Prioritization Model for Pipeline Improvements to Limit Increasing Operational Costs

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PRIORITIZATION MODEL FOR PIPELINE IMPROVEMENTS TO LIMIT INCREASING OPERATIONAL COSTS

Philip Rossnagel

**A thesis submitted in partial fulfilment
of the requirements for the degree of**

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PRIORITIZATION MODEL FOR PIPELINE IMPROVEMENTS TO LIMIT INCREASING OPERATIONAL COSTS

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Executive Summary

Water is needed for all forms of human development and is equally essential to most major industries. Most water today is transported by gravity. However, a growing volume is being conveyed through pumped pipeline systems that are consuming staggering amounts of electricity. Additionally, the cost of electricity is rising in most countries, increasing the cost of operations for municipalities and utilities that operate these water networks.

There is significant need to review existing pumped pipeline systems to identify pipelines improvements that can be made to improve energy efficiency. These pipelines can be improved by hydraulic or operational changes to increase their operational efficiency. Decreased energy use will lower operating costs and reduce the environmental effects of electrical production.

A pipeline improvement selection and prioritization (PISP) system was developed to evaluate a group of pipelines, determine the appropriate improvement option(s) for each, and prioritize the order in which the improvements should be implemented. The PISP system models hydraulic degradation and energy cost escalation to determine the baseline operating cost of the system over a long term (20 year) analysis period. The system then models the effect of five selected hydraulic improvements (foam swabbing, rigid pigging, intensive cleaning and

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scraping, rehabilitation, and total replacement) and eight operational improvements (eight different scenarios of limiting and altering the pumping hours to selected time periods) to determine the potential cost savings over the analysis period and the pipelines with the greatest savings are prioritized. The operational and hydraulic characteristics of the prioritized pipelines are then field tested to verify the results of the analysis and make a final recommendation for pipeline system improvements.

The PISP system was applied to analyse nine selected pipelines from the City of Tshwane's bulk water system.

- The preliminary evaluation prioritized three pipelines that were in relatively poor hydraulic condition, and three pipelines that were likely to see significant cost savings from operational changes.
- The economic evaluation found a potential savings of approximately R100 million for the analyzed pipelines over the twenty year analysis period.
- It also determined that the Roodeplaat Raw Water Pipeline – supplying water to the Roodeplaat WTP – and the Roodeplaat to Montana Pipeline – conveying water from the Roodeplaat WTP to the Montana Reservoir – would have the greatest potential cost savings.
- The final results suggest that utilizing pump scheduling a 12-15% reduction in yearly electrical cost can be achieved through operational improvements with minimal capital investment. With the addition of a reservoir upstream of the WTP and the expansion of the WTP's clear water reservoir, the cost savings could be increased to the approximately 25%.
- No hydraulic improvements to either pipeline resulted in a long term cost savings for the twenty year analysis period. However, a general inspection found two unnecessary strainers, the removal of which would result in an additional savings of an estimated R100 000 a year.

The development of the PISP system highlighted the need to include potential additional reservoir storage to optimize pump system operation. The additional storage allows for the pumps to be operated only when the electrical cost is lowest. Building on these results is an important step in developing a complete system for optimal pumped pipeline operation.

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List of Symbols and Abbreviations

Abbreviation or Symbol	Description	Units (if applicable)
A	Cross sectional Area	m^2
AADD	Annual Average Daily Demand	m^3
α	Roughness growth rate	mm/yr
C	Hazen Williams Roughness Coefficient	
C_d	Decommissioning costs	Rand
C_e	Energy cost	Rand
C_{env}	Environmental costs	Rand
C_{ic}	Initial costs	Rand
C_{in}	Installation costs	Rand
C_m	Maintenance costs	Rand
C_o	Operating costs	Rand
C_s	Down time losses	Rand
D	Diameter	mm
g	Gravity	9.81 m/s^2
H	Head	m
H_s	Static Head	m
h_f	Friction Losses	m
h_L	Secondary Losses	m
K_S	Absolute Roughness	mm
K	Secondary Loss Coefficient	
K_{SO}	Initial Pipe Roughness	mm
kWh	Kilo Watt Hour	kWh
L	Length	m
LCC	Life Cylce Cost	Rand
LSI	Langelier Saturation Index	
n	Manning's Number	$s/m^{1/3}$
P	Power	watts
Q	Flow	m^3/s
Re	Reynolds Number	
S_f	Friction Slope	m/km
TWh	Terawatt Hour	1 million kWh
V	Velocity	m/s
ρ	Density	kg/m^3
η	Efficiency	%
λ	Friction Factor (Lambda)	
ν	Kinematic Viscosity	m^2/s
VSD	Variable Speed Drive	

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1 Introduction

1.1 Background

Water is required for all forms of human development, we drink it, wash in it, cook with it, generate electricity with it, and it is likewise essential to most major industries. Because of its vitality, it has been transported for millennia in systems ranging from the canals of Mesopotamia and China, the Puquios of ancient Peru, and the iconic Roman Aqueducts to the modern pressurized networks that serve many millions of people today. The majority of water is transported via gravity, but since the times of ancient Greece and Egypt, pumps, in their primitive form, have been used to aid in the movement of water. Today, there are millions of kilometres of water pipes powered by pumps to meet the growing water demands of farmers, industries, and domestic users.

In 2001 the world used 15 000 terawatts hours (TWh) of electricity while in 2011 (the last year of available data) the world used 22 000 (BP, 2012). This seven thousand terawatt hour increase over ten years is far greater than any other time in history, and no predictions show that the rate of increase will decrease in the next twenty years. Worldwide, pumps are estimated to use approximately twenty per cent of all electricity (Hydraulic Institute, 2001), which in 2011 translated to roughly 4 400 TWh of electricity, more electricity than the continent of Africa used in the last 7 years. The growing water usage leads to increased energy demands to pump water at a time when electrical demand is already growing at a significant rate. Following basic economics, demand increasing faster than supply will lead to an increase in price. Electricity prices are rising worldwide, with the largest increases being seen by developing countries [(US EIA, 2012): (IEA, 2012)]. Rising energy costs increase the price of labour, production, materials, transportation, etc., all leading to an increase in the cost of operating water supply and distribution systems.

In addition to reducing energy usage to lower operating costs, there are significant environmental costs associated with the production of electricity. Coal for example, which is currently used to generate 40% of the world's electricity, produced an estimated 60 million metric tons of sulphur dioxide, 35 million metric tons of nitric oxide and 8 billion metric tons of carbon dioxide last year alone (Mittal et al., 2012). Sulphur dioxide and nitric oxide are

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known to cause asthma, bronchitis, and emphysema (US EPA, 2012). They can also cause acidic atmospheric conditions, producing acid rain which can have significant adverse effects on the environment, specifically the water systems (US EPA, 2012). It is also well known that carbon dioxide contributes to anthropogenic global warming by acting as a greenhouse gas, trapping radiant heat and increasing global temperatures [(US EPA, 2013) (NASA, 2013) (National Academy of Science, 2005) (AAAS, 2009) (US NOAA, 2013), (UK Royal Society, 2010), (etc.),] Additionally "increasing atmospheric carbon dioxide levels can cause ocean acidification, threatening marine ecosystems and the societies that depend on them." (UK Royal Society, 2013). Investigations and actions should be undertaken to examine uses of electricity to determine where, if possible, efficiency gains can be made to reduce the operational cost of delivering water to users and lower environmental cost of producing electricity.

Centrifugal pumps, which account for 80% of all pumps, are the largest single user of electricity in the world, and up to 75% of those pumps are oversized, operating with inefficient controls, or powering inefficient systems (Tolvanen, 2007). The massive amount of electricity used by pumps means that evaluation of the energy efficiency of pumping systems is vital.

A pumping system can be defined as a system that moves water from a supply (i.e. reservoir, dam, pipeline, tank, etc.) to a demand (water tower, reservoir, distribution system, industrial user, etc.) through the use of a pump. The system can be divided into two major parts: the pump station and the pipeline. For general purposes, the pump station is considered to include the connection to the supply, the pump(s) and pump/flow control; while the pipeline consists of the physical pipe that guides the water from the pump station to the end demand. Both the pump station and the pipeline have predictable energy losses.

The main losses in a pump station will occur inside the pump and in the pump/flow control. Pumps have an average efficiency range of 60-80%, with some as high as 94% (Nolte, 2004). The efficiency will depend on the specific pump and the combination of head and flow required and will often degrade over time as the system ages. Additionally, pumps are often "controlled" through throttling, bypassing, variable speed drives, etc., to adjust the flow from

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the pump to match the demands of the system. These controls, with the exception of variable speed drives, introduce additional energy losses.

The pipeline itself will introduce further energy losses to the system. These losses are caused by turbulence surrounding valves and bends, the friction created from moving water interacting with the pipe walls, and through water's inherent resistance to movement, also known as viscosity. The viscosity of water cannot be controlled, and as bends and valves are necessary to operate the pipeline, the resulting losses cannot be eliminated; only slightly minimized. However the frictional losses of a pipeline can and should be controlled. These frictional losses are dependent on the roughness of the pipe wall, the internal diameter of the pipe, and the velocity of the water. The roughness and diameter of a new pipeline are known, but those characteristics change with time, in an often unpredictable manner. They are changed by corrosion, deposition, scaling, internal erosion, leaching, biofilm, etc., that will affect the velocity and likely increase the frictional losses (sometimes significantly).

The frictional losses can be mitigated through several options: maintenance and/or upgrades to the existing pipeline, or replacing (all or part) of the pipeline. Maintenance of the pipeline can include monitoring the flow and pressure, controlling the water quality, cleaning the pipeline, or replacing valves and/or pipe sections all to assist in maintaining or improving the pipelines hydraulic and structural characteristics. Upgrading the pipeline can include relining the internal pipe walls or the addition of design features (such as air valves) to improve the hydraulic performance of the pipeline. The final option is to the replace the system. A new system would be designed to minimize frictional losses through decreased roughness and likely a larger diameter.

It can be seen from the information above that there is a significant need to review existing pumped pipeline systems to identify pipelines improvements that can be made to improve energy efficiency. These pipelines can be improved by hydraulic or operational changes to increase their energy efficiency. Decreased energy use will lower operating costs and reduce the environmental effects of electrical production.

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1.2 Hypothesis

It is hypothesized that energy costs of operating a pipeline can be reduced through hydraulic and operational improvements, the cost of which will be offset by the energy cost savings created.

1.3 Objectives of the Study

The objective of this study was to develop a system for prioritizing pumped pipelines to assist operators in determining which pipelines are in need of improvements. Additionally, the system will determine where limited capital should be spent to gain the greatest cost reductions. The system will also determine the most cost efficient operating scenarios for the remaining pipelines.

1.4 Scope of the Study

This study entailed the development of a prioritization system for pumped pipelines, with special attention paid to: the detrimental effects of biofilm; the hourly cost variations of energy; and increasing energy prices. The study focused on bulk water transfer lines, while smaller distribution network lines fell outside of the scope of the study. The specifics of: pipeline construction, rehabilitation and upgrades, as well as the financing of capital costs, fell outside the scope of the study.

1.5 Methodology

First, comprehensive reviews of the relevant practical, technical and economic factors relating to pumped pipeline operation were performed.

Second, concepts to prioritize pipelines were developed and their advantages and limitations discussed. The concepts focus on the effects of friction, velocity, and hourly cost variations of electrical prices.

Third, a prioritization system for pipeline replacement was developed on a Microsoft Excel-based spread sheet utilizing the developed relationships to facilitate the calculations involved in prioritizing pipelines for upgrades and developing more cost efficient operating scenarios for all pipelines.

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Finally, the prioritization system was evaluated on a case study of specific pipelines through both desktop and field evaluations.

