (Rands) | 223883.17 | 56560.80 | 102437.50 | 32680.67 | 27717.21 | 76207.86 | 100124.50 | 214157.00 | 86442.42 |

5.3 Pat Marshal Housing Project

5.3.1 Existing Network Conditions

5.3.1.1 The General Site Details

This section will describe the general site location details of the Pat Marshal Housing Project WDN (hereon referred to as 'Pat Marshal WDN'). The site slopes gently from the north to the south westerly direction, having slopes ranging from 3.5% to 10%. Figure 5-18 shows the key used to evaluate Figure 5-19.

The highest elevation is at Reservoir R1 at 174.81m, and the lowest point is junction RJ32 at 111.87m, shown in Figure 5-19. The total elevation difference is 62.94m. The Pat Marshal WDN is a gravity network.

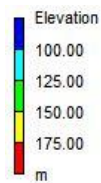


Figure 5-18: Elevation (m) Key showing elevations of the Pat

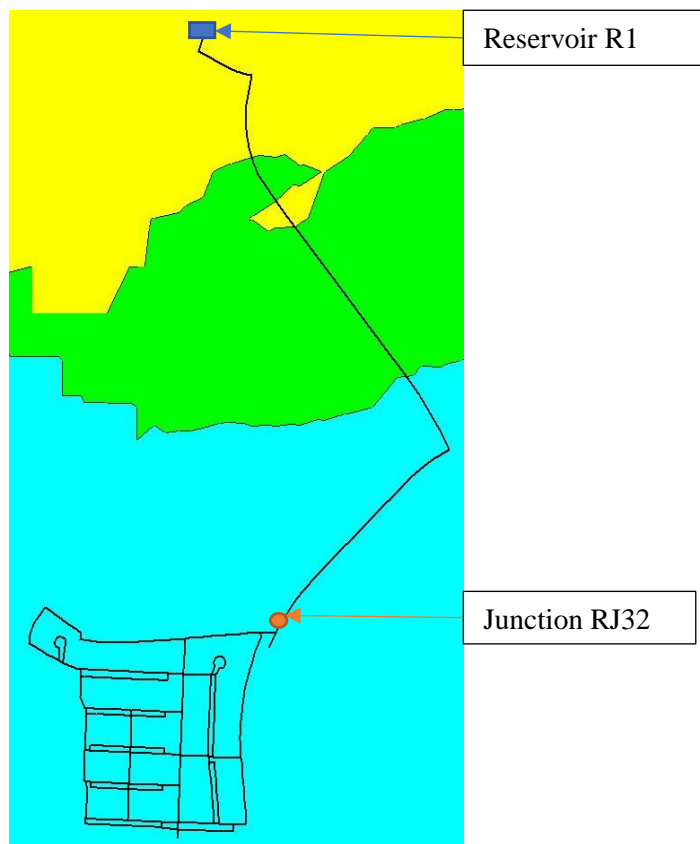


Figure 5-19: Elevations of Pat Marshal Housing Project WDN

5.3.1.2 The Current Pressure Distribution within the Pat Marshal WDN

The leakage rate within a pipe is directly proportional to the pressure within that pipe (Van Zyl, 2004). Figure 5-20 shows the pressure contour plot for the Pat Marshal WDN before any PRVs have been placed. The Pat Marshal WDN has no existing PRVs. A minimum pressure of 24m and a maximum pressure of 90m will be used in the key, in line with the requirements set out in the Guidelines for Human Settlement Planning and Design – Volume 2 (2005). Regions in Figure 5-20 shaded in green indicate high-pressure zones within the network, which needs to be regulated to reduce the leakage rate in those areas and consequently the entire network. The region in dark blue indicated pressures below the minimum 24m near the water inlet.

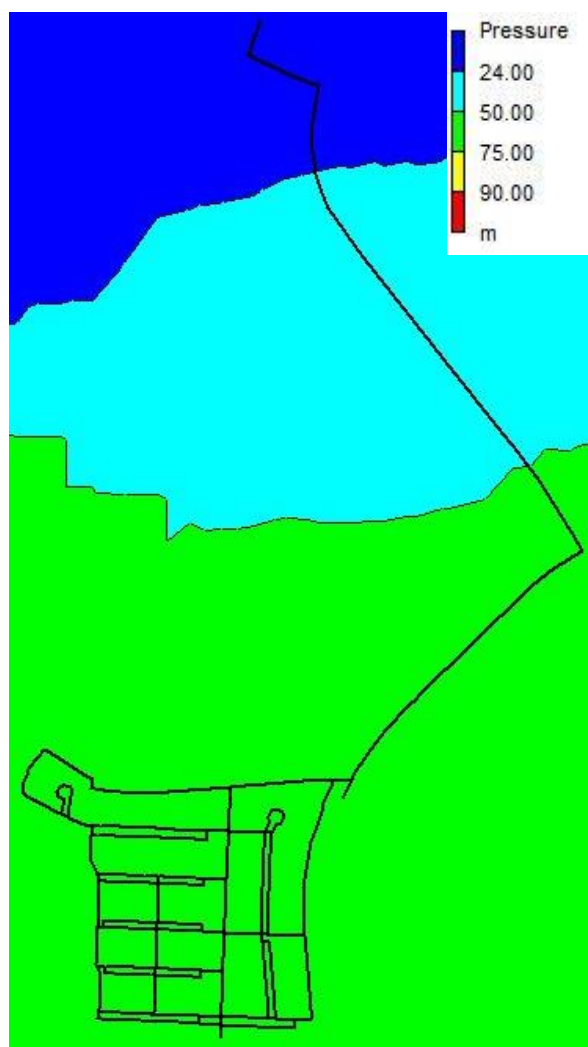


Figure 5-20: Existing Pressure Contour for the Pat Marshal WDN

Figure 5-21 indicates no negative pressures within the dark blue zone in Figure 5-20.

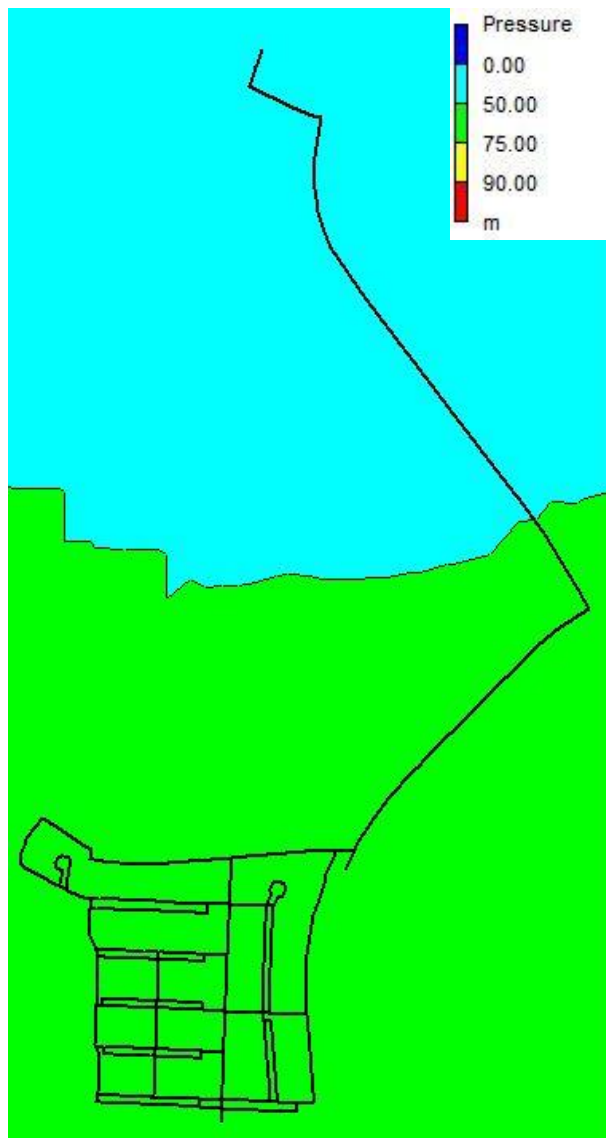


Figure 5-21: Existing Pressure Contour for the Pat Marshal WDN showing no negative pressures.

5.3.2 Summary of Results: Optimum PRV Location and Configuration for Leakage Reduction

This section of the results deals with Stage 1 of the Objective Function. The Pat Marshal WDN has no existing PRVs.

The optimum location of a PRV is determined by the PRV placement that results in the highest network leakage reduction percentage while maintaining downstream conditions as set out in Chapter 4, Methodology. The optimum configuration of PRVs is the maximum number of PRVs that can be placed before any of these conditions are breached.

Every additional PRV added to the network will be regarded as a new Scenario, as adding a PRV changes the hydraulic characteristics of the entire network. Each subsequent scenario includes all the PRVs placed in the scenarios preceding it.

The optimal number of additional PRVs added to the Pat Marshal WDN has been determined to be 2 PRVs. The addition of a third PRV results in the second PRV being set to open, thus negating its effects on reducing pressure within the network. It can be concluded that the most optimal number of PRVs added to the PAT Marshal network is two, shown in Table 5-3.

Table 5-3 summarises the results obtained from the automation program created to optimise the placement of additional PRVs within a WDN to maximise the leakage rate reduction in the network.

The flow conditions in the WDN change with each added PRV. Each new Scenario requires a hydraulic analysis to determine the optimum location for that PRV to be added.

The average flow rate and head loss across the PRV is determined using the variable demand pattern shown in Figure 4-2. The PRVs will only be utilized during periods that warrant pressure reduction, such as periods of high pressure when there is less demand on the network. The program considers these times by running a hydraulic analysis over 24 hours (1 day) and averaging the results when the PRV is in use only. This ensures that the pressure downstream is not reduced during high demand periods (during the peak morning usage at 7 am and the peak evening water usage at 8 pm).

Table 5-3: Summary of Results for the Optimum Placement of PRVs within the Pat Marshal WDN

| Table Showing Results for the Optimum PRV placement into the Pat Marshal WDN to reduce the leakage rate. | | |
|---|---------|---------|
| Additional PRV Number (Scenario) | 1 | 2 |
| Pipe being Replaced | RP21 | RP30 |
| PRV Optimal Setting (m) | 33 | 33 |
| Average Flow Rate across PRV (LPS) | 52.7058 | 37.4081 |
| Average Head Loss across PRV (m) | 28.6933 | 0.6954 |
| Total Network Leakage Reduction (%) | 27.0598 | 27.9070 |

The leakage reduction shown in Table 5-3 is calculated by determining the network's nodal base demand and comparing it to the actual nodal demand. Every node in the network was checked before and after PRV implementation, i.e., before and after pressure control, to determine the change in leakage rate. The Pat Marshal WDN consists of 349 nodes and 375 pipes before the addition of additional PRVs. The network has one inlet, modelled as a reservoir and no existing PRVs. The network is analysed using a demand-driven analysis.

5.3.2.1 Scenario 1: Addition of Optimally placed PRV 1

The addition of additional PRV 1 into the network results in its optimal placement being in pipe RP21. This PRV is optimally placed and results in a total network leakage reduction of 27.0598%.

PRV 1 has an optimum setting of 33m. All the downstream and network constraints set out in Stage 1 of the objective function have been met. The flow rate across the PRV is 52.7058 LPS. The PRV has a headloss of 28.6933m. The location of PRV 1 is shown circled in red in Figure 5-22.