1.6 Organization of the Report

The report consists of the following chapters and appendices:

- Chapter 1 presents an introduction to the report. It provides background information to the purpose, the hypothesis, scope and methodology for the study.
- Chapter 2 serves as a literature review focusing on the various technicalities related to pumped pipeline design, operation and improvement. These aspects include an overview of pumped pipeline systems, a review of the hydraulic relationships that effect pipeline operation, the effect of roughness and biofilm, and an overview of the operating cost of a pipeline focusing on the pipelines energy usage. The literature review continues with an overview of the options to lower the cost of operation and the economic analysis needed to determine the cost efficiency of pipeline improvements.
- Chapter 3 explains the conceptual development of a system that can be used to prioritize pipelines and recommend improvements for further investigation.
- Chapter 4 describes all the aspects of the developed Pipeline Improvement and Selection Prioritization System.
- Chapter 5 provides a discussion of a case study conducted on nine pipelines selected from the City of Tshwane Metropolitan Municipality's bulk water distribution system, using the prioritization system developed in the previous chapters.
- Chapter 6 serves as a conclusion to the study, including recommendations for future use and development of the system, areas in which it can be implemented and general recommendations for further research on the topic.
- Chapter 7 list the references used in the study.

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2 Literature Review

This chapter focuses on the factors that will tend to increase the cost of operating a pumped pipeline system, the options that can counteract the increasing operational costs, and the economic analysis needed to determine what, if any, options should be taken to lower the increasing operational costs. The first sections focus on the energy losses throughout a pumping pipeline system and the hydraulic relationships that govern energy use. The next sections focus on the trends that will likely increase the operational cost, including hydraulic influences, as well trends within the global energy market. The following sections discuss how operational or hydraulic improvements can counteract those increasing costs, and how life cycle cost analysis can be used to determine which if any improvement should be implemented.

2.1 Pumped Pipeline System Components

To understand how energy is lost in a pipeline, the pipeline system must be discussed. A pumped pipeline can be divided into two physical categories, the pump station and the pipeline. Though this report will focus on the pipeline, background information about the pump station, including its features, design, and inefficiencies, is required to properly understand the operation of a pipeline.

2.1.1 Pump Station

Pumps are the heart of a pumped pipeline system; they provide the power to pressurize the water, forcing it through the pipeline. There is a large range of configurations of intakes, number of pumps, pump control, flow and pressure control, and end storage options, all of which will affect when, how frequently, how often, and how efficiently a pump (or multiple pumps) will run at a pump station.

The head required to move water through a pipeline system is dependent on the flow rate and can be depicted graphically as the system curve. The pressure head created by a pump is also dependent on the flow rate and this relationship is known as the pump curve. These two curves can be overlaid as show in Figure 2.1.

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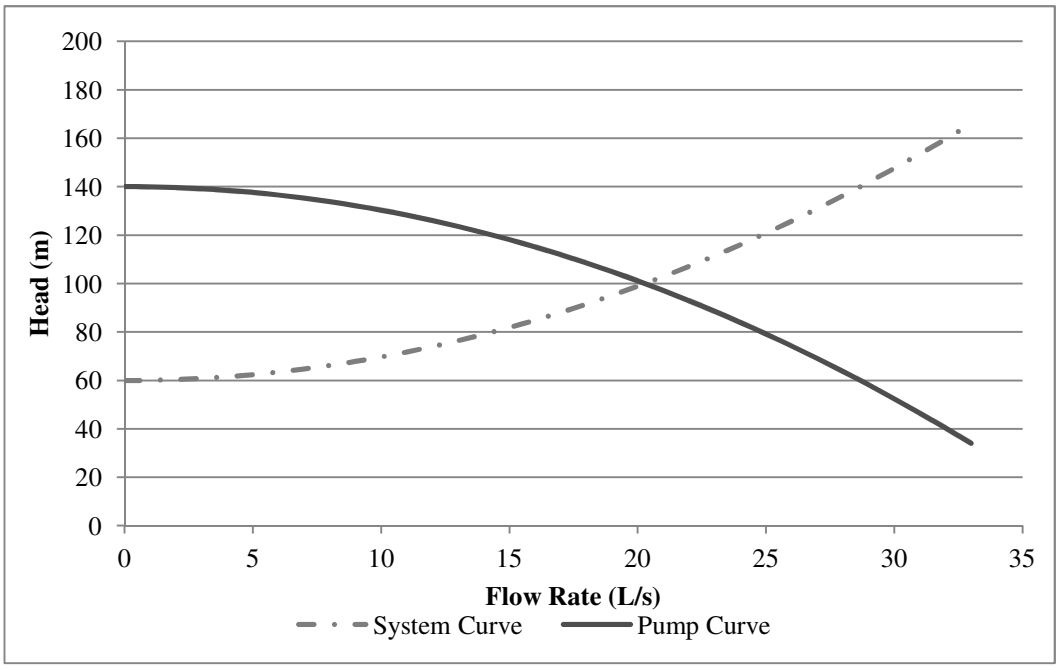

Figure 2.1- Example of System and Pump Curves

A pump should be sized so that the pump curve intersects the system curve at the design flow rate, which should ideally correspond to, or be very near to the pump's best efficiency point. The highest reported pump efficiency is approximately 95%, while the peak efficiency of most pumps is in the range of 60-80% (Nolte, 2004). Pumps are often oversized to ensure capacity for expansion; this means the pump curve is shifted upwards, moving the duty point to a higher flow rate, requiring controls to reduce the flow (US Department of Energy, 2006). Methods of pump/flow control include throttling the pipeline, bypass lines, varying hours, multiple pump arrangements, and/or pump speed control. Throttling and bypassing have low upfront costs, but introduce potentially significant energy losses into the system, while multiple pump arrangements and pump speed control have high upfront costs, but allow for more efficient pump operation.

There are intrinsic difficulties in generalizing the operation of a pumped pipeline system, which will depend on the supply and end demand connections. Ideally a pump should operate only when the price of electricity is cheapest and provide a flow velocity in the pipeline of no greater than 1.5m/s, which is the historical normative design flow velocity (CSIR, 2000); however this is not always achievable.

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There is a range of externalities that can affect the operation of a pipeline and its pumping hours, including, but not limited to:

- Supply availability
- Supply side storage
- Water treatment plant operation
- End user demand
- End storage
- System reliability and maintenance
- Power supply
- Electrical Cost
- Pipeline hydraulics

2.1.2 Pipeline

The pipeline consists of the physical pipeline (to guide the pressurized water from the pump station to the end use), and potentially control valves (to regulate pressure or flow), isolating valves (to isolate sections of the pipeline), air valves (to allow for release and entry of air) or scour valves (to drain sections of the pipeline). Each component of the pipeline introduces energy losses, which can be grouped into three categories, static head, friction head, and secondary losses. As the pipeline's function is to move water from the pump station to the end use, the static head between the hydraulic grade lines of the supply and demand cannot be altered in an existing system. Secondary losses are generated at valves, bends, constrictions, etc. that are inherent in the system: as such, they are difficult to control and as they are minimal in comparison to the other losses, they are often not taken into account. Friction losses are created both by the internal resistance to movement of the water, known as viscosity, and by the friction generated between the moving water and the internal pipe wall. Unlike the static of secondary losses, friction losses are controllable to an extent.

2.2 Hydraulic Relationships Relating to Energy Losses

The basis for energy savings is reducing the power or pumping time required to transfer a given demand from point A to point B in a pipeline. The power used by pumps to pressurize a pipeline system is dependent on the flow rate, the total head to be overcome, and the efficiency of the pump for the pumping conditions as shown in Equation 2.1.

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$$P=\frac{\rho g Q H}{\eta}$$

Equation 2.1

Where:
P= mechanical power required (W),
ρ= density of water (kg/m^3)
g= gravitational acceleration (m/s^2)
Q= flow rate required (m^3/s)
H = total hressure head required (m)
η= efficiency of the pump (%)

The flow rate is determined by the volume of water to be pumped on a given day, and the hours allowed for the pump to transfer the water. The total head to overcome in a pipeline system is defined as the sum of the static head, friction headloss, and secondary losses.

Both friction and secondary losses are proporational to the square of the velocity of the water, meaning that as the pipe diameter is increased, the lower velocity will result in lower frictional headloss, resulting in a decrease of energy usage. The head loss generated at valves, bends, constrictions, etc. can be calculated using Equation 2.2.

$$h_L=\Sigma K\,\frac{V^2}{2g}$$

Equation 2.2

Where:
h_L = *secondary head loss (m)*
ΣK = *sum of secondary loss coefficients (where the velocity is similar)*
V = *velocity of water flow in pipeline (m/s)*
g = *acceleration due to gravity (m/s^2)*

The K values will depend on the number and type of valves, degree of bends, rate of constrictions, etc. Chadwick et al. (2004) provides a summary of the methods to calculate the K values.

The friction loss is dependent mostly on the roughness factor of the pipeline and the velocity of the water pumped as shown in the well-known Hazen Williams equation, reflected in Equation 2.3, and the Darcy – Weisbach Equation, reflected in Equation 2.4.

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$$h_f = \frac{10.69\, L\, Q^{1.852}}{C^{1.852}\, D^{4.87}}$$

Equation 2.3

Where:
h_f = *friction loss (m)*
L = *length of pipeline (m)*
Q = *flow rate (m³/s)*
C = *Hazen Williams roughness coefficient*
D= *diameter of the pipeline (m)*

The Darcy – Weisbach Equation is only valid for rough turbulent flows; however, the vast majority of pumped pipelines are in the rough turbulent flow regime, so it is valid for most pipeline applications.

$$h_f = \frac{\lambda\, L\, V^2}{2\, g\, D}$$

Equation 2.4

Where:
h_f = *friction loss (m)*
λ = *(lambda) friction factor of the pipeline*
L = *length of pipeline (m)*
V = *velocity of water flow in pipeline (m/s)*
g = *acceleration due to gravity (m/s^2)*
D = *diameter of the pipeline (m)*

Lambda, the friction factor, is primarily dependent on the diameter and the roughness of the pipeline; however it is also dependent on the velocity and viscosity of the fluid. The next section will address how the friction factor is calculated, the effect that roughness has on a pumping pipeline system, pipeline materials and their properties, and the influences that will affect a pipelines roughness as it ages.

2.3 Overview of the Effect of Roughness

2.3.1 Formulae Development

A historical review of the development of lambda provides an understanding of the current methods used to calculate friction losses in pipelines. The first major development in hydraulics relating to friction loss was the distinction between turbulent and laminar flow, which was developed by Osborne Reynolds in 1883, quantified in the Reynolds number.

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This lead to the establishment that for laminar flow, frictional head loss was proportional to the velocity, where in turbulent flow, frictional head loss was proportional to the velocity squared, indicating the Darcy – Weisbach head loss equation is applicable for turbulent flow (Reynolds, 1883). In the 1930s Nikuradse then made the differentiation between smooth and rough pipes, identifying 3 distinct flow regions and 2 transition flow regions. Nikuradse's research determined that for laminar flow, the Reynolds number and diameter determined the friction factor, the roughness had no effect, while in the transitional and rough turbulent flow region, the roughness, diameter, and Reynolds number determined the friction factor (Nikuradse, 1933).

Von Karman (1931) and Prandtl (1933) then extended Nikuradse's results by developing empirical relationships for smooth and rough pipes. Prandtl, in conjunction with Colebrook and White (Colebrook, 1939), then developed an implicit formula that could be applied to the transition region as well as the turbulent region. Further refinements of methods to calculate the friction factor have been made, and a summary of the common methods used for calculating the friction factor is included as equations 2.5 to 2.17 as shown in Table 2.1.

Table 2.1 - Methods for Calculating the Friction Factor (Genic et al., 2011)

Year	Contributor	Equation		Eq.
1908	Blasius	For smooth pipes	$\lambda = \frac{0.316}{Re^{0.25}}$	2.5
1933	Karman & Prandtl	For smooth pipes	$\frac{1}{\sqrt{\lambda}} = 2\ \log\left(\frac{Re\sqrt{\lambda}}{2.51}\right)$	2.6
		For rough pipes	$\frac{1}{\sqrt{\lambda}} = 2\ \log\left(\frac{3.7\ D}{k_s}\right)$	2.7
1939	Colebrook-White transition	$\frac{1}{\sqrt{\lambda}} = -2\ \log\left(\frac{k_s}{3.7\ D} + \frac{2.51}{Re\sqrt{\lambda}}\right)$		2.8
1939	Colebrook-White combination	$V = -2\sqrt{2gDS_f}\log\left[\frac{k_s}{3.7\ D} + \frac{2.51\ \nu}{D\sqrt{2gDS_f}}\right]$		2.9

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Year	Contributor	Equation	Eq.
1944	Moody	$\lambda = 0.0055\left[1+\left(\frac{20000k_s}{D}+\frac{10^6}{Re}\right)^{1/3}\right]$	2.10
1952	Altshul	$\lambda = \left(\frac{68}{Re}+k_s\right)^{0.25}$	2.11
1973	Churchill	$\lambda = \left[-2\log\left(\frac{k_s}{3.7}+\frac{7}{Re^{0.9}}\right)\right]^{-2}$	2.12
1975	Barr	$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{k_s}{3.7\,D}+\frac{5.1286}{Re^{0.89}}\right)$	2.13
1976	Swamee, Jain	$\lambda = \left[-2\log\left(\frac{k_s}{3.7}+\frac{5.74}{Re^{0.9}}\right)\right]^{-2}$	2.14
1980	Round	$\lambda = \left[-1.8\log\left(0.135k_s+\frac{6.5}{Re^{0.9}}\right)\right]^{-2}$	2.15
1997	Manadilli	$\lambda = \left[-2\log\left(\frac{k_s}{3.7}+\frac{95}{Re^{0.983}}-\frac{96.82}{Re}\right)\right]^{-2}$	2.16
2011	Brkic	$\lambda = \left[-2\log\left(\frac{2.18\beta}{Re}+\frac{k_s}{3.71}\right)\right]^{-2}$ $\beta = \ln\frac{Re}{1.816\ln\frac{1.1Re}{\ln(1+1.1Re)}}$	2.17

Where:

Q = flow rate (m³/s)
V = flow velocity (m/s)
D = inside diameter (m)
g= gravitational acceleration (m/s²)
L = pipe length (m)
P = wetted perimeter of inside pipe (m)
A = internal area of pipe (m²)
h_f = friction loss (m)
h_l = secondary losses (m)
S_f = friction slope (m/m)
k_s = absolute pipe roughness (m)
λ = friction factor – lambda
K= secondary loss coefficient
v = kinematic viscosity (1.14 x 10^{-6} m²/s for water at 20°C)

As shown in equations 2.5 to 2.17 the determination of the Darcy – Weisbach head loss coefficient, commonly referred to as the friction factor or lambda (λ) is dependent on several variables: flow velocity, the internal diameter and roughness of the pipeline, and the viscosity of the water.

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2.3.2 Materials and Roughness

The types of pipe materials commonly used for pressurized bulk water pipelines are discussed in the following sections. For each material, the history, liners and exterior coatings as well as the influences specific to the material that can affect how the material will age are discussed.

Steel Pipe

Steel is the most common material for larger water pipelines; it is available in virtually any size, and can be made to withstand almost all pressures. The principle benefits are its ability to bend without breaking, the ease of production and installation, high shock resistance, relatively light weight, and being easily modifiable in the field into special configurations. To prevent internal corrosion, the South African Department of Water Affairs commonly specifies the steel pipes to be factory lined with a cement mortar, hot or cold applied coal tar enamel, epoxy paint, or fusion bonded epoxy (Van Niekerk, 2010). In corrosive soils, many of the liners as well as cold applied petroleum based tape wrapping coatings can be used as exterior coatings (Robor, 2013).

Steel pipes undergo a variety of changes as they age. Depending on the liner, coating, soil and water interactions, steel pipes are likely to corrode. Internal corrosion is caused either by imperfections in the liner, failure of the liner, or a change in water characteristics. This can result in increased roughness and/or area restrictions caused by tubercles. Similarly, exterior corrosion is caused either by imperfections in the exterior coating, failure of the coating, or changes in the soil conditions. Both types of corrosion can result in loss of structural strength, leaks, or total failure of the pipeline.

Ductile Iron Pipe

Ductile Iron (DI) pipe (DIP) is also used in water distribution systems, most often for diameters smaller than 400mm, while steel is more common for larger dimensions (Mays 2000). Ductile Iron is a cast iron product, differing only in the addition of magnesium to decrease its brittleness and increase its strength. To prevent internal corrosion, it is commonly lined with cement mortar, epoxy paint, fusion bonded epoxy, coal tar enamel, or

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polyethylene. In corrosive soils, many of the liners can be used as exterior coatings as can plastic wrapping, cold applied petroleum based tape wrapping coatings, or hot applied coal tar tape, which all are used to prevent corrosion (Mays 2000).

Similar to steel pipes, DIP is subject to both internal and external corrosion. Internal corrosion is caused either by imperfections in the liner, failure of the liner, or a change in water characteristics. This can result in increased roughness, and/or area restrictions caused by tubercles. Similarly, exterior corrosion is caused either by imperfections in the exterior coating, failure of the coating, or changes in the soil conditions. Both types of corrosion can result in loss of structural strength, leaks, or total failure of the pipeline.

Asbestos Cement

Asbestos cement (AC) was introduced to the pipeline market in the 1940s as a non-ferrous alternative to DI or steel pipelines. AC was used for transmission mains ranging from 100-1000mm. The principle reason for its use was that it was not subject to corrosion related problems, therefore no liners or exterior coatings were required (Mays 2000). The cement portion of the pipeline however is subject to attack from soft water. This lead to significant debate over health concerns, soft water would remove calcium hydroxide from the cement, leading to deterioration of the interior, causing the softening and release of the asbestos fibres. The health debate, and the introduction of PVC pipe, led the production of AC to almost cease (US EPA 2009). The attack on the cement from soft water can be minimized by utilizing Type II Portland cement; however this was not always done.

Glass Reinforced Plastic Pipe

Glass Reinforced Plastic (GRP) is a relatively new pipe material that is only recently gaining traction for use in water transmission lines. It is not subject to corrosion, is able to handle pressures similar to steel or DI, and is relatively lighter weight in comparison to steel or DI. Laboratory tests imply that its interior roughness is likely to only moderately increase throughout its lifespan.

Polyvinyl Chloride Pipe

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PolyVinyl Chloride (PVC) is the most commonly used plastic pipe in water distribution systems because it is not subject to corrosion, has high strength to weight ratio, low internal roughness, and simple installation. It does not require any liners for most applications.

As PVC pipe ages, it can suffer from softening, degradation, and erosion, all of which can weaken the structural integrity of the pipeline and increase the internal roughness of the pipe. Softening results from straining the pipe material through a combination of temperature, pressure or external stress in excess of design criteria. This results in "ballooning", ductile rupture or distortion of the system. Degradation is the chemical breakdown of the pipe materials and can result from extended exposure to ultra violet (UV) light or the reaction to certain trace chemicals in the water. This results in loss of structural strength and increased internal roughness. Erosion results from impingement of particles on the pipe wall, allowing the flow to erode the surface. This results in loss of structural strength and increased internal roughness (Knight 2002).

Reinforced Concrete Pressure Pipe

Several kinds of Reinforced Concrete Pressure Pipes (RCPP) are used in water distribution systems; the most common kind being pre-stressed reinforced concrete cylinder pipes. It is commonly installed unlined, but plastic liners (such as PVC or HDPE), polymer based spray-on liners (such as epoxy, polyurethane, or polyurea) or sacrificial layers of calcium aluminate cement can be used to prevent internal corrosion for aggressive soft waters, however liners are only commonly used for transporting wastewater (Rocla, 2009).

Concrete itself does not suffer from corrosion, however the internal metal reinforcing does. Commonly, the concrete suffers from cracking, allowing either external groundwater or internal water to reach and corrode the metal reinforcing, ultimately to the point of failure. The loss of the metal reinforcing would then cause the concrete pipe to fail. Additionally, internal attack by corrosive water can cause increased roughness, loss of structural strength, and potential failure or leakage (Romer et al., 2008).

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High-Density Polyethylene Pipe

Only relatively recently, in 1992, did High-Density Polyethylene (HDPE) become commonly used for water distribution pipelines (Mays, 2000). Similar to PVC, HDPE has a high strength to weight ratio, low internal roughness, simple installation, and because it is not subject to corrosion, HDPE pipe does not require a liner.

HDPE pipe is subject to the same ageing ailments as PVC pipe, however it is also subject to premature interior surface degradation from oxidation caused by high concentrations of chlorine based water disinfectants (Duvall and Edwards, 2009).

Overview of Pipeline Properties

Pipe sizes and pressure classes range by manufacture and location, but a general overview of the range of size and pressure class for each material is shown in Figure 2.2.

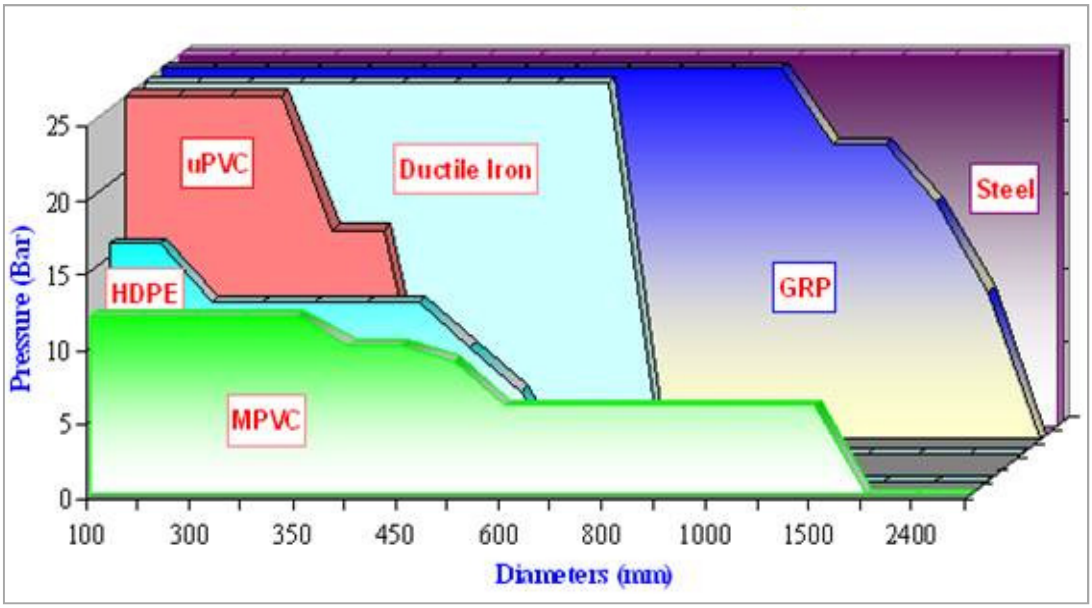

Figure 2.2 - Pipeline Material Diameter and Pressure Selection

Steel, DI, AC GRP, PVC, RCP, and HDPE are the common materials that can be used to manufacture bulk water pipelines; however, other materials can be encountered when examining pipeline systems. A summary of the materials that can be encountered in bulk water systems is included Table 2.2. Additionally, Table 2.2 summarizes the expected roughness of these materials and the influences that will affect the specific material.

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Table 2.2 – Typical Absolute Roughness Values (Wallingford et al., 2006)

Material	Roughness Values (mm)			Influences
	Good	Normal	Poor	
Brass, copper,	-	0.003	-	Corrosion
Wrought iron	0.03	0.06	0.15	Corrosion
Cast Iron - uncoated	0.15	0.3	0.6	Corrosion
Cast iron - epoxy lined	-	0.015	0.03	Corrosion
Ductile iron - polyethylene liner		0.06	0.15	Corrosion
Steel - unlined	0.15	0.03	0.06	Corrosion
Steel - epoxy liner	0.03	0.06	0.15	Corrosion
Steel - spun bitumen or concrete liner		0.03		Corrosion, leaching
Asbestos cement	0.15	0.03	0.06	Leaching
Concrete – pre-stressed	0.03	0.06	0.15	Leaching, corrosion
Concrete – pre-casted	0.06	0.15	0.6	Leaching, corrosion
Concrete - spun pre-casted	0.06	0.15	0.3	Leaching, corrosion
Concrete - cast in place, steel forms	0.3	0.6	1.5	Leaching, corrosion
Concrete - cast in place, rough forms	0.6	1.5	-	Leaching, corrosion
Clay	0.03	0.06	0.15	
Glass Reinforced Plastic (GRP)	0.03	0.06	-	
uPVC	0.003	0.006	-	UV degradation
HDPE	0.03	0.06	0.15	UV degradation, chlorine softening
Rock Tunnels - unlined	60	150	300	
Rock Tunnels - Shotcrete or Gunite Lined	5	14	43	leaching

2.3.3 Influences on Pipeline Capacity

There are several influences that will affect the hydraulics of the system, including scaling, depositions, corrosion, and biofilm. These influences will affect the pipeline in two ways; by changing the cross sectional flow area, and by changing the internal roughness.