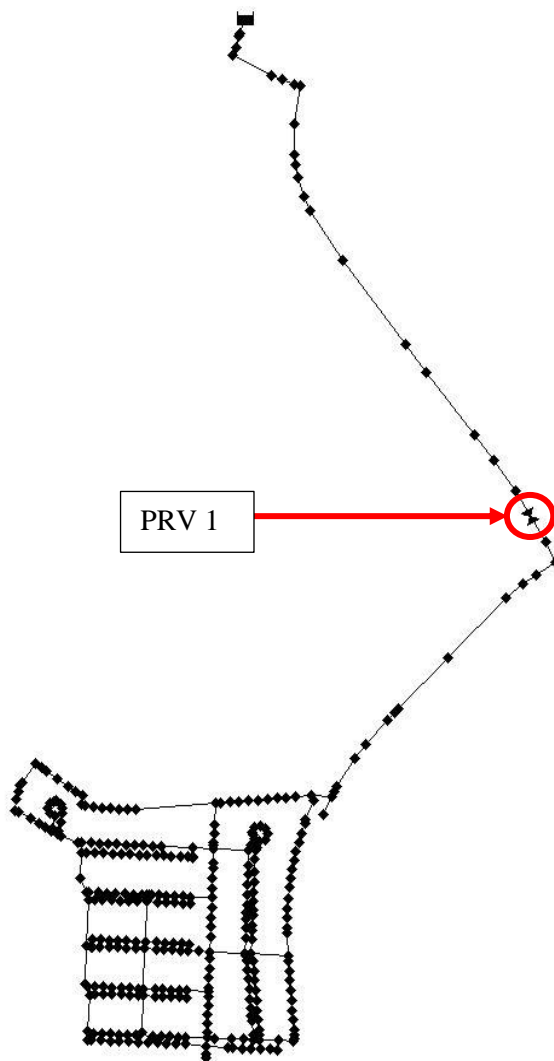


Figure 5-22: Location of PRV 1 in the Pat Marshal WDN

The addition of PRV 1 has significantly reduced the pressures downstream, as shown in Figure 5-23. This is evident as there are no longer green zones in the pressure contour. The network, after the addition of PRV 1, has no pressures exceeding 50m. There are, however, pressures at some nodes below the minimum 24m, outlined in red in Figure 5-23. The program allows for a 10% tolerance to the total number of nodes permitted to be below 24m, shown in section 4.5.1.3. The number of nodes within the dark blue zones are below the 10% limit.

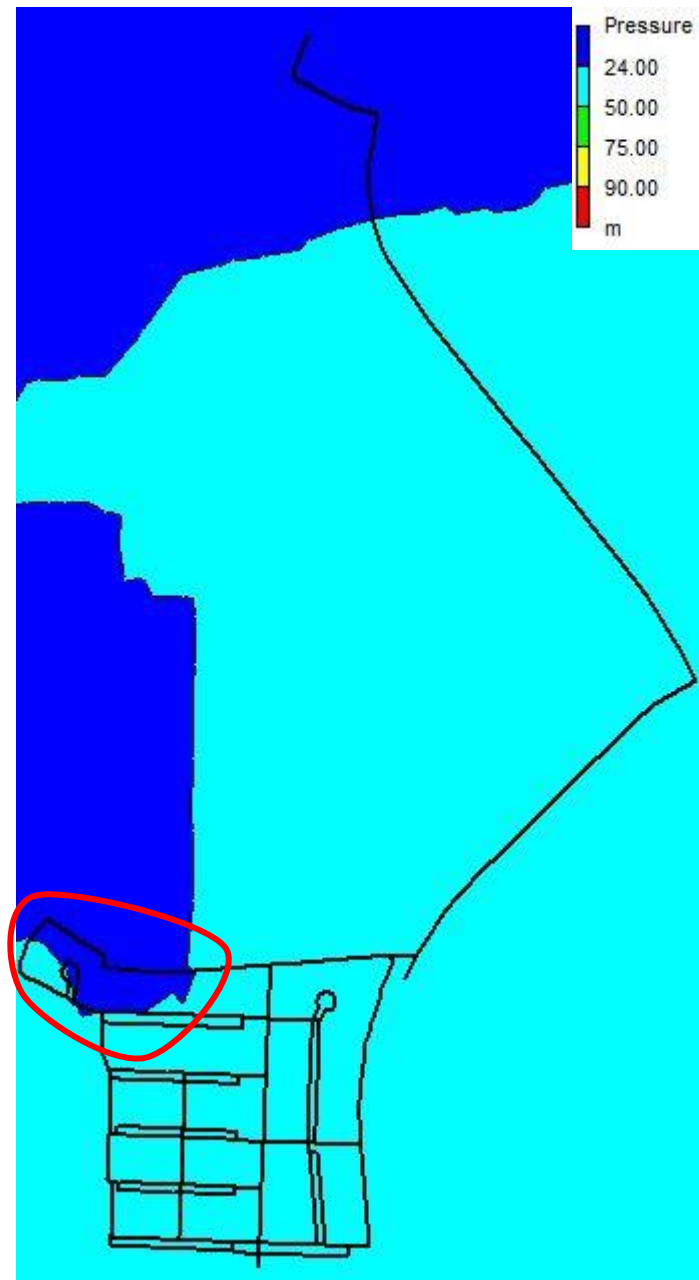


Figure 5-23: Pressure contour plot of the Pat Marshal WDN with the addition of PRV 1

Figure 5-24 indicates no negative pressures in the Pat Marshal WDN after the addition of PRV 1. The light blue pressure region in Figure 5-24 is thus acceptable.

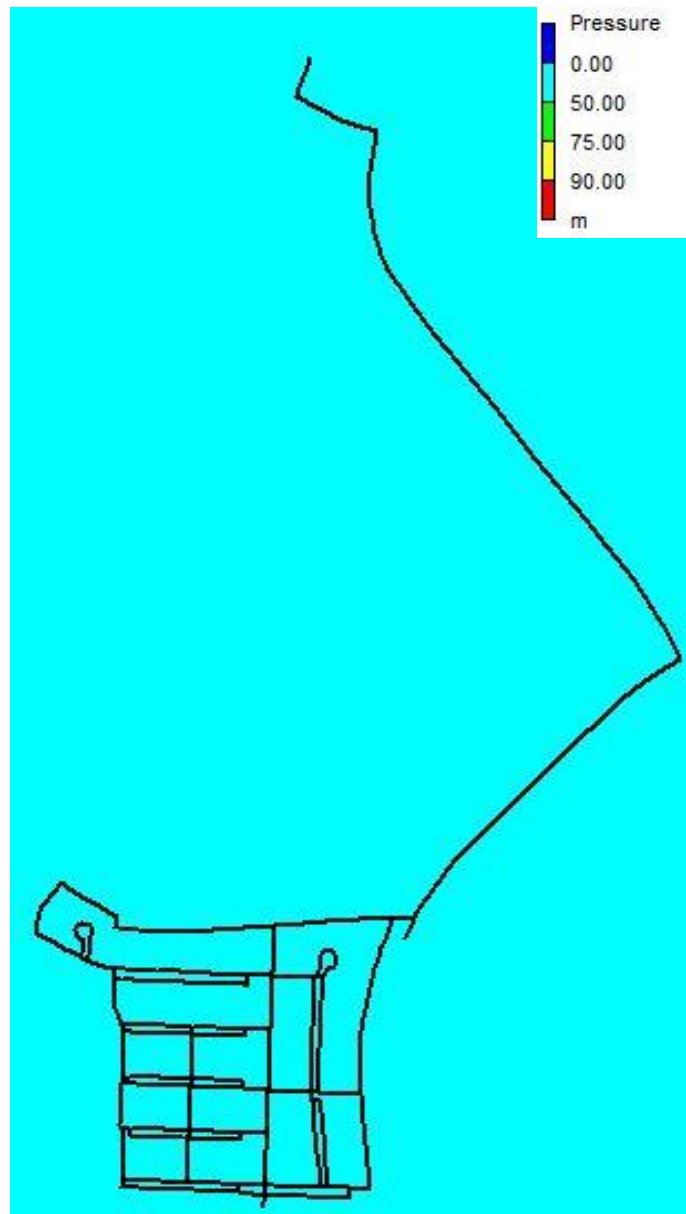


Figure 5-24: Pressure contour plot of the Pat Marshal WDN with the addition of PRV 1 showing low pressure range.

5.3.2.2 Scenario 2: Addition of Optimally placed PRV 2

The addition of PRV 2 into the network results in its optimal placement being in pipe RP30. This PRV is optimally placed and results in a total network leakage reduction of 27.907%, increasing the leakage reduction by a further 0.8472%.

PRV 2 has an optimum setting of 33m while maintaining downstream conditions according to the constraints outlined for the Stage 1 OF, section 4.5.1. The flow rate across the PRV is 37.4081 LPS. The PRV has a headloss of 0.6955m. The location of PRV 2 is shown circled in green in Figure 5-25.

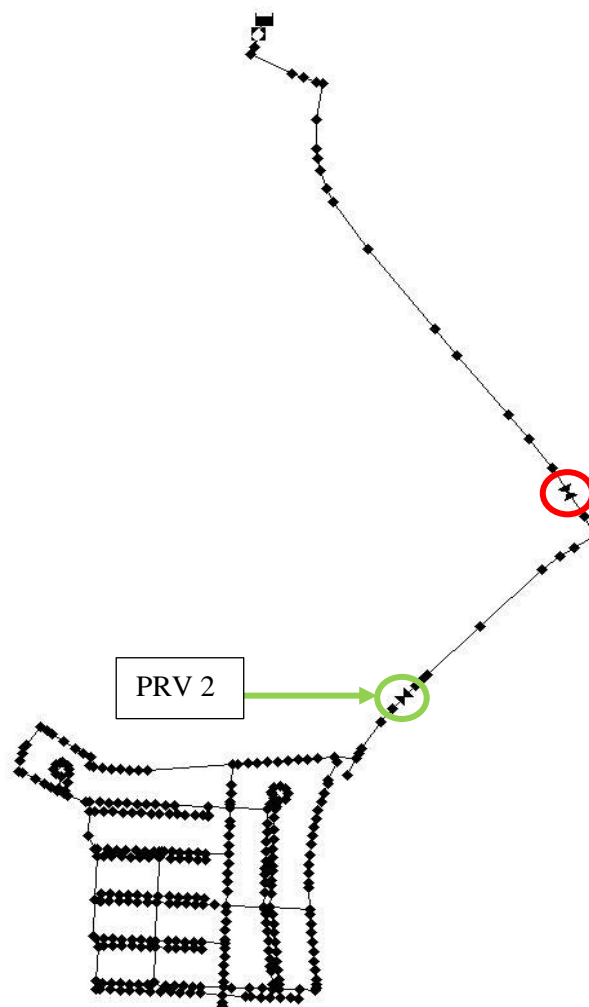


Figure 5-25: Location of PRV 2 in the Pat Marshal WDN

The addition of PRV 2 has not significantly or visually reduced the pressures downstream, as the contours in Figure 5-23 almost match that of Figure 5-26. This is why the leakage rate reduction increased by such a small amount (less than 1%). The optimum number of PRVs to be placed within the Pat Marshal WDN is thus two. The number of nodes with pressure below 24m is less than 10% of the total nodes within the WDN.