There are two types of solids that can form depositions in a pipeline: dissolved solids, which cause scaling, and suspended solids which lead to depositions, and both types of depositions will decrease the cross sectional flow area.

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Scaling is the deposition of dissolved solids and is caused by high mineral content of the water. The scales are most commonly composed of calcium carbonate ($CaCO_3$). The concentration of $CaCO_3$ dissolved in the water can be measured in several ways including the Langelier Saturation Index (LSI), the Ryznar Stability Index, and the Larson Index (McNeill et al., 2001). The most widespread used formula would be the LSI, a simple calculation where positive values tend to precipitate $CaCO_3$, while negative values tend to dissolve $CaCO_3$ (Larson et al., 1942). The capacity of water to hold $CaCO_3$ is significantly dependent on temperature with higher temperatures holding more $CaCO_3$ in solution, resulting in increased depositions on areas of a pipeline that tend to be subject to decreases in temperature (Schock, 1984). Potable water tends to be slightly negative LSI value, where raw water, especially from boreholes, tends to have positive LSI values.

Deposition is the result of solids suspended in the water being allowed to settle to the pipe walls. This does not often occur in potable water pipelines, but is problematic in some raw water and waste water lines. Unlike the dissolved solids that cause scaling, suspended solids will remain in solution if the velocity is high enough to maintain a homogeneous suspension. However, if the velocity slows, a heterogeneous suspension will be formed allowing particles to settle (Copeland et al., 2012). The particles will then be deposited on the internal pipeline wall. The growth of these depositions will restrict the diameter, forcing the water to flow at a higher velocity. Once the growth causes a "self-cleansing" velocity, the particles will remain in solution, limiting further depositions. Self-cleansing velocities range from 0.6 m/s to 2.4 m/s depending on the characteristics of the suspended solids in the water (EPA, 2000).

On ferrous pipelines, corrosion can become a significant issue. There are several different types of corrosion that will both affect the structural integrity of the pipeline as well as change the internal roughness and diameter. Uniform corrosion will affect the entire interior surface area of a ferrous pipeline while concentrated cell, galvanic, pitting and crevice corrosion will affect specific areas. Uniform corrosion tends to increase the internal roughness, however, it fairly uncommon to see uniform corrosion lead to structural failures (NASA, 2013). Concentrated cell, galvanic, pitting and crevice corrosion will tend to have more significant structural effects at specific points, but generally not have a significant effect on the internal roughness as their effects are generally over small but specific areas of the pipeline. All forms of corrosion can lead to tuberculation, the transport and deposition of

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mounds of corrosion by products on the interior pipe walls. The formation of tubercles can decrease the cross sectional area of the pipeline, as well as greatly increase the internal roughness.

On certain pipelines, biofilm could have a significant effect on the pipeline's hydraulic characteristics, effects that can be so significant that they can completely negate the effect of other influences. The science and understanding of biofilm is still emerging, but it is well known that it can cause significant flow and water quality problems. Biofilm is discussed in detail in Section 2.4 below.

2.3.4 Ageing

The internal roughness and the internal diameter of pipes change as they age. The process becomes very complicated with the interplay between corrosion, erosion, scaling, depositions, and biofilm, and the interplay between these processes will vary depending on pipe material, water quality and system operation. Hudson (1966) evaluated major pipelines from seven cities across the United States in an effort to quantify the degradation of pipe quality over 45-70 years. With an assumption of an initial C value of 140, he found that the systems decreased from 140 to 75-110 over a 75 year period as shown in Figure 2.3.

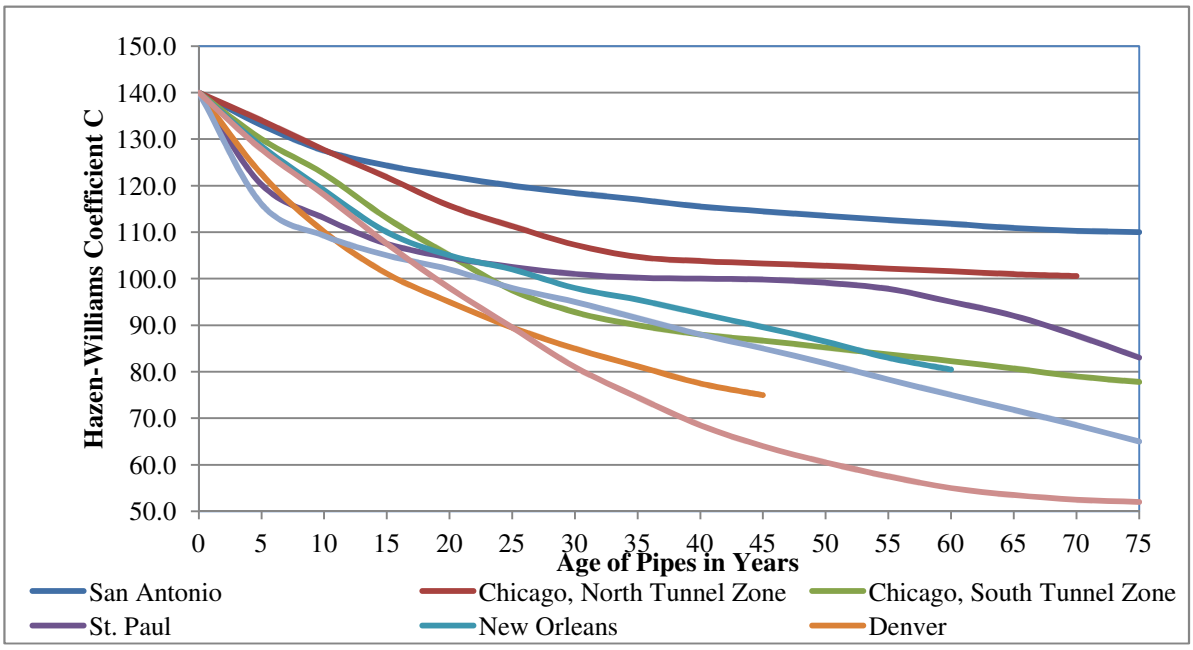

Figure 2.3 - Change of Hazen Williams Roughness Coefficient (C values) for Seven Midwestern Cities (Adapted from Hudson (1966))

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Several attempts at developing relationships to predict the roughness of pipelines as they age have been attempted, but the wide range of variables and relative lack of information have prevented effective formula development. A simple linear relationship for roughness growth is commonly assumed. Though it can be seen in Figure 2.3 that pipelines do not follow a linear relationship, a linear relationship can be used to approximate pipeline degradation for limited (20-30 year) periods. The relationship is shown in Equation 2.18.

$$k_s = k_{so} + \alpha\, t$$

Equation 2.18

Where:
k_s=Absolute Roughness (mm)
k_{so} = Roughness at time zero (mm)
α =roughness growth rate (mm/year)
t = time (year)

Two relationships for calculating the growth factor are worth noting (Colebrook and White 1937), (Lamont, 1981).

$$\alpha = 25.38984e^{(1.9-0.5*pH)}$$

Equation 2.19

$$\alpha = 304.8 * 10^{-(4.08+0.38*LSI)}$$

Equation 2.20

Where:
a=roughness growth rate (mm/year)
pH=pH (alkalinity)
LSI = Langelier Saturation Index

The LSI and the pH of the water are indications of how the water will affect the pipeline, however the authors of both of the formulas admitted that it was "[a] little better than a guess" (Walski et al., 1988), and "it was by no means a universal method for controlling corrosion" (Langelier, 1936). The American Water Works Association now recommends that calcium precipitation indexes no longer be used in corrosion determinations, "In light of much empirical evidence contradicting the presumed connection between the LSI and corrosion, this practice should be abandoned" (McNeill and Edwards, 2001).

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The initial roughness depends on the pipe material, while the growth rate is dependent on the pipe material, water characteristics and system operation. Growth rates will vary widely, some examples include the California Section of the American Water Works Association (1962) measured growth rates range between 0.34 and 0.61 mm/year, where Hudson (1966) determined growth rates range between 0.015 and 0.61 mm/year, and Lamont (1981) determined growth rates range between 0.025 and 0.76 mm/year.

The most reliable source of growth rates is to examine pipelines of similar materials transporting similar water to see how the specific pipeline will react to the site specific water characteristics.

2.4 Overview of the Effect of Biofilm

"Biofilms are so common that they are not really noticed" (Van Vuuren and Van Dijk, 2013). The effect of biofilm on most pipelines is insignificant in comparison to other factors, although with the right conditions the effect of biofilm can be very significant. By definition, biofilm is an accumulation of organic material, in the form of microorganisms, on the internal surfaces of pipeline systems. For smooth pipes, the thickness of the biofilm often exceeds the depth of the roughness, completely negating the pipe's original roughness characteristics (Van Vuuren & Van Dijk, 2013). Biofilm may also "promote the accumulation of larger organic and inorganic particles because of its adhesive properties" (Guzman et al., 2007). These particles, in addition to the biofilm can affect both the roughness, and cause a constriction of the pipeline's cross sectional area. Figure 2.4 shows extreme biofilm (>15mm) on a 1200mm steel pipeline, causing a 5% reduction in cross sectional area. This 5% reduction in area will result in a 13% increase of friction losses simply due to the increased velocity and decreased area for the given flow rate.

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Figure 2.4 - Biofilm on the Inyaka Pipeline – South Africa
Courtesy of Corrie Marx

Biofilm growth is a natural process that occurs on all possible interfaces – solid-liquid, liquid-liquid, liquid-gas, and solid-gas – on organic and inorganic surfaces, living or dead. Biofilms can range in thickness from micron to centimetres thick and have been around for 3.5 billion years, making them the oldest organisms on this planet (Van Vuuren and Van Dijk, 2013). Biofilm consists mostly of water held together by Extracellular Polymeric Substances (EPS). In aqueous environments, they are generally heterogeneous structures consisting of cell structures, voids, and channels (Stoodley et al., 1999). The matrix of biofilms acts as a diffusion barrier for oxygen and nutrients, leading to differential aerobic and anaerobic environments. The top layers, up to a depth of 50-150µm, consume the oxygen, leading to an anaerobic environment below – an anaerobic environment in an aerobic system.

Biofilm growth rates are the result of numerous physical, chemical and biological processes. The growth of a biofilm colony is the result of either adhesion/attachment to the pipe wall or the growth/replication of adhered cells where the losses are a product of detachment, cell death, or "grazing" by larger organisms. The shape and density of biofilm colonies vary not only throughout their lifecycles, but also with the shear stress applied by the fluid.

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In addition to the organic compounds created by the growth of biofilm, biofilm can also capture and precipitate metals from the fluid, notably iron and manganese. These particles can accumulate in significant volumes to further decrease the cross sectional flow area. This precipitated material can be substantial; analysis of the Lower Blyde River Irrigation System in South Africa found that up to 14% of the mass of biofilm can be ferrous, and up to 19% can be manganese (Van Vuuren and Van Dijk, 2013).

Biofilm varies in its response to shear, the same shear that limits biofilm growth in one pipe, may encourage biofilm growth in another pipe. Stoodley et al. (1999) found that "biofilms behave like elastic or viscoelastic solids below the shear stresses which they are grown, but behave like viscoelastic liquids at elevated shear stresses." That can be summarized as follows: at low shears, they deform and return to their original shape, while at higher shears, they will slowly "flow" down the pipeline, deforming to the increased shear.

Higher flows can increase the shear force on biofilms, but also provide larger nutrient sources, indicating that until the shear of the fluid reaches the strength to detach the biofilm, higher flows will lead to increased biofilm growth. Percival et al. (1999) showed that in turbulent flows less than 4 m/s, increased velocity increases the growth of the biofilm; at velocity above 4 m/s, the increased shear of the fluid limits growth. They also found that biofilm growth is greatest in cavities and grooves on a rough surface as it provides shelter from the shear force of the fluid and increased surface area for attachment.

Biofilm also exhibits an unusual behaviour in the formation of "streamers." These filamentous strands are the process by which biofilms grow to new areas – similar to a vine. They significantly increase the surface area of biofilm, allowing for increased nutrient uptake as they oscillate in the fluid (Characklis, 1979). Similar to general biofilm, streamers are viscoelastic, becoming thinner and longer in response to increased shear stresses from higher velocities. Figure 2.5 shows the side view of a streamer grown by Stoodley et al. (1999) at a shear of 5.09 N/m^2 and the reduction of length and an increase in height when the shear is decreased to 0.12 N/m^2.

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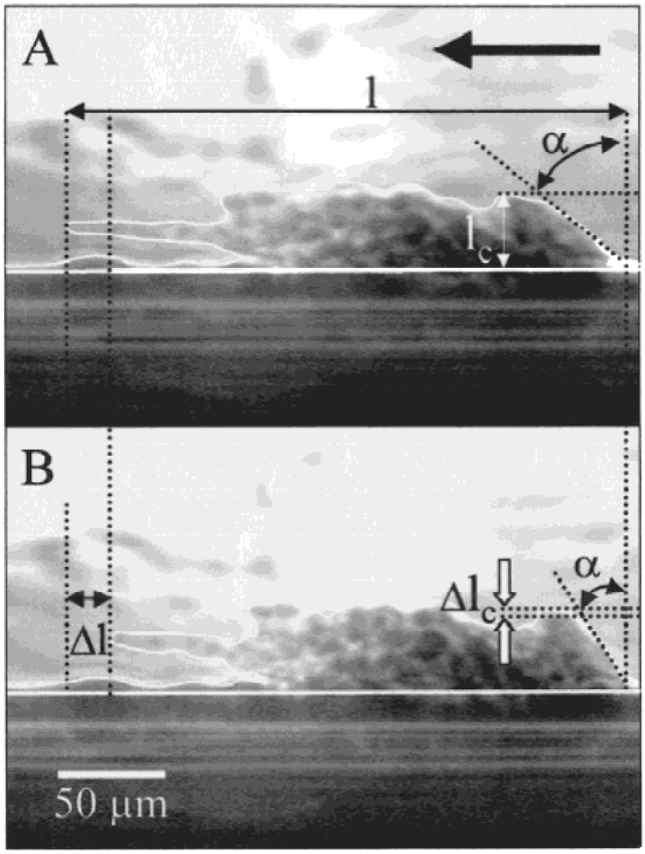

Figure 2.5 - Side View of a Streamer (Stoodley et al., 1999)

Lambert et al. (2008) cited Picologlou's (1980) summary of how biofilm may increase the friction losses of a pipeline in the following ways:

i. A reduction of the pipe diameter due to biofilm accumulation;
ii. Viscous dissipation with the biofilm, due to its creeping flow in the downstream directions, or due to its viscoelastic nature;
iii. Increased energy dissipation caused by the increased roughness of the pipeline wall caused by biofilm accumulation;
iv. Change in fluid viscosity resulting from the presence of solution suspended biofilm and other macro molecules; and
v. Increased energy dissipation caused by the oscillation of biofilm streamers.

The friction effects of the biofilm are dependent on the initial roughness of the pipe, the thickness of the biofilm, and the velocity or Reynolds' number of the fluid. Additionally, when the biofilm is thinner than the laminar sub layer, the thickness of the biofilm has little to no effect, and when the biofilm is thicker than the laminar sub layer, the thickness of the

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biofilm has significant effects on the friction factor. Table 2.3 summarizes selected cases of biofilm and the frictional effects that biofilm has on the friction factor.

Table 2.3 - Selected Case Studies Showing the Effects of Biofilm

Source	Year	Pipeline Description	Biofilm Thickness	Hydraulic Losses
Guzman et al	2007	Laboratory Experiment of 200mm PVC pipe	Not reported	Manning's values increased from 0.011 to 0.015
Lambert	1954	375 km pipeline	9.5mm growth over 10 years	36% increase in friction factor
Lambert citing Picologlou	1980	900mm diameter, 13km long pipeline	1.6mm	23% reduction in flow capacity
Lambert citing Sharp	1954	90 km pipeline	Not reported	Reduced capacity of 22% increasing pumping costs by 13%
Barton et al	2008	1980 mm diameter, 526 meter long penstock	2-5mm	Absolute roughness decreased from 0.24 to 0.04mm after cleaning
Barton et al	2008	2590 mm diameter, 2.7km long penstock		Absolute roughness decreased from 0.36 to 0.02mm after cleaning
Barton et al	2008	3500 to 2580 mm diameter penstocks, totalling 2.7 km		Absolute roughness decreased from 2.15 to 0.05mm after cleaning

The friction losses caused by biofilm can be controlled in several ways, from mechanical removal, to chemical treatment, to flow variations, all with varying levels of success. However, a differentiation must be made between controlling growth, killing, or detaching biofilm.

Mechanical removal (pipeline cleaning) will detach biofilm, but not kill it or retard its growth. Cleaning can restore pipeline capacity, and when removing 2-5 mm thick biofilm, can decrease head losses by up to 25% (Barton et al., 2008). However, the gain in energy efficiency can be temporary, as the biofilm will return and often grow faster on the freshly cleaned surface.

Chemical treatment can control biofilm growth, but has not been shown to completely kill and to only minimally detach biofilm. Chen and Stewart (2000) did significant work

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quantifying the kill and detachment rates of different chemicals and found that no chemical could kill 100% of biofilm, and that even the strongest chemicals rarely dislodged more than 70% (by mass) of biofilm. The most successful chemicals at killing biofilm were a basic pH shift (from pH 7 to 11.2), and chloramines. The most successful chemicals for biofilm detachment were salt (NaCl), sodium dodecyl sulphate (SDS), and chloramines. Hattan (2012) showed that chlorine treatment was a cost-effective method for controlling the seasonal variations in friction created by seasonal biofilm growth.

Flow variations are often discussed as a method of biofilm control; however, research presenting its effectiveness is scarce and contradictory. Lambert et al. (2008) showed that biofilm growth was minimized at greater flow velocities. However, Percival et al. (1999) showed that from 0.4-4.0 m/s the higher flow correlated with the higher biofilm growth rates and Van Vuuren and Van Dijk (2006) found that, depending on the material, detaching velocities were achieved at 3-4 m/s. However, Lambert's experiment was conducted on small diameter (25 mm) pipes, which may not be applicable to significantly larger pipe diameters as the thickness of the laminar sub layer varies with diameter. Velocities of 3-4 m/s are highly inefficient and often unachievable on bulk water pipelines.

2.5 Overview of the Costs Associated with Operating a Pumping Pipeline

The costs to operate a pumping pipeline system vary widely but can be grouped into several categories: energy costs, maintenance and labour costs, and repair costs, with energy costs being the most significant cost for almost all systems (US DOE, 2006). Maintenance and labour vary widely, but would include regular maintenance and refurbishment of pumps and valves, maintenance of the supply side inlet, maintenance on galvanic corrosion systems, pipeline cleaning, etc. Repair costs are the unexpected costs associated with pipeline breaks, valve failure, pump breakdowns, etc. Maintenance, labour, and repair costs vary widely between pipelines depending on numerous external factors, however; energy, the most significant cost, can be calculated.

The focus of this section was to investigate trends that will affect the long term price of energy, specifically the increasing global demand, and growing environmental concerns and

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regulations. The long term electrical price trend will affect the design and operation of pumping pipeline systems and the related operational cost.

2.5.1 Global Electrical Cost Trends

With an increasing global population becoming more developed, global energy demand is rising significantly. Additionally, countries are now more thoroughly examining the environmental costs of electricity production, responding by placing environmental restrictions on traditional fossil fuel based productions, and requiring renewable energy sources for certain percentages of electricity production. The increasing demand and restrictions on traditionally cheap energy sources are leading to increased electricity prices worldwide.

The global electrical consumption in 2012 was over 22 000 TWh (22 billion kWh) and has been growing at an average annual rate of 3.4% for the last ten years, with no signs of decreasing in the immediate future. It is predicted that electrical demand will grow by almost 70% by 2035, to a total demand of 32 000 TWh (IEA, 2012). The largest users are China and the United States, with China and India growing the fastest. Figure 2.6 details the yearly electricity usage by region, showing the significant growth in the Asia Pacific region, dominated by India and China (BP, 2012).

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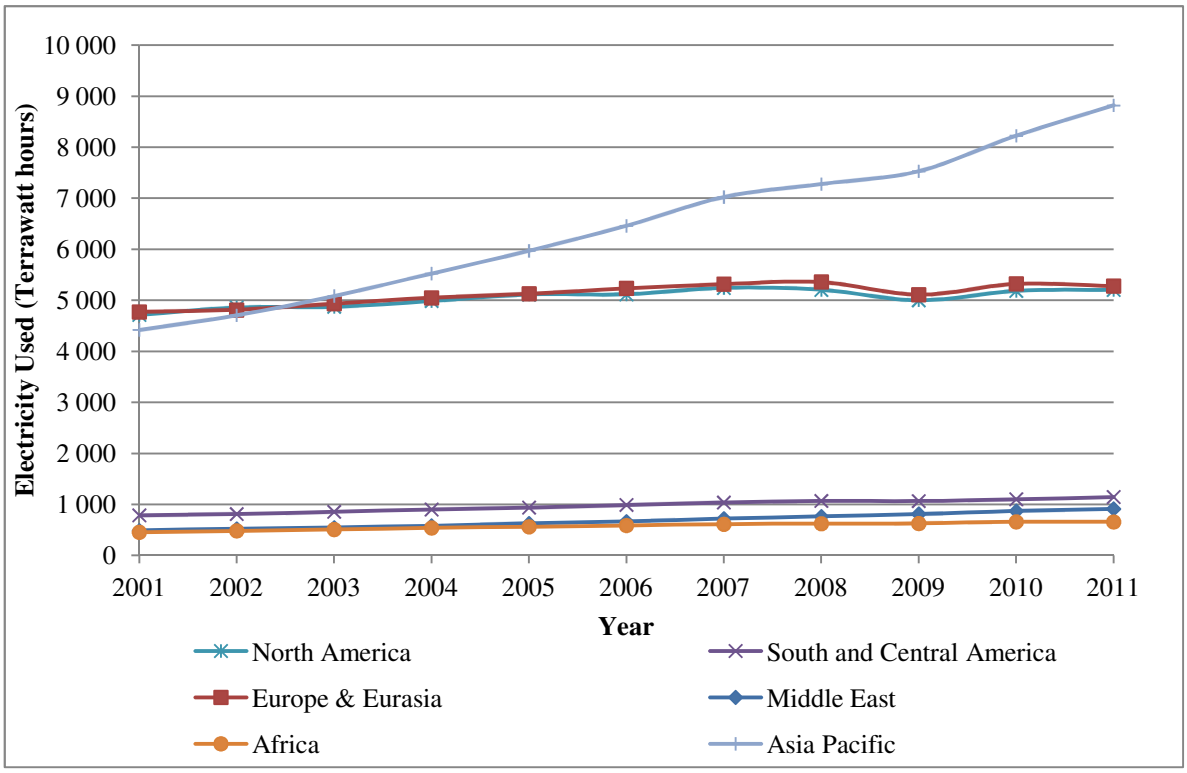

Figure 2.6 - Worldwide Energy use by Region (BP, 2012)

According to the EIA (2012), coal is currently the largest fuel source for electricity production, followed by natural gas, renewable sources (dominated by hydroelectric), nuclear, and liquid (oil/diesel) fuel sources. The increasing global demand for electricity, coupled with increasing regulations on traditionally cheap fuel sources are predicted to push average global electricity prices to continue to grow. Though the global trend is for prices to rise, some developed countries – such as the US, Switzerland, and the United Kingdom – will see stable or even declining electricity prices for the foreseeable future (BP, 2012).