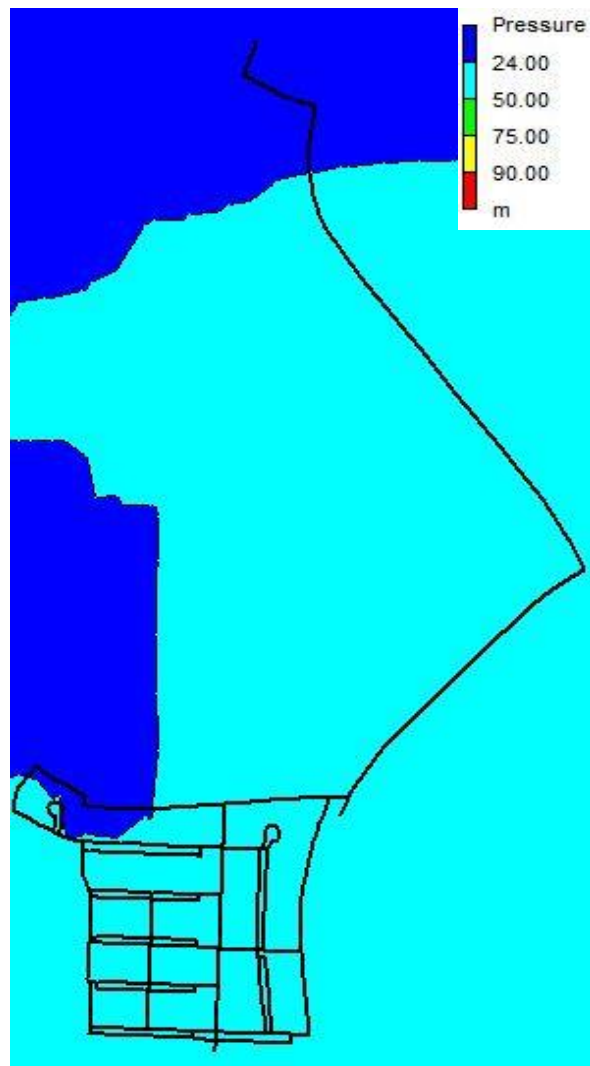


Figure 5-26: Pressure contour plot of the Pat Marshal WDN with the addition of PRV 2

5.3.2.3 Scenario 3: Addition of Optimally placed PRV 3

The placement of a third PRV into the Pat Marshal WDN results in PRV 2 being switched to open. The open setting results in no pressure reduction due to PRV 2. Thus, PRV 3 cannot be added to the network as there is no optimum placement.

5.3.2.4 The Optimum PRV Configuration

The optimum configuration of additional PRVs to be placed in the Pat Marshal WDN consists of two PRVs, namely PRV 1 and 2. This configuration of PRVs realises a total network leakage reduction rate of 27.907%. The two additional PRVs have been optimally located and set for the network.

5.3.3 Summary of Results: Replacement of PRVs with PATs to Harness Energy from the WDN.

This section of the results deals with Stage 2 of the Objective Function. Stage 1 has optimally placed two PRVs into the Pat Marshal WDN, making the total PRVs in the network equal to 2.

The program determined 1 PRV that can be feasibly replaced by a PAT to generate renewable energy from the excess pressure within the Pat Marshal WDN, as shown in Table 5-4. The feasibility study was based on a maximum capital payback period of 2.5 years. The PAT operational time depends on when the network conditions coincide with the PATs operational limits to function at BEP.

The final PAT configuration has a total power output of 24.5542 kW. The power output of the PATs in the Pat Marshal WDN produces 131.610 MWh per annum. The EGE cost of PAT implementation is R65 000. The PAT configuration would generate a total gross margin of R127 662.30 per year if the Pat Marshal WDN were to sell the electricity generated to the national power grid. The power output of the Pat Marshal WDN can be classified as a Micro-hydropower plant based on its energy output.

Table 5-4: PRVs to be replaced by PATs in the Pat Marshal WDN

| | |
|---|--------------|
| Additional PRV | 1 |
| PRV to be replaced by a PAT (E = Existing; N = Newly placed) | PRV 1 (N) |
| Average Head Loss (m) | 28.6933 |
| Average Flow Rate (LPS) | 52.6844 |
| PAT Operational Time (Hours) | 16 |
| Power Output of the PAT (kW) | 24.5542 |
| Power generated Annually (kWh/year) | 131 610.61 |
| PAT Type (Refer to Table 4-2) | 2 |
| CPP (Years) | 0.408 |
| Gross Margin generated per Year (Rands) | 127 662.30 |

5.4 Summary

The program used to optimally place and set PRVs within a WDN was created using the newly proposed Methodology in Chapter 4. The two-stage objective function was used first to determine the optimal location and setting for a PRV to be placed within a WDN. This is based on which pipe would result in the greatest network leakage reduction rate to minimise leakage losses. The hydraulic characteristics of the network change with each addition of a PRV. Once a constraint is broken by implementing a PRV, the previous configuration of PRVs is said to be the optimum configuration, and the program is stopped.

The optimum configuration of PRVs for the Cornubia WDN consists of five additional PRVs, realising a network leakage reduction of 12.8011%. The optimum configuration of PRVs for the Pat Marshal WDN consists of two additional PRVs, achieving a network leakage reduction of 27.907%.

The performance of the created algorithm, and consequently the program, demonstrates its ability to accurately determine the optimal location and setting for a PRV within a WDN to maximise the leakage reduction rate, minimising network leakage losses. Using a computer program automates the placement process, removing the guesswork usually used in placing PRVs. The program can also run mathematical models and hydraulic analysis much faster and more accurately than if it were to be done by hand calculations or manual iterations. The equations inputted into the program quickly determine whether a PRV is suitable for placement based on numerous network restrictions. This greatly reduces the computational effort and time needed as possible PRVs can be discarded based on constraints early on, allowing the program to skip the subsequent checks and analyse the next possible PRV placement.

The program uses many nested loops and 'if' statements to optimise various aspects of PRV placement. These loops include: the location of the PRV; the optimal setting for the PRV; the optimal number of PRVs to be added to the network; and the optimal number of PRVs that can be replaced by PATs based on their operational times, which are dependent on the variable demand pattern of the WDN.

The addition of the optimally placed and set PRVs significantly reduces the network's leakage rate and consequently lowers the NRW in the network. The leakage reduction within the network is a direct result of pressure reduction, as stated by Van Zyl (2004). The feasibility study conducted in Stage 2 of the objective function approximately determines the possibility of renewable energy generation from excess pressure in the WDN using PATs. The PATs' energy generated can be sold to nearby consumers or used by the network to cover power needs.

The amount of energy produced by the Cornubia WDN is 135.48kW, sufficient to classify its output as a Mini-hydroelectric powerplant equivalent. The Cornubia WDN would have an annual power output of 948.67 MWh. The amount of energy produced by the Pat Marshal WDN is 24.5542 kW, sufficient to classify its output as a Micro-hydroelectric powerplant equivalent. The Pat Marshal WDN would have an annual power output of 131.61 MWh.

CHAPTER 6

6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Reduction in leakage is crucial to increase the efficiency of water networks. Leakage losses within water distribution networks are incredibly high, costly to municipalities and negatively affect communities' access to freshwater. The high cost of water is a direct result of high leakage rates and high amounts of NRW in WDNs. Leakage losses make up the majority of NRW in a network. In recent years, many regions in South Africa have been subjected to water shortages due to inadequate supply volumes. Water is a valuable resource that needs to be saved wherever possible to minimise the occurrence of future water shortages.

In this thesis, a new method to optimise PRV placement and PRV setting has been developed, as well as a method to determine which PRVs can be feasibly replaced by PATs for renewable energy generation. The study uses pressure management to reduce excess network pressure and consequently the leakage rates within WDNs to increase water security. Leakage reduction by pressure control is the simplest and most effective method to reduce the leakage losses within existing WDNs. Only pipe pressure can be controlled once the pipes have been laid. Pressure reduction can be achieved through the inclusion of pressure reduction valves at critical points in WDNs. Determining the fluid characteristics in water networks is no easy task. Thus, there is a need to apply formal optimisation techniques to determine the optimum placement and setting for PRVs. Optimum PRV placement and optimum PRV setting can be regarded as two separate topics of study due to the optimisation problem's high dimensionality and the nonlinearity of water network models.

The current placement of PRVs within WDNs can be seen as outdated and inefficient. Automation will significantly improve the leakage rate reduction within a WDN as calculations are carried out with greater accuracy, as well as decreases the computational requirements needed. Every pipe in the network was checked for possible PRV placement. The pipe that maximised the leakage rate reduction was determined to be the optimal PRV location. The optimal setting for the PRV was also determined for every possible PRV position to determine the final combination of the optimal PRV placement and setting.

Water leakages can result in infrastructure damage and a reduction in water quality to consumers downstream. High pressures within the WDN increase the probability of pipe bursts and damage to pipelines, decreasing their operational lifespan and requiring frequent maintenance. Water saved from losses is comparable to increasing the production of clean drinking water and effectively increases fresh water supply to communities.

PATs can be an attractive alternative to turbines to recover energy. Instead of dissipating energy using PRVs, PATs have been proposed to harness this energy. A mathematical model was run after determining optimal PRV placement to determine which PATs can feasibly replace PRVs. PATs provide adequate pressure management with the added benefit of energy production. The potential revenue generated by PAT implementation was approximated for the two WDNs. The results showed that a relatively large amount of energy could be recovered from each WDN while significantly reducing leakage losses.

6.2 Overall Findings and Review of the Aims and Objectives of the Research

1. Aim 1: In this thesis, a new algorithm was created to optimise the placement and setting of pressure reducing valves within a water distribution network whose placement maximises the reduction in leakage rate within the network, satisfying the study's first aim.
2. Aim 2: The proposed model encompasses various standards and limitations for WDNs, that can be found in the Guidelines for Human Settlement Planning Volume 2 book (2005). The new algorithm contains a secondary model used to determine which PRVs in the network can be feasibly replaced by pumps operating as turbines to generate energy from the excess pressure within the network, satisfying the study's second aim.
3. Aim 3: The third aim of this thesis has been accomplished. A computer algorithm has been created that automates the PRV placement and setting process (primary) and automates replacing PRVs with PATs to generate renewable energy (secondary). The program was created in MATLAB 2018b using the equations shown in the methodology, Chapter 4 of this thesis. EPANET version 2.2 was used as the hydraulic solver for the network. The MATLAB EPANET Toolkit was used to communicate between MATLAB and EPANET and formed the basis for the commands used in my program (the code for the program is presented in Appendix A). The program has been run on two real-world water distribution networks: the Cornubia Integrated Human Settlement Development Phase 2A – Zone 1 and the Pat Marshal Housing Project.

The results from the two WDNs presented show the potential of the proposed algorithm in reducing the excess network pressures, thus reducing the leakage rates within the networks. The new mathematical model optimising the placement and setting of additional PRVs has achieved leakage rate reductions of 12.8011% and 27.907% for the Cornubia WDN and the Pat Marshal WDN, respectively.

1. This thesis's first and second objectives have been achieved as the mathematical model created optimally places and sets PRVs following all hydraulic, mathematical, and linear

constraints. The newly added PRVs have been optimally set to maintain downstream network constraints to the allowable tolerances, accounting for fluctuating consumer demand patterns. The network is hydraulically stable after PRV placement, and the optimal number of additional PRVs has also been determined. Five additional PRVs can be added to the Cornubia WDN, and two additional PRVs can be added to the PAT Marshal WDN to minimize the leakage rate in the respective networks.

2. The third objective has been achieved as the proposed mathematical model automatically determines which PATs can feasibly replace PRVs to harness energy from excess pressure in the network. The PATs operating characteristics have been considered as well as the demand pattern of the WDN. This ensures that the PATs only operate when network conditions permit and are not statically set to “on” for the whole day but can be bypassed during periods of high demand.
3. The fourth objective of this thesis has been accomplished. The Cornubia WDN can feasibly replace 9 PRVs with PATs to generate 135.48kW of energy, equivalent to a Mini hydroelectric powerplant. The potential gross margin generated by the Cornubia WDN power plant equivalent is R920 211.97 per annum. The Pat Marshal WDN can feasibly replace 1 PRV with a PAT to generate 24.5542kW of energy, equivalent to a Micro hydroelectric powerplant. The potential gross margin generated by the Pat Marshal WDN power plant equivalent is R127 662.30 per annum.
4. The fifth objective has been accomplished. The proposed methodology has been automated using computer software, specifically MATLAB and EPANET using the MATLAB EPANET Toolkit to communicate between the two programs. Automating the newly proposed methodology allows for easy parameter changes and time-efficient computations for hydraulic analysis that can be used for networks of any size. By automating the placement process, the program can easily compare multiple PRV placement and setting combinations compared to manually determining these factors. This is especially useful for more extensive networks, such as the Cornubia WDN with over 3100 pipes. Incorporating EPANET, a well-known hydraulic solver, into the program allows for increased calculation accuracy.