2.5.2 Trends among Developing Countries

By comparing developing countries, generalizations can be made about electrical trends. The first is increasing demand, from new electrifications, increasing standard of living, new industrial developments, etc., driving the need for substantial capital investment in new plant construction and increasing current electric prices both to limit the demand and to finance the new plant construction. Additionally, easily exploitable sites for electrical generation have already been developed, so new construction will require longer transmission distances, increasing transmission losses. Similarly, rural electrification of low density settlements will require long distance transmission, also increasing transmission losses. Finally, countries are

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learning from the example of China, and its rampant air pollution, to increase environmental regulations, further increasing capital construction costs. These factors will lead to increasing electricity prices until the point where demand plateaus, allowing for prices to stabilize.

2.5.3 Example Country Developing Country– South Africa

South Africa used 262 terawatt hours of electricity in 2011, roughly 1% of total worldwide consumption, ranking South Africa 18th in domestic consumption. Domestic demand has been growing at an average of 2.3% over the last ten years, with two years of decreased consumption in 2008 and 2009, likely caused by the global recession. The demand is likely to continue growing because of aggressive rural electrification projects and an increase in the country's standard of living. The vast majority of electricity is generated and distributed by Eskom, a state owned utility. The majority of electricity, 223 terawatt hours, is generated through the combustion of coal. The abundance of coal, coupled with its low cost of mining and relatively relaxed environmental regulations (compared to developed countries) will lead to coal continuing to be a main source of fuel for electricity for the foreseeable future. Additional electrical sources include nuclear (12 TWh), hydroelectric (3.6 TWh), Gas (15 TWh), and pumped hydroelectric storage (9 TWh) as shown in Figure 2.7.

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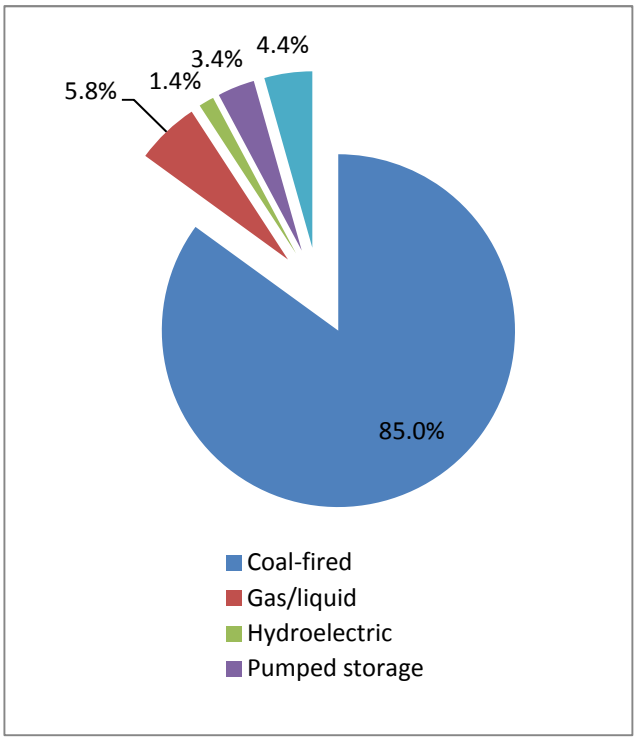

Figure 2.7 - South African Electrical Sources (Eskom, 2012)

To account for varying demand throughout the day, Eskom has implemented peak, off peak, and standard hourly rates for non-residential users. The time ranges for each price range is shown in

Figure 2.8 while an example of the tariff structure municipalities are likely to pay for each time range is shown in Table 2.4 (Eskom, 2012).

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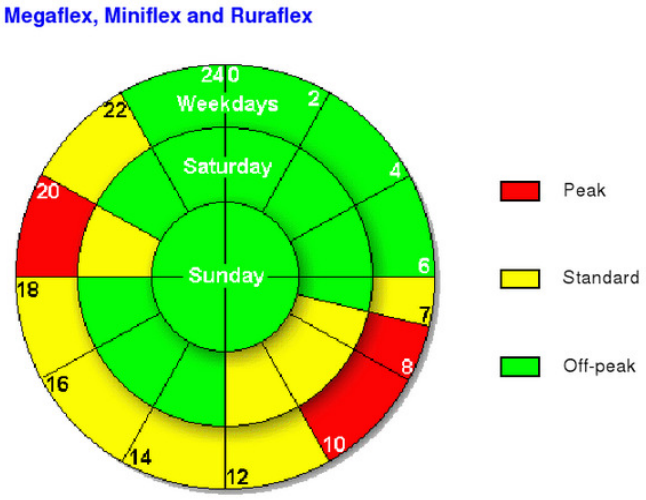

Figure 2.8 - Eskom's Defined Time Periods for Megaflex, Miniflex and Ruraflex

Table 2.4- Megaflex Local Authority Rates 2012-2013

		Active energy charge [c/kWh]						Transmission network charges [R/kVA/m]	
Transmission zone	Voltage	High demand season [Jun - Aug]			Low demand season [Sep - May]				
		Peak	Standard	Off Peak	Peak	Standard	Off Peak		
		VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	
≤ 300km	< 500V	216.99 247.37	56.37 64.26	30.10 34.31	60.54 69.02	37.06 42.25	25.89 29.51	R 5.40	R 6.16
	≥ 500V & < 66kV	210.06 239.47	54.61 62.26	29.16 33.24	58.65 66.86	35.95 40.98	25.13 28.65	R 4.94	R 5.63
	≥ 66kV & ≤ 132kV	202.47 230.82	52.68 60.06	28.18 32.13	56.58 64.50	34.70 39.56	24.28 27.68	R 4.81	R 5.48
	> 132kV	195.39 222.74	50.91 58.04	27.28 31.10	54.65 62.30	33.55 38.25	23.53 26.82	R 6.09	R 6.94
> 300km and ≤ 600km	< 500V	219.14 249.82	56.90 64.87	30.37 34.62	61.13 69.69	37.39 42.62	26.15 29.81	R 5.46	R 6.22
	≥ 500V & < 66kV	212.11 241.81	55.12 62.84	29.43 33.55	59.22 67.51	36.26 41.34	25.36 28.91	R 4.98	R 5.68
	≥ 66kV & ≤ 132kV	204.44 233.06	53.18 60.63	28.47 32.46	57.13 65.13	35.01 39.91	24.51 27.94	R 4.84	R 5.52
	> 132kV	197.32 224.94	51.42 58.62	27.52 31.37	55.19 62.92	33.86 38.60	23.69 27.01	R 6.15	R 7.01
> 600km and ≤ 900km	< 500V	221.28 252.26	57.44 65.48	30.61 34.90	61.70 70.34	37.75 43.04	26.37 30.03	R 5.52	R 6.29
	≥ 500V & < 66kV	214.23 244.22	55.64 63.43	29.71 33.87	59.77 68.14	36.59 41.71	25.58 29.16	R 5.04	R 5.75
	≥ 66kV & ≤ 132kV	206.47 235.38	53.69 61.21	28.71 32.73	57.65 65.72	35.32 40.26	24.73 28.19	R 4.89	R 5.57
	> 132kV	199.30 227.20	51.86 59.12	27.79 31.68	55.74 63.54	34.17 38.95	23.92 27.27	R 6.23	R 7.10
> 900km	< 500V	223.48 254.77	58.00 66.12	30.92 35.25	62.29 71.01	38.08 43.41	26.63 30.36	R 5.54	R 6.32
	≥ 500V & < 66kV	216.33 246.62	56.18 64.05	29.98 34.18	60.35 68.80	36.92 42.09	25.84 29.46	R 5.09	R 5.80
	≥ 66kV & ≤ 132kV	208.53 237.72	54.19 61.78	28.97 33.03	58.21 66.36	35.68 40.68	24.95 28.44	R 4.91	R 5.60
	> 132kV	201.26 229.44	52.37 59.70	28.01 31.93	56.22 64.09	34.49 39.32	24.15 27.53	R 6.27	R 7.15

The National Environmental Management Air Quality Act of 2004 set 10 and 15 year regulations for new plant construction, requiring new coal power plants to drastically decrease sulphur and nitrous oxide emissions, increasing the cost of new plants. The South

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African government is also promoting renewable energy generation by buying renewable power at above market price. With the end of government subsidies for electricity, and increasing demand requiring new power stations with high capital construction costs, the price of electricity has risen 180% compared to only an 80% increase in the consumer price index over the last 15 years. Additionally, the price of energy has been approved to increase 8% yearly for the next five years (NERSA, 2013), with similar or greater increases likely to continue.

2.5.4 Trends among Developed Countries

By comparing developed countries, generalizations can be made about electrical trends. For most developed countries, demand has remained relatively stable, allowing for electricity prices to stabilize. The vast majority of people in these countries have access to electricity, so unlike developing countries, significant transmission projects are not needed. Environmental issues and subsequent regulations do have the potential to increase the cost of electricity. However, by the time likely regulations are implemented, the cost of renewable sources and natural gas based sources will have fallen significantly, negating, or potential offsetting the effect of those regulations (IEA, 2012).

2.6 Options to Lower Operational Costs

To lower the cost of operating a pumped pipeline, the main cost, energy, should be scrutinized. The energy cost can be lowered by changes to the operation of the system, improving the existing systems hydraulic efficiency, replacing all or part of the pipeline, or a combination of these options.

2.6.1 Operational Changes

Operational changes become very specific to each pipeline, its flow rate, operating hours, and restrictions on operating hours. There are two main, seemingly contradictory, options to lower operational costs through changing the operation of the system: (1) to lower the flow velocity, therefore increasing the pumping hours, to reduce friction head loss or (2) by adjusting and potentially reducing the pumping hours to operate when electricity pricesare lowest. The option appropriate for a given pipeline system will depend on the system's

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operating flow velocity, source and supply reservoir capacity, current pumping hours, pump capacity and efficiency, and the electrical price schedule.

Decreasing the flow rate (and flow velocity) will move the operating point on the system curve to a point with lower head losses. This can be done by either introducing a pump/flow control to the system, or replacing the pump. Introducing a pump control, such as throttling, bypassing, or pump speed control, can introduce energy losses and change the operating efficiency of the pump. However, when designed properly these losses will be offset by the lower friction and secondary losses achieved by operating at a lower velocity. The second option to decrease flow velocity is to change the pump, so that the pump produces a lower flow rate, intersecting with the system curve at a point with less losses. Unfortunately, limiting the flow velocity leads to increasing the pumping hours which can force the pump to operate in the time periods with higher electrical costs.

The other option, adjusting the pumping hours, limits the operation of the pump when electrical rates are highest, which lowers the average electrical price. The options to adjust the pumping hours will depend on the pipeline, but can include; operating more pumps simultaneously, replacing the pumps with pumps that can operate at a higher flow rate, or removing schedule restrictions by adding additional storage, etc.

A higher flow rate requires a higher flow velocity, increasing the secondary and friction losses of the system. The trade-off between higher energy use and lower average electricity prices will depend on the specific system.

2.6.2 Pipeline Cleaning and Inspection

The first option to improve the hydraulic efficiency of a pipeline is to clean the pipeline, restoring the diameter and improving the internal roughness. There are several methods of pipeline cleaning; arranged from least to most aggressive, these include flushing, ice pigging, foam swabbing, jet cleaning, rigid pigging, or mechanical cleaning. The method that will work best for any given pipeline will depend on the pipeline material and age, the nature of the depositions, presence of scaling, biofilm, and tuberculation, and the presence of valves, bends and constrictions. In addition to increasing hydraulic capacity, pipeline cleaning can reduce the rate of water quality degradation in pipelines, allowing for lower treatment costs

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and higher quality water delivered to end users. All cleaning methods will require the disposal of the removed materials, which on large diameter pipelines can be significant, as well as disposal of the effluent from the cleaning process.