The primary desired outcome of the study has been met as the new proposed model optimally places and sets PRVs to reduce and regulate pressure at the nodes in the WDN to acceptable levels, proportionally decreasing the leakage rate in the WDN. A computer algorithm has been created which automates this process. The secondary desired outcome of the study has been met as PRVs have been identified in both networks for feasible PAT replacement to harness energy using the excess pressure in the WDN.

6.3 Sustainability and Environmental Impact

Traditionally, when communities were faced with a water shortage problem, new sources were developed. Finding new water sources has become increasingly difficult, resulting in alternate methods of sourcing water, such as desalination. Desalination is costly and has a substantial negative environmental impact. By creating more efficient water networks, less water is lost through leakages. Leakage reduction improves the quality and quantity of water available to consumers. Damages caused by leakages will be reduced, and less energy will be required to treat more water. Less water needs to be stored, resulting in a reduction in the environmental impact of structures such as dams. By reducing leakages, communities have greater access to water and a sustainable water supply.

6.4 Future Scope

The current methodology only caters for ‘gravity driven’ WDNs; further extensions should be made to incorporate the effects of pumps in WDNs. Future research can incorporate the energy saving achieved as a direct result of a reduced leakage loss rate. Energy savings can be in the form of less water needed to be treated, stored, and transported. The cost-benefit of a longer-lasting network requiring less maintenance and experiencing fewer pipe bursts can also be investigated. Networks can be analysed using different sensitivity criteria for PRV implementation. The choice of the objective function will depend on the extent to which the pressure limitations in the network can be violated. By changing various network parameters, different configurations of PRVs can be achieved. The methodology can be extended to optimise the setting of existing PRVs in the network. The objective function can be changed to focus on optimising energy generation, instead of leakage reduction, as a primary objective.

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APPENDIX A: PROGRAM CODE FOR OBJECT FUNCTION

The following program has been coded in MATLAB using the EPANET MATLAB Toolkit version 2.2. MATLAB version 2018b and EPANET version 2.2 were used. The program was created using the newly created algorithm shown in Chapter 4, Methodology. The program is used to optimise the placement and setting of additional PRVs in WDNs and determine which PATs can feasibly replace PRVs to harness renewable energy from the WDNs' excess pressure. Below is the script created to automate the method described in Chapter 4, methodology:

```
% Clear
clc; clear; close('all');

%Determine the number of PRVs you would like to implement into the network. Using a large
number will allow the program to determine the optimum number to add based on constraints.
    numberofPRVs = 10;

%System Settings
    MinNodalPressure = 24;
    MaxNodalPressure = 90;
%Optimise PRV setting
    PressureTolerance = 0.1; %Allow for 10% of the nodes after PAT implementation to be
below the minimum nodal pressure

%The value of the emitter coefficient and emitter exponent
    emitterCoeff = 0.001;
    emitterExp = 0.5;
    ZeroEmitterCoeff = 0;

%Start at Link index number
StartAtLink = 1;

%assign the name of the network
inpname = 'OriginalNetwork2.inp';

d = epanet (inpname);
PermanentPRVs = cell(25,20);

%
%PART 2: Leakage Determination
%set the emitter exponent to determine leakage rate in the network
d.getOptionsEmitterExponent;
d.setOptionsEmitterExponent(emitterExp);
%-----
%set emitter coefficient for all nodes
nodeEmitterCoef = sum(d.getNodeEmitterCoeff);
nodes = d.getNodeCount;
if nodeEmitterCoef == 0
    nodemovement = 1;
    for node = 1:nodes
        d.setNodeEmitterCoeff(nodemovement,emitterCoeff);
        nodemovement = nodemovement+1;
    end
```

```

end
%-----
%Determine Leakage using base and actual demand for the whole system
%BEFORE PRVs
d.openHydraulicAnalysis;
d.initializeHydraulicAnalysis;
tstep=1;beforeNodeActualDemand=[];
while (tstep==1)
    t=d.runHydraulicAnalysis;
    beforeNodeActualDemand = [beforeNodeActualDemand, d.getNodeActualDemand];
% determines the actual demand for each node
    tstep=d.nextHydraulicAnalysisStep;
end
beforeNodeBaseDemand = d.getNodeBaseDemands;
BeforeNodeBaseDemand = cell2mat(beforeNodeBaseDemand);
BeforeLeakageforEachNode = beforeNodeActualDemand -
BeforeNodeBaseDemand;% actual demand - base demand = leakage for each node
BeforeTotalLeakageforNetwork =
sum(BeforeLeakageforEachNode(BeforeLeakageforEachNode>0)); % Total leakage for the
whole network
LeakageUnits = d.getUnits;%LPS are the units
d.closeHydraulicAnalysis;
%
%-----
%Finds links connected to each node in the system

%-----
%Add a V_ to all existing valves in the network to easily identify
%them

NumberOfValves = d.getLinkValveCount;
OldNameValve = d.getLinkNameID;

for RenameValves = 1:NumberOfValves

    ExistingValvesIndex = d.getLinkValveIndex; % Valve index only
    ExistingValveIndexIndividual = ExistingValvesIndex(RenameValves); %One valve at a
time
    OldNameValve1 = OldNameValve(ExistingValveIndexIndividual); %gets valve name
    OldNameValves = cell2mat(OldNameValve1);
    NewPRVName = sprintf('%s_%s','V_',OldNameValves); %New valve name
    NewPRVNameV = NewPRVName;
    RenameExistingValves = d.setLinkNameID(ExistingValveIndexIndividual,
NewPRVNameV); %Adds a V_ to each valve name so they can be identified
    NewNameValve = d.getLinkNameID;

end
fprintf('Valve Names Updated. ');
fprintf('\n');
fprintf('\n');
%-----
%
%-----

%To perform the whole iteration process m times
for m = 1:numberofPRVs %The number of permanent PRVs required

```



```

    %Get the total number of pipes in the network
    N = d.getLinkPipeCount ;
    fprintf ('Total Pipes = %d\n',N);

%set simulation duration
hrs = 24;
d.setTimeSimulationDuration(hrs*3600)
%Run Hydraulic Analysis over this time
hyd_res = d.getComputedTimeSeries;

%Define the cells that will record the answers for each iteration
PRVchecker = cell (20,N);
Rawdata = cell(36,N);

%recording the values of PRVs
tstep = 1;Headf = [];HL = [];Flow = [1,N]; Headt = []; Pressure=[];

PRVFlow = []; PRVHL = [];
%-----
%-----

for i = 1:N

    try

        %Run Hydraulic Analysis over this time
        hyd_res = d.getComputedTimeSeries;

        %Identify which pipe to place the PRV in
        %Get Existing Pipe Data.
        aLinkIndex = d.getLinkPipeIndex;
        LinkIndex = StartAtLink; %Starts the iterations at this Link Index

        %_____
        %check for adjacent PRVs in the network

        %Iterate for all pipes in network - for loop

        %Finds links connected to each node in the system
        connmatrix = d.getConnectivityMatrix;
        nodesConnectingLinksIndex = d.getNodesConnectingLinksIndex;

        nodeConnLinkIDs = { };
        for p = 1:size(connmatrix, 1) %number of nodes
            nodeIndices = find(connmatrix(: , p));
            linksconnFrom = find(nodesConnectingLinksIndex(:, 1) == p);
            linksconnTo = find(nodesConnectingLinksIndex(:, 2) == p);
            nodeConnLinkIDs{p} = d.getLinkNameID(unique([linksconnFrom', linksconnTo']));
        end

        Rawdata{16,i} = nodeConnLinkIDs;
        if m ==1

```

```

        valvebothnodes1 = nodesConnectingLinksIndex(1,1); %node 1 connecting to link
        valvebothnodes2 = nodesConnectingLinksIndex(1,2); %node 2 connecting to link
    else
        valvebothnodes1 = nodesConnectingLinksIndex(m-1 + NumberOfValves ,1); %node 1
connecting to link
        valvebothnodes2 = nodesConnectingLinksIndex(m-1 + NumberOfValves ,2); %node 2
connecting to link
    end
    Rawdata{14,i} = valvebothnodes1;
    Rawdata{15,i} = valvebothnodes2;

    VfromNode = Rawdata{14,i};%Index value
    VtoNode = Rawdata{15,i};%Index value
    nodenotjunction = d.getNodeTypeIndex;

    PRVtvalvecheck =find(contains(Rawdata{16,1}{1,VtoNode},'V')); %finds if connected
to a valve
    PRVfvalvecheck =find(contains(Rawdata{16,1}{1,VfromNode},'V'));%finds if
connected to a valve
    Rawdata{17,i}=1; %No illegal connection

    %Check for illegal valve connections to adjacent valves
    if PRVtvalvecheck >= 1
        Rawdata{17,i}=0;
    elseif PRVfvalvecheck >= 1
        Rawdata{17,i}=0;
    end

    %check for illegal valve connections to tanks, reservoirs etc.
    if nodenotjunction(VfromNode)>0
        Rawdata{17,i}=0;
    elseif nodenotjunction(VtoNode)>0
        Rawdata{17,i}=0;
    end

    %-----

    try

linknames=d.getLinkPipeNameID;
linkid=linknames{LinkIndex};

connection=d.getNodesConnectingLinksID; %Get connection matrix for nodes connecting to
links

    if m == 1

        exlinkdiam=d.getLinkDiameter(LinkIndex + m-1);
        exlinklength=d.getLinkLength(LinkIndex + m-1);
        exlinkrough=d.getLinkRoughnessCoeff(LinkIndex + m-1);
        exlinkminor=d.getLinkMinorLossCoeff(LinkIndex + m-1);
        exlinkinitial=d.getLinkInitialStatus(LinkIndex + m-1);

        befNodes=connection(LinkIndex + m-1,:);

```

```

else

    exlinkdiam=d.getLinkDiameter(LinkIndex + NumberOfValves + m-2);
    exlinklength=d.getLinkLength(LinkIndex + NumberOfValves + m-2);
    exlinkrough=d.getLinkRoughnessCoeff(LinkIndex + NumberOfValves + m-2);
    exlinkminor=d.getLinkMinorLossCoeff(LinkIndex + NumberOfValves + m-2);
    exlinkinitial=d.getLinkInitialStatus(LinkIndex + NumberOfValves + m-2);

    befNodes = connection(LinkIndex + NumberOfValves + m-2 ,:);
end
%Determine which node is a from and a to node
fromNode=befNodes{1};
toNode=befNodes{2};

%-----
%Part 2: Leakage Determination
%Pressure at the nodes BEFORE PRV placement
    beforePRVPressure = mean(d.getBinComputedNodePressure );
    PressurefNode = beforePRVPressure(VfromNode);
    PressuretNode = beforePRVPressure(VtoNode);
    if PressurefNode<0 %To remove extremely small values close to zero, such as from
reservoirs and tanks
        PressurefNode = 0;
    elseif PressuretNode<0
        PressuretNode = 0;
    end
    averagePressureInPipe = (PressurefNode + PressuretNode)/2;%average pressure in the
pipe before PRVs added

    %Leakage determination
    LeakageBeforePRV = emitterCoeff .* averagePressureInPipe.^(emitterExp);

    %-----
    %Remove the emitter coefficient when adding PRV to prevent errors
    %set emitter coefficient for all nodes
    if nodeEmitterCoef == 0
        RnodeEmitterCoef = d.getNodeEmitterCoeff;
        Rnodes = d.getNodeCount;
        Rnodemovement = 1;
        for Rnode = 1:Rnodes
            d.setNodeEmitterCoeff(Rnodemovement,ZeroEmitterCoeff);%sets each node to have the
emitter coeff value
            Rnodemovement = Rnodemovement+1;
        end
    end
    %-----
%-----
%Determine PRV Setting
%Get the number of nodes in the network below minimum nodal pressure
%before PRV added
    NodesBelowMinPressure_Before = mean(d.getBinComputedNodePressure);
    NumNodesBelowMinPressure_Before = sum(NodesBelowMinPressure_Before(:)<=
MinNodalPressure);%Gets the number of nodes below min nodal pressure before PRVs added
    NumNodesTotal = d.getNodeCount;

```

```

    %Tolerance
    ToleranceAllowed_Node = ceil(NumNodesTotal .* PressureTolerance); %Ceil function
rounds up
    TotalToleranceAllowed = ToleranceAllowed_Node + NumNodesBelowMinPressure_Before
+ 1;%The plus one includes the affect of a PRV set to 24m
%
%
%Delete the pipe to be replaced by a PRV
d.deleteLink(linkid);

%Add PRV
PRVCode = sprintf('%s_%d','PRV',i) ;
valve_index = d.addLinkValvePRV(PRVCode,fromNode,toNode);
PRVsetting = 24;
minpressureall = 0;

%To add the Emitter Coefficient back for all nodes
%Set emitter coefficient for all nodes
    if nodeEmitterCoef == 0
        AnodeEmitterCoef = d.getNodeEmitterCoeff;
        Anodes = d.getNodeCount;
        Anodemovement = 1;
        for Anode = 1:Anodes
            d.setNodeEmitterCoeff(Anodemovement,emitterCoeff);%sets each node to have
the emitter coefficient value
            Anodemovement = Anodemovement+1;
        end
    end

%
%Add PRV
    d.setLinkDiameter (valve_index,exlinkdiam);
    d.setLinkInitialSetting(valve_index,PRVsetting);
%
%Run Hydraulic Analysis over this time
    hyd_res = d.getComputedTimeSeries;
%

%Determine OPTIMAL PRV setting

    %Get the number of nodes in the network below minimum nodal pressure after
    %PRV added
    NodesBelowMinPressure_After = mean(d.getBinComputedNodePressure); %average value
for the 24hr analysis
    NumNodesBelowMinPressure_After =
sum(NodesBelowMinPressure_After(:)<=MinNodalPressure); %Gets the number of nodes
below min nodal pressure after PRVs added

if Rawdata{17,i} == 1 %only optimise if pipe is NOT connected to reservoir or tank

    if NumNodesBelowMinPressure_After <= TotalToleranceAllowed
        %Optimum setting
        PRVchecker{1,i} = 'Optimal Setting';
        PRVchecker{2,i} = PRVsetting;
    end
end

```

```

else
    try
        while (NumNodesBelowMinPressure_After > TotalToleranceAllowed-1); %Have to
exclude the PRV end node as it is no longer 24
        %increase the PRV setting so that the downstream conditions are
        %satisfied within the allowable tolerance - this ensures
        %downstream nodes are within the tolerance limit

        PRVsetting = PRVsetting +1;

        if PRVsetting <= MaxNodalPressure
            d.setLinkDiameter (valve_index,exlinkdiam);
            d.setLinkInitialSetting(valve_index,PRVsetting);
            %Run Hydraulic Analysis over this time
            hyd_res = d.getComputedTimeSeries;

            NodesBelowMinPressure_After = mean(d.getBinComputedNodePressure);
            NumNodesBelowMinPressure_After =
sum(NodesBelowMinPressure_After(:)<=MinNodalPressure);

            PRVchecker{1,i} = 'Optimal Setting';
            PRVchecker{2,i} = PRVsetting;
        else
            PRVsetting = MaxNodalPressure +1;
            NumNodesBelowMinPressure_After = 0;
        end

    end
catch

end
end
else
    %Do nothing
end
%_____

%Get number of nodes experiencing negative pressure
NodesBelowZeroCheck = min(d.getBinComputedNodePressure);
NodesBelowZero = sum(NodesBelowZeroCheck(:) <= 0 ); %Gets the number of nodes
experiencing negative pressure

if NodesBelowZero > 0
    Rawdata{36,i} = 0;
end

%_____

%Run Hydraulic Analysis over this time
hyd_res = d.getComputedTimeSeries;

%Get raw data from the network
HL = mean(d.getBinComputedLinkHeadloss);
%get the pressure of all the nodes in the network for each
%iteration

```

```

    Pressure = mean(d.getBinComputedNodePressure );
    Flow = abs(mean(d.getBinComputedLinkFlow));

%Run Hydraulic Analysis over the time
hyd_res = d.getComputedTimeSeries;
%
%Part 2: Leakage Determination
%Pressure at the nodes AFTER PRV placement
    afterPRVPressure = mean(d.getBinComputedNodePressure);
    afterPressurefNode = afterPRVPressure(VfromNode);
    afterPressuretNode = afterPRVPressure(VtoNode);
    if afterPressurefNode<0 %To remove extremely small values close to zero, such as from
reservoirs and tanks
        afterPressurefNode = 0;
    end
    if afterPressuretNode<0
        afterPressuretNode = 0;
    end
    averagePressureInPipeAfterPRV = (afterPressurefNode +
afterPressuretNode)/2;%average pressure in the pipe before PRVs added

%Leakage determination
    LeakageAfterPRV = emitterCoeff .* averagePressureInPipeAfterPRV.^(emitterExp);
    PercentageLeakageReduction = (LeakageBeforePRV -
LeakageAfterPRV).*100/(LeakageBeforePRV);
%-----
%PART 2:Leakage Determination
%Determine Leakage using base and actual demand for the WHOLE system
%AFTER PRVs
%Run Hydraulic Analysis over the time
hyd_res = d.getComputedTimeSeries;

d.openHydraulicAnalysis;
d.initializeHydraulicAnalysis;
wPRVtstep=1;WafterNodeActualDemand=[];
while (wPRVtstep==1)
    PRVt=d.runHydraulicAnalysis;
    WafterNodeActualDemand = [WafterNodeActualDemand, d.getNodeActualDemand];
%determines the actual demand for each node
    wPRVtstep=d.nextHydraulicAnalysisStep;
end
    WafterNodeBaseDemand = d.getNodeBaseDemands;%determines the before demand for
each node
    WafterNodeBaseDemand = cell2mat(WafterNodeBaseDemand);
    WafterLeakageforEachNode = WafterNodeActualDemand -
WafterNodeBaseDemand;%actual demand - base demand = leakage for each node
    WafterTotalLeakageforNetwork =
sum(WafterLeakageforEachNode(WafterLeakageforEachNode>0)); %Total leakage for the
whole network - This eliminates reservoirs, tanks from the total leakages

    Rawdata{33,i} = WafterNodeBaseDemand;
    Rawdata{34,i} = WafterLeakageforEachNode;
    Rawdata{35,i} = WafterTotalLeakageforNetwork;
    d.closeHydraulicAnalysis;
%-----

```

```

%Reduction in total leakage in the network
WholeNetworkPercentageLeakageReductioninNetwork = (BeforeTotalLeakageforNetwork -
WAfterTotalLeakageforNetwork).*100/BeforeTotalLeakageforNetwork;

%
Rawdata{29,i}=1;
%Removes the possibility of the valve increasing the leakage rate in the
%network
if WholeNetworkPercentageLeakageReductioninNetwork <=0
    Rawdata{29,i} = 0; %Determines if the PRV added will increase the leakage rate
end

catch
%eliminates the occurrence of a valve connected from a node that already has
%a valve
fprintf('cannot put valve here \n');
Rawdata{29,i} = 0; %Determines if the PRV added will increase the leakage rate
end

%Get specific data for each added PRV
PRVFlow = Flow (1,end); %The program places the most recently edited pipe at the end of the
index
PRVHL = HL (1,end);
PRVflowtimesheadloss = PRVFlow * PRVHL;

%Record the result of the PRV
PRVNAME = i+LinkIndex-1;
fprintf('%s_%d\n','PRV',PRVNAME);
fprintf('Original Pipe %s\n', linkid);
NewLinkIDName = sprintf('%s_%s','P_',linkid); %New LinkID Name for each pipe
NewLinkIDNAME = NewLinkIDName;
Rawdata{31,i} = NewLinkIDNAME;

%Add original Pipe back and remove PRV
removeprv = d.deleteLink(valve_index);
try
    newpipe = d.addLinkPipe(linkid, fromNode, toNode,exlinklength, exlinkdiam, exlinkrough,
exlinkminor, exlinkinitial);
catch
    newpipe = d.addLinkPipe(NewLinkIDNAME, fromNode, toNode,exlinklength, exlinkdiam,
exlinkrough, exlinkminor, exlinkinitial);
    fprintf('NewLinkIDNAME used. ');
    fprintf('\n');
    %if the error occurs saying duplicate link id used, the new link ID
    %will be used. It is just a pipe name and has no significance.
end
%-----

%get the raw data
Rawdata{1,i} = linkid;%pipe number
Rawdata{2,i} = PRVsetting;
Rawdata{3,i} = Pressure; %pressure for each node in the entire system for each iteration
Rawdata{4,i} = Flow; %flow for each link in the entire system for each iteration
Rawdata{5,i} = toNode; %this node will be the node that gets set to the setting in EPANET
Rawdata{6,i} = valve_index; %if equal to 'a number' then a PRV has been placed

```

```

Rawdata{7,i} = HL;%head loss caused by the PRV
Rawdata{8,i} = PRVFlow; %The flow across each PRV
Rawdata{9,i} = PRVHL; %The Head reduction due to each PRV
Rawdata{10,i} = PRVflowtimesheadloss; %The product of flow * headloss due to the PRV
Rawdata{11,i} = fromNode;
Rawdata{12,i} = LinkIndex;
Rawdata{13,i} = i; %gets the iteration number for the pipe to be replaced
Rawdata{19,i} = PressurefNode;%Pressure in from node before PRV Placement
Rawdata{20,i} = PressuretNode;%Pressure in to node before PRV Placement
Rawdata{21,i} = averagePressureInPipe;%Average pressure in the pipe before PRV Placement
Rawdata{22,i} = LeakageBeforePRV; %Leakage in the pipe before PRV Placement
Rawdata{23,i} = afterPressurefNode; %Pressure in the from node after PRV Placement
Rawdata{24,i} = afterPressuretNode; %Pressure in the to node after PRV Placement
Rawdata{25,i} = averagePressureInPipeAfterPRV; %Average pressure in the pipe after PRV
Placement
Rawdata{26,i} = LeakageAfterPRV; %Leakage in the pipe after PRV Placement
Rawdata{27,i} = PercentageLeakageReduction; %Percentage reduction in leakage due to PRV
Placement
Rawdata{30,i} = WholeNetworkPercentageLeakageReductioninNetwork; %Total Network
Leakage reduction percentage
Rawdata{18,i} = Rawdata{30,i} .* Rawdata{17,i} .* Rawdata{29,i};

```

catch

end

end

%set simulation duration

hrs = 24;

d.setTimeSimulationDuration(hrs*3600)

%Find the PRV with the *highest leakage rate reduction*

a = Rawdata(9:9,:); %to get the values of headloss from the Rawdata matrix

b = Rawdata(1:1,:); %to get all the linkids for each PRV

c = Rawdata(5:5,:); %gets the toNode for the pipe to be replaced

e = Rawdata(11:11,:); %gets the fromNode for the pipe to be replaced

f = Rawdata(13:13,:); %gets the iteration number for the pipe to be replaced

g = Rawdata(2:2,:); %gets the PRV setting

k = Rawdata(17:17,:); %gets if the link is connected from a valve, if the link is connected to a valve, then it returns a zero

w = Rawdata(18:18,:); %gets max adjusted percentage PRV leakage reduction

o = Rawdata(8:8,:); %Flow across PRV

q = Rawdata(22:22,:); %Leakage before PRV Placement in THAT pipe

aa = Rawdata(26:26,:); %Leakage after PRV Placement in THAT pipe

ab = Rawdata(27:27,:); %Percentage Leakage reduction in that Pipe

ac = Rawdata(28:28,:); %Determines if the nodes are below the min pressure allowable

ad = Rawdata(30:30,:); %Determines the total network percentage leakage reduction