Flushing is a process of running high velocity water through the pipeline in an attempt to dislodge and remove loosely attached material and sediment. This can be achieved through opening scour valves and or hydrants on pipelines 300 mm or smaller. It is a very low cost cleaning option, but it utilizes large volumes of water, so treatment/disposal of the effluent can become problematic (Friedman et al., 2012).

Ice pigging is a relatively new process that involves forming an ice slurry that is then pumped through the pipeline like a pig. The ice pig is more aggressive at removing depositions and materials than flushing and doesn't require a pig launching or retrieval station (a scour valve or air valve can be used). It also has no potential issues of getting stuck; if it gets stuck, the ice just melts, the system is flushed and the process is repeated, instead of the excavation required when a normal pig gets stuck. The ice pig can negotiate most valves, bends, and constrictions unlike other forms of pigging. However, the process is limited to 450 mm and smaller pipelines, and specialized equipment for ice generation and monitoring is required (Griffin, 2013).

Swabbing, or foam pigging is the process of using water pressure to push a low density foam cylinder through the pipeline. The foam pigs can range in size from the pipelines diameter to 125% of the diameter to boost the shearing forces. The process is more aggressive that flushing or ice pigging, and can be used on any diameter pipeline. However, for pipelines greater than 300 mm pig launching and retrieval locations are required. The foam pigs are not able to pass through most valves and significant bends, requiring additional access points, and stuck pigs will require excavation for removal (Friedman et al., 2012).

Jet cleaning is the process of cleaning the internal pipe walls with high pressure water, sprayed from a jet head which is feed through the pipeline. The jets can be stationary or spinning, arranged to clean forward, radially and rearward to ensure a thorough cleaning of the pipes walls. The rearward facing jets provide force to move the head forward, and the speed is regulated by tension either on the hose or a guide rope. Abrasive additives can be

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added to the high pressure water for a more aggressive cleaning. Jet cleaning can be highly effective at removing calcium carbonate depositions, but requires thorough flushing after completion to ensure all the dislodge depositions have been removed (Black et al., 1993) The process can be completed on pipelines 100 mm and larger, only limited by the availability of jet heads.

Rigid pigging is a process of using water pressure to force a bullet-shaped rigid pig through the pipe, scraping deposits and other loose materials from the walls. It is more aggressive than swabbing or jet cleaning and can be used on any diameter pipeline, however for pipelines greater than 300 mm pig launching and retrieval locations are required. The pigs are not able to pass through most valves and significant bends, requiring additional access points, and stuck pigs will require excavation for removal (Friedman et al., 2012). Pigs of different sizes, materials, and configurations can be used. For example, pigging and jet cleaning can be combined with a special pig that allows some of the pressurized water used to move the pig, to go through tube inside the pig, to jet clean the walls ahead of the pig. Pigging can be used on almost any diameter pipeline; however a pumper truck is sometimes needed to provide the pressure to move the pig through the pipeline. After aggressive cleaning on ferrous pipelines, relining the pipe is recommended as the pigging process can damage the internal liner.

Mechanical cleaning is a process of pushing or pulling a rigid scraping device through the pipeline until the original diameter is restored. The scrapper is moved without relying on water pressure, allowing for more aggressive removal of obstructions, however brittle or structurally weakened pipelines can be damaged. The process is time consuming, so temporary water service may be needed. When used on ferrous pipelines, relining is recommended as the cleaning process will damage the existing liners, leading to increased corrosion.

The cleaning process suitable for a particular pipeline will depend on the amount of deposition, presence of scaling, biofilm, tuberculation, or corrosion, the age and strength of the pipeline, as well as time and budget constraints. Cleaning can reduce energy losses and improve water quality; therefore it should be undertaken regularly to lower operational costs.

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2.6.3 Pipeline Rehabilitation

Pipeline rehabilitation focuses on the renewal or renovation of the existing pipeline as opposed to replacement in which the existing pipeline is abandoned. Rehabilitation utilizes the existing pipes cross sectional area, therefore it is important to remove depositions, scaling and other obstructions to ensure that the cross sectional area is maintained. Rehabilitation can range from simply protecting the interior of the pipeline from corrosion, through improving the flow characteristics, to providing semi or full structural support.

The easiest and fastest method for pipe rehabilitation is a spray-on liner. The primary objective of the liner is to prevent interior corrosion of the pipeline. The two categories of spray-on linings commercially available are cement mortar or polymer, i.e. epoxy, polyurethane, or polyurea based. Spray-on liners require the existing pipeline to be thoroughly cleaned to remove any deposits, deteriorated coatings, oil, grease, water, and corrosion by-products. This can be accomplished using mechanical cleaning, or aggressive pigging, with an additional foam pigging (Mathews et al., 2012).

Cement mortar linings (CML) involve centrifugally casting a Portland cement based mortar with enough force to densely pack the mortar on the interior of the pipe wall. The mortar can be installed with fine steel mesh reinforcement to enhance the structural strength and increase crack resistance. Additionally, CML can be cast with significant thickness to provide some structural support to augment the strength of the existing pipe (Morrison et al., 2012). CML is not recommended for sewer or soft water applications as it would suffer from both degradation from transporting waste water attack and leaching from transporting soft water. The installation of a CML can be seen in Figure 2.9.

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Figure 2.9 – Installation of a Cement Mortar Lining
Courtesy of SunnySteel.com

Spray-on polymer based liners are a relatively recent development. The liners are an improvement over CML as they have a lower internal roughness, are not subject to soft water deterioration, and have a shorter drying time, allowing for the pipeline to return to service faster. Epoxy based liners were the first to be commercially available. They have no structural properties, and are recommended to be installed in thin (1-2mm) layers. The recommended drying time is in the range of 16 hours. Polyurethane liners are now replacing epoxy as the liner of choice. They use the same equipment as epoxy liners, but can be installed in thickness sufficient to bridge over small (>25mm) holes and can provide some structural support. Polyurethane liners require a cure time of 30 minutes. Polyurea liners have been used extensively in manholes, wet wells, and other aggressive environments, and are now starting to be used as a pipeline liner. Similar to polyurethane, polyurea can be used as a semi-structural liner with the principle benefit of drying times in the range of 5-40 seconds. The installation of a polymer based spray-on lining can be seen in Figure 2.10.

Figure 2.10 - Installation of a Polymer Based Spray-on Liner
Courtesy of PRD Company

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A summary of the general properties of each spray-on liner is included in Table 2.5.

Table 2.5 - Summary of Spray-On Lining Characteristics

Spray-on Liner Type	Diameter Range (mm)	Structural Support	Liner Thickness (mm)	Pressure Range
Cement mortar	150-1250	Semi – fully structural	8-50	Depends on liner thickness
Epoxy Based Polymer	75-1250	None	1-2	N/A
Polyurethane Based Polymer	75-1250	Semi structural	>1	Depends on liner thickness
Polyurea Based Polymer	75-1250	Semi – fully structural	6-25	Depends on liner thickness

Slip-lining consists of the insertion of a smaller pipe inside a structurally deteriorated pipe. Plastic pipes are commonly used, while steel DI and GRP can be used on larger pipes in special circumstances. The area between the existing pipe and the new pipe is filled with low density grout acting both as an anchor for the slip-liner as well as increasing its structural strength. The loss of cross sectional area is often offset by the improved flow properties and decreased roughness. Slip-lining can be done with fused PVC- forming a continuous length up to 1000m – or with discrete pipe lengths joined together with modified couplings. The installation of a fusible PVC slip-liner can be seen in Figure 2.11.

Figure 2.11 - Installation of a Fusible PVC Slip-liner
Courtesy of Underground Solutions

A summary of the general properties of each slip lining material is included in Table 2.6.

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Table 2.6 - Summary of Slip-Lining Characteristics

Slip-Liner Type	Diameter Range (mm)	Structural Support	Pressure Range (m)
PVC	100-900	Fully structural	±214
PE	100-1200	Fully structural	No information available

Close fit liners can also be referred to as modified slip-lining. It involves the insertion of a thin walled PE liner, whose diameter is similar, but slightly smaller than the inner diameter of the existing pipeline – forming a "close fit". The diameter of the liner is temporarily reduced for installation and once in place it is reverted to its original size, only slightly reducing the cross sectional area. Close fit liners can be used as semi structural to fully structural liners. The diameter can be temporarily reduced by an onsite symmetrical reduction process, or through a "fold and form" process either on site or at the factory. The installation of a fold and form liner can be seen in Figure 2.12.

Figure 2.12 - Installation of a Ford and Form Liner
Courtesy of Insituform.co.uk

A summary of the general properties of each close fit liner is included in Table 2.7.

Table 2.7 - Summary of Close Fit Liner Characteristics

Close Fit Liner Type	Diameter Range (mm)	Structural Support	Pressure Range (m)
Symmetrical Reduction	50 -1300	Semi – fully structural	105-163

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Fold & Form PE	75-1500	Semi – fully structural	±105
Fold & Form PVC	100-750	Semi – fully structural	Low pressure
Expandable PVC	150-750	Semi – fully structural	No information available

Cast in place pipe (CIPP) was first developed in 1971 and is by far the leading method of rehabilitation (Morrison et al., 2012). With the expiration of the original patent, several variations of the original, polyester resin impregnated felt tube have been developed. The CIPP tube is constructed of a felt based composite, which is typically pulled or inverted into position. The resin is then cured either by hot or cold water, steam, or ultraviolet light. The installation of a CIPP liner via inversion can be seen in Figure 2.13.

Figure 2.13 - Installation of a CIPP liner by Inversion
Courtesy of williamstesting.com

Woven hose liners are a specific type of CIPP liner, where the tube is constructed similarly to the design of a fire hose. The liners are typically pulled into place instead of inverted, and can include adhesive to bond to pipe wall. The different materials used for the tube construction and resin, and several ways to install each type are summarized in Figure 2.14.

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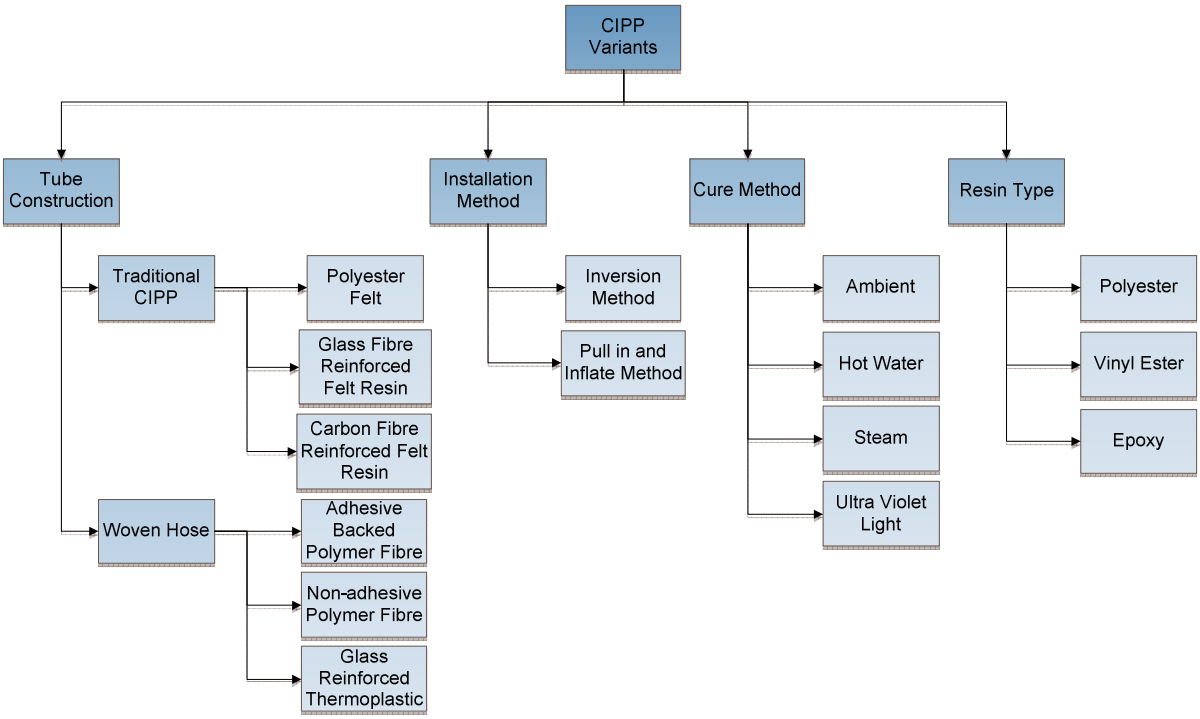

Figure 2.14 - Summary of CIPP Technologies (Morrison et al., 2012)

A summary of the general properties of each CIPP liner is included in Table 2.8.