A=cell2mat(a);

F=cell2mat(f);

G=cell2mat(g);

K=cell2mat(k);

W=cell2mat(w);


```

O=cell2mat(o);
Q=cell2mat(q);
AA=cell2mat(aa);
AB=cell2mat(ab);
AC=cell2mat(ac);
AD=cell2mat(ad);

amaxHL = max(W);
[~,maxHLPRV] = max(W); %finds the max leakage rate reduction due to PRV

amaxpositionlinkid = b(1,maxHLPRV); %finds the associated pipe name for the PRV with
max Headloss
atoNodepermanent = c(1,maxHLPRV); %finds the associated toNode for the PRV with max
Headloss
afromNodepermanent = e(1,maxHLPRV);%finds the associated fromNode for the PRV with
max Headloss
aiterationnumber = F(1,maxHLPRV); %finds the iteration number for the permanent PRV
aPRVsetting = G(1,maxHLPRV); %finds the PRV setting for the permanent PRV
PRVflowpermanent = O(1,maxHLPRV);%Flow rate across permanent PRV
PRVheadlosspermanent = A(1,maxHLPRV);%HL across permanent PRV
LeakageBeforePRVpermanent = Q(1,maxHLPRV);%leakage before permanent PRV
LeakageAfterPRVpermanent = AA(1,maxHLPRV);%leakage after permanent PRV
PercentageLeakageReductionDueToPRV = AB(1,maxHLPRV); %Percentage leakage
reduction at PRV
TotalNetworkLeakageReductionPercentage = AD(1,maxHLPRV);%Percentage leakage
reduction in whole network

%Get Existing Pipe Data for permanent placement.
bLinkIndex = aiterationnumber;
bexlinkdiam=d.getLinkDiameter(bLinkIndex);
bexlinklength=d.getLinkLength(bLinkIndex);
bexlinkrough=d.getLinkRoughnessCoeff(bLinkIndex);
bexlinkminor=d.getLinkMinorLossCoeff(bLinkIndex);
bexlinkinitial=d.getLinkInitialStatus(bLinkIndex);
bconnection=d.getNodesConnectingLinksID;

%Determine which node is a from and a to node
bfromNode=char(afromNodepermanent);
btoNode=char(atoNodepermanent);

PermanentPRVs{1,m}= bLinkIndex;
PermanentPRVs{2,m}=amaxpositionlinkid;
PermanentPRVs{4,m}=atoNodepermanent;
PermanentPRVs{3,m}=afromNodepermanent;
PermanentPRVs{5,m}=aPRVsetting;
PermanentPRVs{6,m}=PRVflowpermanent;
PermanentPRVs{7,m}=PRVheadlosspermanent;
PermanentPRVs{8,m}=m;
PermanentPRVs{9,m}=LeakageBeforePRVpermanent;
PermanentPRVs{10,m}=LeakageAfterPRVpermanent;
PermanentPRVs{11,m}=PercentageLeakageReductionDueToPRV;
PermanentPRVs{12,m}=TotalNetworkLeakageReductionPercentage;
PermanentPRVs{13,m}=0;
PermanentPRVs{14,m}=0;
PermanentPRVs{15,m}=0;

```

```

LeakageCalc = 0;

if amaxHL>0

%Delete the pipe to be permanently replaced
d.deleteLink(amaxpositionlinkid);

%Add permanant PRV into network
bPRVCode = sprintf('%s_%d','permanentPRV',m) ;
bvalve_index = d.addLinkValvePRV(bPRVCode,bfromNode,btoNode);
bPRVsetting = aPRVsetting;
d.setLinkDiameter (bvalve_index,bexlinkdiam);
d.setLinkInitialSetting(bvalve_index,bPRVsetting);

%Save new file
savename = sprintf('%s%d','PRVsPlaced_',m,'.inp');
d.saveInputFile (savename);
LeakageCalc = 1;

fprintf ('\nSuccessful PRV Placement \n \n');

elseif amaxHL == 0
%if the PRV placed results in a missing pipe where the PRV should be,
%reduce m by one.
fprintf (2,'\nThe amount of PRVs requested is too high. ');
fprintf (2,'\nReduce numberofPRVs by 1 \n \n');
end

%-----
%Save individual Workspaces
if N < 1000
%Save each m iteration workspace (variables and answers)
save(['ValvesPlaced_m_iteration_' num2str(m)]);

else
%This takes roughly 1 hour as there are a lot of variables. Only
%use for networks over 1000 pipes.

save(['Rawdata_m_iteration_' num2str(m)], 'Rawdata', '-v7.3'); %Saves Rawdata
save(['PermanentPRVs_m_iteration_' num2str(m)], 'PermanentPRVs', '-v7.3'); %Saves
PermanentPRVs
end

end

%_____
%PART 2:Leakage Determination
%Determine Leakage using base and actual demand for the whole system
%AFTER PRVs
if LeakageCalc == 1; %No errors
hyd_res = d.getComputedTimeSeries;

```

```

d.openHydraulicAnalysis;
d.initializeHydraulicAnalysis;

PRVtstep=1;afterNodeActualDemand=[];
while (PRVtstep==1)
    PRVt=d.runHydraulicAnalysis;
    afterNodeActualDemand = [afterNodeActualDemand, d.getNodeActualDemand];
    %determines the actual demand for each node
    PRVtstep=d.nextHydraulicAnalysisStep;
end
afterNodeBaseDemand = d.getNodeBaseDemands;%determines the before demand for each
node
AfterNodeBaseDemand = cell2mat(afterNodeBaseDemand);
AfterLeakageforEachNode = afterNodeActualDemand - AfterNodeBaseDemand;%actual
demand - base demand = leakage for each node
AfterTotalLeakageforNetwork =
sum(AfterLeakageforEachNode(AfterLeakageforEachNode>0)); %Total leakage for the whole
network - This eliminates reservoirs, tanks from the total leakages

d.closeHydraulicAnalysis;
%-----
%Reduction in total leakage in the network
PercentageLeakageReductioninNetwork = (BeforeTotalLeakageforNetwork -
AfterTotalLeakageforNetwork).*100/BeforeTotalLeakageforNetwork;
FlowUnits = d.getFlowUnits;

fprintf('\n');
fprintf('%s%d%s','Cumulative Percentage leakage reduction in the network due to the
added PRV configuration = ', TotalNetworkLeakageReductionPercentage ,'%');
fprintf('\n');
fprintf('\n');

%_____
end
d.saveInputFile('ValvesPlaced_Final.inp'); %successful
%_____

%PART 3: Determine the properties of all PRVs in the network
%Open Last Output file
ValveOutput = 'ValvesPlaced_Final.inp';
valve = epanet (ValveOutput);

%set simulation duration
hrs = 24;
valve.setTimeSimulationDuration(hrs*3600)

%Run Hydraulic Analysis over this time
hyd_res = valve.getComputedTimeSeries;

%Determine the valves in the network
TotalValvesInNetwork = valve.getLinkValveCount;%Gets the number of valves in the network
AllPRVs = cell(20,TotalValvesInNetwork);
PATdetermination = cell(20,TotalValvesInNetwork);

```

```
for AllValves = 1:TotalValvesInNetwork
```

```

    ValvesInNetworktotal = valve.getLinkValveIndex; % Valve Index
    ValvesInNetwork = ValvesInNetworktotal(AllValves); % Gets value for each valve in the
    valve index
    ValvesInNetworkNameAll=valve.getLinkNameID;
    ValvesInNetworkName = ValvesInNetworkNameAll{ ValvesInNetwork };
    aPRVHL = mean(valve.getBinComputedLinkHeadloss);
    FinalPRV_HL = aPRVHL(ValvesInNetwork); % gets the Headloss across each PRV
    % get the pressure of all the nodes in the network for each
    % iteration
    aPRVPressure = mean(valve.getBinComputedNodePressure);
    aPRVFlow = abs(mean(valve.getBinComputedLinkFlow));
    FinalPRV_Flow = aPRVFlow(ValvesInNetwork); % gets the flow rate across each PRV

    % PAT within operating range
    PRVhl_totalTimeAll = valve.getBinComputedLinkHeadloss; % Gets the HL that the
    PAT can operate within
    PRVHL_PATtotalTime = PRVhl_totalTimeAll(:, ValvesInNetwork); % Gets the HL that
    the PAT can operate in for that specific PAT for the total time period
    PRVflow_totalTimeAll = valve.getBinComputedLinkFlow; % Gets the FLOW that the
    PAT can operate within
    PRVFlow_totalTime = PRVflow_totalTimeAll(:, ValvesInNetwork); % Gets the Flow that
    the PAT can operate in for that specific PAT for the total time period
    %-----
    % Determine the Power output for each PRV
    % power = rho * gravity * flow rate * headloss due to PRV * efficiency
    Rho = 1000;
    Gravity = 9.81;
    PAT_Efficiency = 0.85;
    LPS_m3persec = 0.001;
    Wto_kW = 0.001;

    PowerGenCalc = Rho.*Gravity.*PAT_Efficiency.*LPS_m3persec.*Wto_kW;
    %-----
    % Determine the Profit for each PRV
    % Profit = Power generated by each PRV * Profit per kW
    SellingPricePkWh = 2.17; % R/kWh Selling Price
    CostPricePkWh = 1.2; % R/kWh cost price
    NetProfitPkWh = SellingPricePkWh - CostPricePkWh; % R/kWh Profit
    % Number of operating days in a year
    YearlyOperationTime = 335; % Days per year

    %-----
    % Record the Answers
    AllPRVs{1, AllValves} = ValvesInNetworkName; % Name of each PRV
    AllPRVs{2, AllValves} = FinalPRV_HL; % Average Headloss due to each PRV during the full
    time period
    AllPRVs{3, AllValves} = FinalPRV_Flow; % Average Flow rate across each PRV during the full
    time period
    AllPRVs{4, AllValves} = PowerGenCalc.*AllPRVs{2, AllValves}.*AllPRVs{3, AllValves};
    % Power generated by each PRV in kW - Total not considering PAT HL restraints
    TotalpowerforAllduration = AllPRVs(4, AllValves); % Total Power output if PAT was
    operating for total time period - even during low HL

```

```

TotalPowerforAllDuration = cell2mat(TotalpowerforAllDuration);

%-----
%PAT PROPERTIES

%Choose which PAT will be implemented based on the total possible power
%production
    if TotalPowerforAllDuration > 0 && TotalPowerforAllDuration <= 5 %Max power
output of PAT higher than range max
        %PAT 1
        PATtobeInstalled = 1;
        PAT_HLmin = 22;
        PAT_HLmax = 60;
        PAT_FLOWmin = 1.5;
        PAT_FLOWmax = 40;
        PAT_PowerMax = 5;
        PumpCostPrice = 60000;
        Actual_PAT_Efficiency = 0.89;
    elseif TotalPowerforAllDuration > 5 && TotalPowerforAllDuration <= 15
        %PAT 2
        PATtobeInstalled = 2;
        PAT_HLmin = 25;
        PAT_HLmax = 65;
        PAT_FLOWmin = 15;
        PAT_FLOWmax = 30;
        PAT_PowerMax = 15;
        PumpCostPrice = 65000;
        Actual_PAT_Efficiency = 0.93;
    elseif TotalPowerforAllDuration > 15 && TotalPowerforAllDuration <= 85
        %PAT 3
        PATtobeInstalled = 3;
        PAT_HLmin = 35;
        PAT_HLmax = 80;
        PAT_FLOWmin = 10;
        PAT_FLOWmax = 600;
        PAT_PowerMax = 85;
        PumpCostPrice = 205000;
        Actual_PAT_Efficiency = 0.93;

    elseif TotalPowerforAllDuration > 85 && TotalPowerforAllDuration <= 170
        %PAT 4
        PATtobeInstalled = 4;
        PAT_HLmin = 35;
        PAT_HLmax = 80;
        PAT_FLOWmin = 10;
        PAT_FLOWmax = 600;
        PAT_PowerMax = 170;
        PumpCostPrice = 410000;
        Actual_PAT_Efficiency = 0.93;

    elseif TotalPowerforAllDuration <= 0 %If no energy is produced
        %PAT 5
        PATtobeInstalled = 5; %No PAT
        PAT_HLmin = 0;
        PAT_HLmax = 0;

```

```

PAT_FLOWmin = 0;
PAT_FLOWmax = 0;
PAT_PowerMax = 0;
PumpCostPrice = 0;
Actual_PAT_Efficiency = 0;

end

%PAT Actual operation taking into consideration the minimum HL for the PAT

PATLimitExceeded = 0; %If the HL or Flow rate of the PAT cannot match the conditions in the
system, then = 1

if PATtobeInstalled == 1
    AllPRVs{20,AllValves} = PATtobeInstalled;
    PATdetermination{1,AllValves} = PRVHL_PATtotalTime;%PAT HL for entire period
    %Determine HL limitations
    PAT_HLLimitmin = PRVHL_PATtotalTime(:) > PAT_HLmin;%Binary function
    PAT_HLLimitmax = PRVHL_PATtotalTime(:) < PAT_HLmax;%Binary function
    PAT_HLLimitRange = PAT_HLLimitmin .* PAT_HLLimitmax;%Where the PATs HL is
within the min and max range - Binary Function

    %Determine Flow limitations
    PATdetermination{8,AllValves} = PRVFlow_totalTime; %PAT Flow for entire period
    PAT_FlowLimitmin = PRVFlow_totalTime(:) > PAT_FLOWmin;%Binary function
    PAT_FlowLimitmax = PRVFlow_totalTime(:) < PAT_FLOWmax;%Binary function
    PAT_FlowLimitRange = PAT_FlowLimitmin .* PAT_FlowLimitmax;%where the PATs
Flow is within the min and max range - Binary Function

    PAT_HourCounter = sum(PAT_HLLimitRange(:).* PAT_FlowLimitRange(:)) ;
    %counts the values in the column above the PAT HL minimum for each PAT -- each true value
will be a 1, sum to get total
    PATdetermination{9,AllValves} = PAT_FlowLimitRange .* PAT_HLLimitRange ;
    %Binary showing when the PAT is switched on and off
    if PAT_HourCounter == 0 %No HL matches PATs operating limits
        PAT_HourCounter = 1000000; %To make PAT unfeasible and to stop a division by
zero
    end
    PATLimitExceeded = 1;
end

PAT_HL_OperationTime = sum( PAT_HLLimitRange(:) .* PRVHL_PATtotalTime(:)
.* PAT_FlowLimitRange(:))/PAT_HourCounter; %PAT average HL within limitations
PAT_Flow_OperationTime = sum( PAT_FlowLimitRange(:).* PRVFlow_totalTime(:)
.*PAT_HLLimitRange(:))/PAT_HourCounter; %PAT average flow rate within limitations
PATdetermination{2,AllValves} = PAT_HL_OperationTime; %PAT's actual HL
PATdetermination{3,AllValves} = PAT_Flow_OperationTime; %PAT's actual Flow
Rate
%Actual Power generation of the PAT - considering the Pump to
%PAT conversion  $Q_t = Q_p/n^{0.8}$  and  $H_t = H_p/n^{1.2}$ 
PATdetermination{4,AllValves} = PowerGenCalc / PAT_Efficiency .*
Actual_PAT_Efficiency .* PATdetermination{2,AllValves}/(Actual_PAT_Efficiency^(1.2)) .*
PATdetermination{3,AllValves}/(Actual_PAT_Efficiency^(0.8)); %Actual Power output of
PAT - kW

```

```

PATdetermination{5,AllValves} = PAT_HourCounter; %Number of hours the PAT is
operational for based on when it is switched on
PATdetermination{6,AllValves} = PATtobeInstalled;
if PATLimitExceeded == 1
    PATdetermination{5,AllValves} = 'PAT operating limits exceeded';
end

elseif PATtobeInstalled == 2
    AllPRVs{20,AllValves} = PATtobeInstalled;
    PATdetermination{1,AllValves} = PRVHL_PATtotalTime;%PAT HL for entire period
    %Determine HL limitations
    PAT_HLLimitmin = PRVHL_PATtotalTime(:) > PAT_HLmin;%Binary function
    PAT_HLLimitmax = PRVHL_PATtotalTime(:) < PAT_HLmax;%Binary function
    PAT_HLLimitRange = PAT_HLLimitmin .* PAT_HLLimitmax;%Where the PATs HL is
within the min and max range - Binary Function

    %Determine Flow limitations
    PATdetermination{8,AllValves} = PRVFlow_totalTime; %PAT Flow for entire period
    PAT_FlowLimitmin = PRVFlow_totalTime(:) > PAT_FLOWmin;%Binary function
    PAT_FlowLimitmax = PRVFlow_totalTime(:) < PAT_FLOWmax;%Binary function
    PAT_FlowLimitRange = PAT_FlowLimitmin .* PAT_FlowLimitmax;%where the PATs
Flow is within the min and max range - Binary Function

    PAT_HourCounter = sum(PAT_HLLimitRange(:).* PAT_FlowLimitRange(:)) ;
    %counts the values in the column above the PAT HL minimum for each PAT -- each true value
will be a 1, sum to get total
    PATdetermination{9,AllValves} = PAT_FlowLimitRange .* PAT_HLLimitRange ;
    %Binary showing when the PAT is switched on and off
    if PAT_HourCounter == 0 %No HL matches PATs operating limits
        PAT_HourCounter = 1000000; %To make PAT unfeasible and to stop a division by
zero
    end
    PATLimitExceeded = 1;
end

    PAT_HL_OperationTime = sum( PAT_HLLimitRange(:) .* PRVHL_PATtotalTime(:)
.* PAT_FlowLimitRange(:))/PAT_HourCounter; %PAT average HL within limitations
    PAT_Flow_OperationTime = sum( PAT_FlowLimitRange(:).* PRVFlow_totalTime(:)
.*PAT_HLLimitRange(:))/PAT_HourCounter; %PAT average flow rate within limitations
    PATdetermination{2,AllValves} = PAT_HL_OperationTime; %PAT's actual HL
    PATdetermination{3,AllValves} = PAT_Flow_OperationTime; %PAT's actual Flow
Rate
    %Actual Power generation of the PAT - considering the Pump to
    %PAT conversion  $Q_t = Q_p/n^{0.8}$  and  $H_t = H_p/n^{1.2}$ 
    PATdetermination{4,AllValves} = PowerGenCalc / PAT_Efficiency .*
Actual_PAT_Efficiency.* PATdetermination{2,AllValves}/(Actual_PAT_Efficiency^(1.2)) .*
PATdetermination{3,AllValves}/(Actual_PAT_Efficiency^(0.8)); %Actual Power output of
PAT - kW
    PATdetermination{5,AllValves} = PAT_HourCounter; %Number of hours the PAT is
operational for based on when it is switched on
    PATdetermination{6,AllValves} = PATtobeInstalled;
    if PATLimitExceeded == 1
        PATdetermination{5,AllValves} = 'PAT operating limits exceeded';
    end

elseif PATtobeInstalled == 3

```



```

AllPRVs{20,AllValves} = PATtobeInstalled;
PATdetermination{1,AllValves} = PRVHL_PATtotalTime;%PAT HL for entire period
%Determine HL limitations
PAT_HLLimitmin = PRVHL_PATtotalTime(:) > PAT_HLmin;%Binary function
PAT_HLLimitmax = PRVHL_PATtotalTime(:) < PAT_HLmax;%Binary function
PAT_HLLimitRange = PAT_HLLimitmin .* PAT_HLLimitmax;%Where the PATs HL is
within the min and max range - Binary Function

%Determine Flow limitations
PATdetermination{8,AllValves} = PRVFlow_totalTime; %PAT Flow for entire period
PAT_FlowLimitmin = PRVFlow_totalTime(:) > PAT_FLOWmin;%Binary function
PAT_FlowLimitmax = PRVFlow_totalTime(:) < PAT_FLOWmax;%Binary function
PAT_FlowLimitRange = PAT_FlowLimitmin .* PAT_FlowLimitmax;%where the PATs
Flow is within the min and max range - Binary Function

PAT_HourCounter = sum(PAT_HLLimitRange(:).* PAT_FlowLimitRange(:)) ;
%counts the values in the column above the PAT HL minimum for each PAT -- each true value
will be a 1, sum to get total
PATdetermination{9,AllValves} = PAT_FlowLimitRange .* PAT_HLLimitRange ;
%Binary showing when the PAT is switched on and off
if PAT_HourCounter == 0 %No HL matches PATs operating limits
    PAT_HourCounter = 1000000; %To make PAT unfeasible and to stop a division by
zero
    PATLimitExceeded = 1;
end

PAT_HL_OperationTime = sum( PAT_HLLimitRange(:) .* PRVHL_PATtotalTime(:)
.* PAT_FlowLimitRange(:))/PAT_HourCounter; %PAT average HL within limitations
PAT_Flow_OperationTime = sum( PAT_FlowLimitRange(:).* PRVFlow_totalTime(:)
.*PAT_HLLimitRange(:))/PAT_HourCounter; %PAT average flow rate within limitations
PATdetermination{2,AllValves} = PAT_HL_OperationTime; %PAT's actual HL
PATdetermination{3,AllValves} = PAT_Flow_OperationTime; %PAT's actual Flow
Rate
%Actual Power generation of the PAT - considering the Pump to
%PAT conversion  $Q_t = Q_p/n^{0.8}$  and  $H_t = H_p/n^{1.2}$ 
PATdetermination{4,AllValves} = PowerGenCalc / PAT_Efficiency .*
Actual_PAT_Efficiency .* PATdetermination{2,AllValves}/(Actual_PAT_Efficiency^(1.2)) .*
PATdetermination{3,AllValves}/(Actual_PAT_Efficiency^(0.8)); %Actual Power output of
PAT - kW
PATdetermination{5,AllValves} = PAT_HourCounter; %Number of hours the PAT is
operational for based on when it is switched on
PATdetermination{6,AllValves} = PATtobeInstalled;
if PATLimitExceeded == 1
    PATdetermination{5,AllValves} = 'PAT operating limits exceeded';
end

elseif PATtobeInstalled ==4
    AllPRVs{20,AllValves} = PATtobeInstalled;
    PATdetermination{1,AllValves} = PRVHL_PATtotalTime;%PAT HL for entire period
    %Determine HL limitations
    PAT_HLLimitmin = PRVHL_PATtotalTime(:) > PAT_HLmin;%Binary function
    PAT_HLLimitmax = PRVHL_PATtotalTime(:) < PAT_HLmax;%Binary function
    PAT_HLLimitRange = PAT_HLLimitmin .* PAT_HLLimitmax;%Where the PATs HL is
within the min and max range - Binary Function

```



```

    %Determine Flow limitations
    PATdetermination{8,AllValves} = PRVFlow_totalTime; %PAT Flow for entire period
    PAT_FlowLimitmin = PRVFlow_totalTime(:) > PAT_FLOWmin ;%Binary function
    PAT_FlowLimitmax = PRVFlow_totalTime(:) < PAT_FLOWmax;%Binary function
    PAT_FlowLimitRange = PAT_FlowLimitmin .* PAT_FlowLimitmax;%where the PATs
Flow is within the min and max range - Binary Function

    PAT_HourCounter = sum(PAT_HLLimitRange(:).* PAT_FlowLimitRange(:)) ;
%counts the values in the column above the PAT HL minimum for each PAT -- each true value
will be a 1, sum to get total
    PATdetermination{9,AllValves} = PAT_FlowLimitRange .* PAT_HLLimitRange ;
%Binary showing when the PAT is switched on and off
    if PAT_HourCounter == 0 %No HL matches PATs operating limits
        PAT_HourCounter = 1000000; %To make PAT unfeasible and to stop a division by
zero
        PATLimitExceeded = 1;
    end

    PAT_HL_OperationTime = sum( PAT_HLLimitRange(:) .* PRVHL_PATtotalTime(:)
.* PAT_FlowLimitRange(:))/PAT_HourCounter; %PAT average HL within limitations
    PAT_Flow_OperationTime = sum( PAT_FlowLimitRange(:).* PRVFlow_totalTime(:)
.*PAT_HLLimitRange(:))/PAT_HourCounter; %PAT average flow rate within limitations
    PATdetermination{2,AllValves} = PAT_HL_OperationTime; %PAT's actual HL
    PATdetermination{3,AllValves} = PAT_Flow_OperationTime; %PAT's actual Flow
Rate
    %Actual Power generation of the PAT - considering the Pump to
    %PAT conversion  $Q_t = Q_p/n^{0.8}$  and  $H_t = H_p/n^{1.2}$ 
    PATdetermination{4,AllValves} = PowerGenCalc / PAT_Efficiency .*
Actual_PAT_Efficiency .* PATdetermination{2,AllValves}/(Actual_PAT_Efficiency^(1.2)) .*
PATdetermination{3,AllValves}/(Actual_PAT_Efficiency^(0.8)); %Actual Power output of
PAT - kW
    PATdetermination{5,AllValves} = PAT_HourCounter; %Number of hours the PAT is
operational for based on when it is switched on
    PATdetermination{6,AllValves} = PATtobeInstalled;
    if PATLimitExceeded == 1
        PATdetermination{5,AllValves} = 'PAT operating limits exceeded';
    end

    elseif PATtobeInstalled ==5 %No Energy
        AllPRVs{20,AllValves} = PATtobeInstalled;
        PATdetermination{1,AllValves} = 0;%PAT HL for entire period
        %Determine HL limitations
        PAT_HLLimitmin = PRVHL_PATtotalTime(:) > PAT_HLmin;%Binary function
        PAT_HLLimitmax = PRVHL_PATtotalTime(:) < PAT_HLmax;%Binary function
        PAT_HLLimitRange = 0;%Where the PATs HL is within the min and max range - Binary
Function

        %Determine Flow limitations
        PATdetermination{8,AllValves} = PRVFlow_totalTime; %PAT Flow for entire period
        PAT_FlowLimitmin = PRVFlow_totalTime(:) > PAT_FLOWmin ;%Binary function
        PAT_FlowLimitmax = PRVFlow_totalTime(:) < PAT_FLOWmax;%Binary function
        PAT_FlowLimitRange = 0;%where the PATs Flow is within the min and max range -
Binary Function

```

```

PAT_HourCounter = 0 ; %counts the values in the column above the PAT HL minimum
for each PAT -- each true value will be a 1, sum to get total
PATdetermination{9,AllValves} = 0 ; %Binary showing when the PAT is switched on
and off
    if PAT_HourCounter == 0 %No HL matches PATs operating limits
        PAT_HourCounter = 1000000; %To make PAT unfeasible and to stop a division by
zero
        PATLimitExceeded = 1;
    end

    PAT_HL_OperationTime = sum( PAT_HLLimitRange(:) .* PRVHL_PATtotalTime(:)
.* PAT_FlowLimitRange(:))/PAT_HourCounter; %PAT average HL within limitations
    PAT_Flow_OperationTime = sum( PAT_FlowLimitRange(:) .* PRVFlow_totalTime(:)
.*PAT_HLLimitRange(:))/PAT_HourCounter; %PAT average flow rate within limitations
    PATdetermination{2,AllValves} = PAT_HL_OperationTime; %PAT's actual HL
    PATdetermination{3,AllValves} = PAT_Flow_OperationTime; %PAT's actual Flow
Rate
    %Actual Power generation of the PAT - considering the Pump to
    %PAT conversion  $Q_t = Q_p/n^{0.8}$  and  $H_t = H_p/n^{1.2}$ 
    PATdetermination{4,AllValves} = PowerGenCalc / PAT_Efficiency .*
Actual_PAT_Efficiency .* PATdetermination{2,AllValves}/(Actual_PAT_Efficiency^(1.2)) .*
PATdetermination{3,AllValves}/(Actual_PAT_Efficiency^(0.8)); %Actual Power output of
PAT - kW
    PATdetermination{5,AllValves} = PAT_HourCounter; %Number of hours the PAT is
operational for based on when it is switched on
    PATdetermination{6,AllValves} = PATtobeInstalled;
    if PATLimitExceeded == 1
        PATdetermination{5,AllValves} = 'PAT operating limits exceeded';
    end

end

%-----
PAToperational = PAT_HourCounter; %Total PAT operational time

AllPRVs{5,AllValves} = PATdetermination{4,AllValves}; %Actual Power Output of the PAT
- Considering the Variable demand pattern and only switching PAT on when HL is above min
AllPRVs{6,AllValves} = PAToperational; %The number of hours the PAT operates
AllPRVs{7,AllValves} =
AllPRVs{5,AllValves}.*YearlyOperationTime.*PAToperational;%Power generated by each
PRV per year = Power(kW) * days per year * hours per day = Power(kW) * hours per year =
kWh generated annually
AllPRVs{8,AllValves} =
AllPRVs{5,AllValves}.*NetProfitPkWh.*YearlyOperationTime.*PAToperational;%Profit per
year for each PRV
%-----
%Determine the Capital Payback Period for each possible PAT

%Capital Payback period calculation
ExchangeRate= 11.27; % Australian Dollar to Rand
EGE = PumpCostPrice .* 1.3; % Energy Generation Equipment is 30% increase on cost price -
allows for installation
CW = EGE .* 0.3; %Civil Works are 30% of the EGE cost
MC = (EGE + CW) .* 0.15; % Maintenance Costs are 15% of the sum of the EGE and CW

```

```

AllPRVs{9,AllValves}=PumpCostPrice;
AllPRVs{10,AllValves}=EGE;
AllPRVs{11,AllValves}=CW;
AllPRVs{12,AllValves}=MC;
AllPRVs{13,AllValves}=SellingPricePkwH.*AllPRVs{7,AllValves} -
AllPRVs{12,AllValves};%AF = Selling price * Power per year - CW
AllPRVs{14,AllValves}=(AllPRVs{10,AllValves} +
AllPRVs{11,AllValves})/AllPRVs{13,AllValves}; %Capital Payback Period (years)
AllPRVs{16,AllValves} = 0;

```

%Max CPP

MaxCPP = 2.5; %for 2.5 years maximum Capital Payback Period

%If CPP is negative or greater than max CPP, then not feasible as a PAT

if AllPRVs{14,AllValves}> MaxCPP

AllPRVs{15,AllValves} = 'Not Feasible'; %CPP too long - too expensive

AllPRVs{16,AllValves} = 0;

AllPRVs{17,AllValves} = 0;

AllPRVs{18,AllValves} = 0;

AllPRVs{19,AllValves} = 0;

elseif AllPRVs{14,AllValves}<= 0

AllPRVs{15,AllValves} = 'Not Feasible'; %CPP negative - too expensive and not enough
power gen to cover costs

AllPRVs{16,AllValves} = 0;

AllPRVs{17,AllValves} = 0;

AllPRVs{18,AllValves} = 0;

AllPRVs{19,AllValves} = 0;

elseif isnan(AllPRVs{14,AllValves}) %Not applicable for PAT

AllPRVs{15,AllValves} = 'Not Feasible'; %CPP negative - too expensive and not enough
power gen to cover costs

AllPRVs{16,AllValves} = 0;

AllPRVs{17,AllValves} = 0;

AllPRVs{18,AllValves} = 0;

AllPRVs{19,AllValves} = 0;

else AllPRVs{15,AllValves} = 'Feasible as PAT'; %CPP less than 2.5 years - feasible to
replace PRV with PAT

AllPRVs{16,AllValves} = 1;

AllPRVs{17,AllValves} = AllPRVs{8,AllValves};%Profit per year for PAT
implementation

AllPRVs{18,AllValves} = AllPRVs{5,AllValves};%Power generated by each PAT kW

AllPRVs{19,AllValves} = AllPRVs{7,AllValves}; %Power generated per year by each
PAT kW per year

end

end

```

fprintf('\n');
fprintf('Final PRV results in AllPRVs. ');
fprintf('\n');
fprintf('\n');
%
%PART 4 - Determine Energy Harnessed
AllPAT = cell(20,1); %record all the energy outputs
AllPAT{1,1} = 'Total Power Output kW';
AllPAT{2,1} = 'Total Profit per year Rands';
AllPAT{3,1} = 'Hydropower equivalent';

%Do total power output from all PATs
allPATPower = AllPRVs(18:18,:); %gets the power output of each feasible PAT
AllPATPower = cell2mat(allPATPower);
TotalPowerOutput = sum(AllPATPower); %Total Power output of all the PATs - kW
AllPAT{1,2} = TotalPowerOutput;
%Do the total profit from all PATs
allPATProfit = AllPRVs(17:17,:); %gets the profit per year for each PAT
AllPATProfit = cell2mat(allPATProfit);
TotalProfitOutput = sum(AllPATProfit); %Total Profit for all PATs per year
AllPAT{2,2} = TotalProfitOutput;
%Determine Hydropowerplant equivalent
if TotalPowerOutput <= 20
    AllPAT{3,2} = 'Pico Hydropower Plant';
elseif TotalPowerOutput > 20 && TotalPowerOutput <= 100
    AllPAT{3,2} = 'Micro Hydropower Plant';
elseif TotalPowerOutput > 100 && TotalPowerOutput <= 1000
    AllPAT{3,2} = 'Mini Hydropower Plant';
elseif TotalPowerOutput > 1000
    AllPAT{3,2} = 'Small Hydropower Plant';
end
fprintf('\n');
fprintf('%s%d%s', 'Total Power output due to PATs in the network = ', TotalPowerOutput
, 'kW');
fprintf('\n');
fprintf('Final PAT results - in AllPAT. ');
fprintf('\n');
fprintf('\n');
fprintf('Leakage reduction in whole network due to each added PRV - in PermanentPRVs. ');
fprintf('\n');
fprintf('\n');

valve.saveInputFile('ValvesPlaced_Final_Config.inp');
%-----
%Save individual Workspaces
if N < 1000
    %Save all the variables for this run
    save('ValvesPlaced_Final_Workspace');
else
    %This takes roughly 1 hour as there are a lot of variables. Only
    %use for networks over 1000 pipes.
    try
        %Save all the variables for this run

```

```

        save('ValvesPlaced_Final_Workspace');
    catch

        save('AllPAT_data','AllPAT','-v7.3'); %Saves Rawdata
        save('AllPRVs_data','AllPRVs','-v7.3'); %Saves PermanentPRVs
        save('PATdetermination_data','PATdetermination','-v7.3');
    end %Save all individual workspaces
end

%unload library
valve.unload;

fprintf('\n');
fprintf('Analysis Completed');

```