Table 2.8 - Summary of CIPP Characteristics

CIPP Liner Type	Diameter Range (mm)	Structural Support	Pressure Range (m)
Traditional CIPP Liners			
Polyester Felt	100- 3000	Semi structural	42-140
Glass Reinforced	125-2400	Semi- fully structural	42-175
Carbon Fiber	>900	Semi – fully structural	±105
Woven Hose Liners			
Adhesive	75-600	Semi-fully structural	105-300
Non-Adhesive	150-1200	Fully structural	150-710
Glass Reinforced Thermoplastic	150-300	Fully structural	105

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2.6.4 New Pipeline Installation

Traditionally, utilities often prefer replacement over rehabilitation to upgrade a pipeline, resulting in a new pipeline, with known flow and structural characteristics, as they are already familiar with how to work with the pipelines. Rehabilitated pipelines would require new techniques and equipment for repair. The new pipeline can be laid "inline" replacing the existing pipe, following its profile and layout, or be installed offline with no regard to the existing pipeline.

Often, it is advantageous to install a new pipeline next to the existing pipeline for all or part of its length, allowing for the original pipeline to operate during construction. After construction the original pipeline can be rehabilitated (if needed) and kept in use. This process allows for a smaller diameter "replacement" pipeline, and can allow for one pipeline to be taken out of service for maintenance, without disrupting the supply to the end user. The new pipeline can be installed with any of the offline construction methods discussed below. The situation that is suitable for a paralleling pipeline is when the original pipeline cannot be taken out of service, flexibility of operation is required, but the pipeline lacks the cross sectional area to transport the water efficiently.

2.6.4.1 Inline Replacement - Pipe Bursting

Inline pipe replacement only slightly differs from fully structural pipe rehabilitation, as they both use the void created by the original pipeline, and follow its line and grade. The flow of the existing pipeline will need to be bypassed during construction, and all connections, valves, or bends will need to be excavated and replaced. While fully structural rehabilitation covered the methods that leave the existing pipe in place, online replacement involves the destruction of the existing pipe to allow for a new pipe to be installed.

Pipe bursting is the general process name for breaking up the existing pipeline and pushing the remains into the surrounding soil. The process is normally used to replace a pipe with a new pipe of the same diameter, but upsizing of 25-50% is possible with favourable soil and site conditions. Pipe bursting can be performed on pipelines from 50-1500mm diameters and

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can be performed on brittle materials such as cast iron, AC, concrete, PVC, and clay pipes. For ductile materials, such as DI or steel, a splitter head is installed, and the process is technically known as pipe splitting (US EPA 2009). The pipe bursting process can be seen schematically in Figure 2.15.

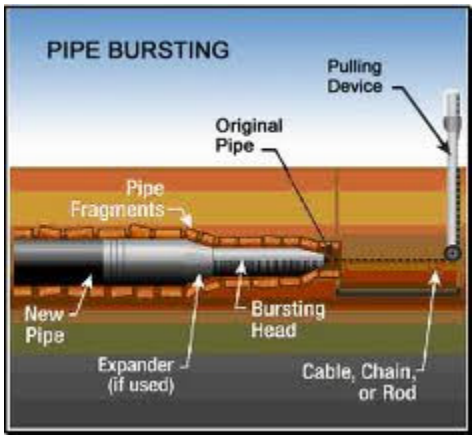

Figure 2.15 - Pipe Bursting Process
Courtesy of gensis-plumbing.com

2.6.4.2 Offline Replacement

Offline replacement is the installation of a new pipeline not directly affected by the location and grade of the existing pipe. This allows for the existing pipe to be kept in service while the new pipe is being installed, eliminating the need for bypassing, and once installed, allows for some operational flexibility in the operation of the two pipelines. The new pipeline can be installed with traditional open cut methods, or trenchless methods such as pipe jacking, micro tunnelling, or horizontal directional drilling.

The most frequent form of pipeline installation is via an open cut, as the process is relatively simple, highly trained personnel are not required, and utilities/contractors are familiar with the method and results. The direct costs of open cut installation is relatively low, but the indirect costs – pedestrian and vehicular traffic disruption, interference with other utilities or underground structures – can raise the cost significantly (Zhao and Rajani, 2002). An example of open cut pipeline installation can be seen in Figure 2.16.

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Figure 2.16 - Open Cut Pipeline Installation
Courtesy of kanapipeline.com

Pipe jacking is the trenchless installation procedure where a pipeline is pushed into place while the material at the leading edge is removed by personnel or personnel operated equipment. Pipe jacking requires man entry sized pipes (>1200mm). Spans of 1000m can be installed from a single pipe jacking pit, for GRP, concrete, and steel pipelines. Pipe jacking requires special internal couplings to minimize the friction between the soil and the pipe, potentially resulting in increased internal roughness (Morrison et al., 2012). The pipe jacking process can be seen schematically in Figure 2.17.

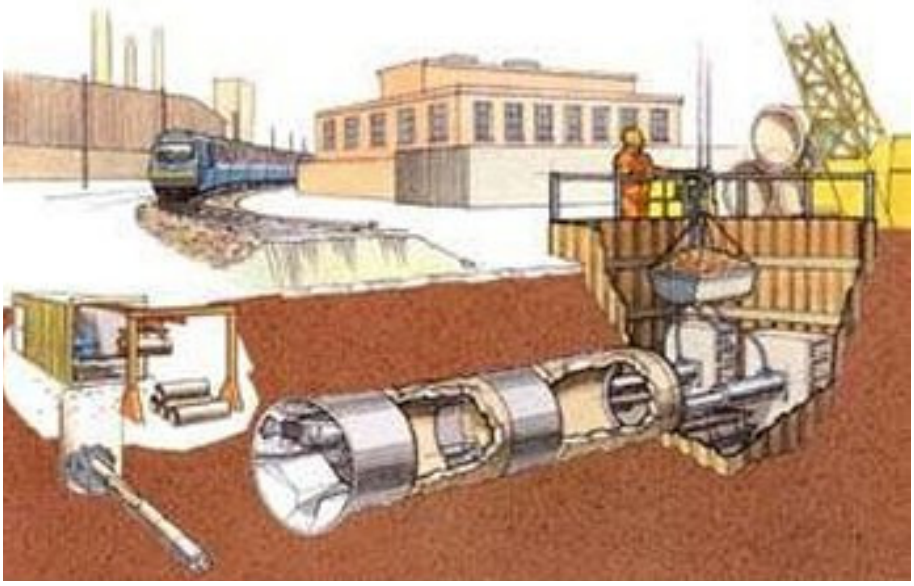

Figure 2.17 - Pipe Jacking Process
Courtesy of pipejackingassociation.com

Micro-tunnelling is a similar process, except the leading edge material is removed by a tunnel boring machine (TBM) and remotely transferred to the surface via the jacking pit. Micro-

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tunnelling does not require personnel at the leading edge of the pipe, so it can be used to install smaller pipes (>300mm). The excavated soil is converted to slurry and pumped to the surface, allowing for a smaller jacking pit, but requires the processing of the slurry on the surface. The micro tunnelling process can be seen schematically in Figure 2.18.

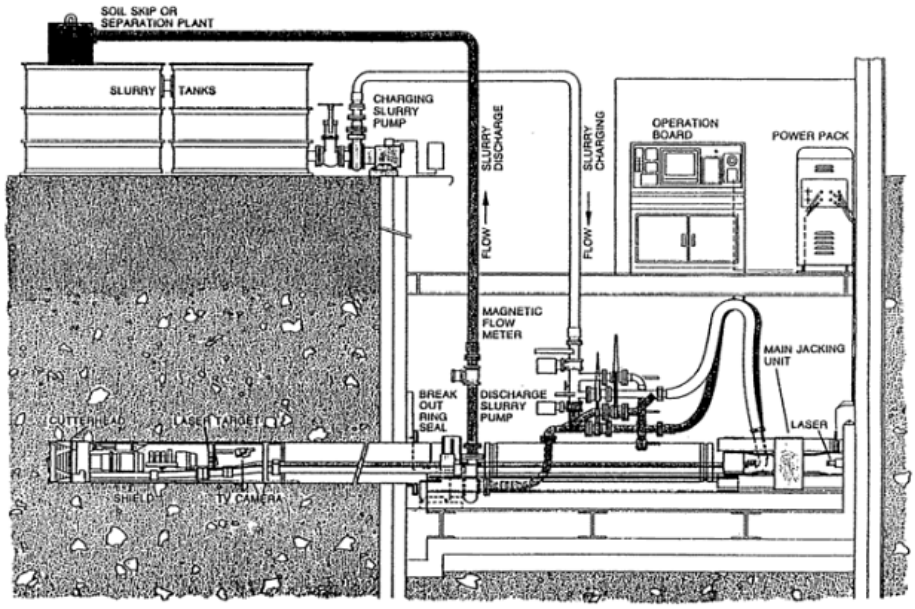

Figure 2.18 - Micro Tunnelling Installation Process
Courtesy of ASCE.org

Horizontal directional drilling (HDD) is a process of trenchless pipeline installation. The process begins with a pilot hole being drilled along the pipeline path, which is steered and powered by the machine on the surface. The pilot hole is then enlarged and the new pipe pulled into place. Pipelines ranging from 50-1500mm and with steel, DI, PVC or HDPE pipe materials can be installed with HDD. The drill rig can perform large radius turns, and lengths up to 3km can be installed from a single drill point. Horizontal directional drilling was originally used for the installation of pipelines below rivers, but is now widely used where open cut installation would be problematic. The installation process can be seen in Figure 2.19.

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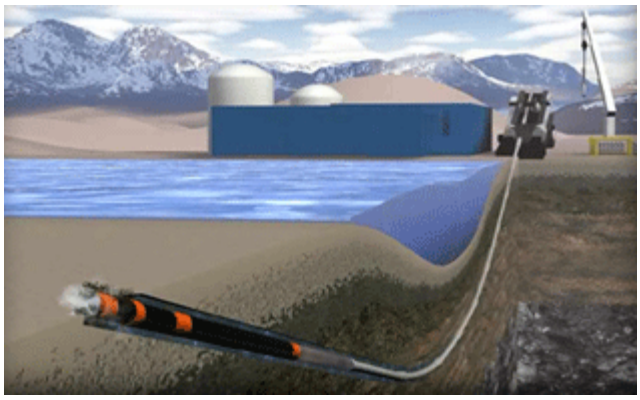

Figure 2.19 - Horizontal Directional Drilling Process
Courtesy of tchdrillers.com

2.6.5 Summary of Upgrade Methods

The options for operational changes, pipeline improvement or replacement can be altered or combined depending on the specific condition of the pipeline as well as external factors. For example, a pipeline can be installed parallel to an existing line, and with that pipeline operational, the original pipeline can be rehabilitated. The costs for each of these improvement methods vary widely and fall outside of the scope of this study. Generally, operational changes and cleaning are the least expensive options, followed by rehabilitation, with new pipe installation being the most expensive.

2.7 Economic Analysis of Upgrade Options and Operational Cost

A pipeline system incurs costs throughout is operating life, including its planning, design, construction, energy - i.e. electricity, operation and maintenance costs, all of which will inevitably vary throughout its lifetime. Figure 2.20 conceptually reflects how these costs may vary with time.

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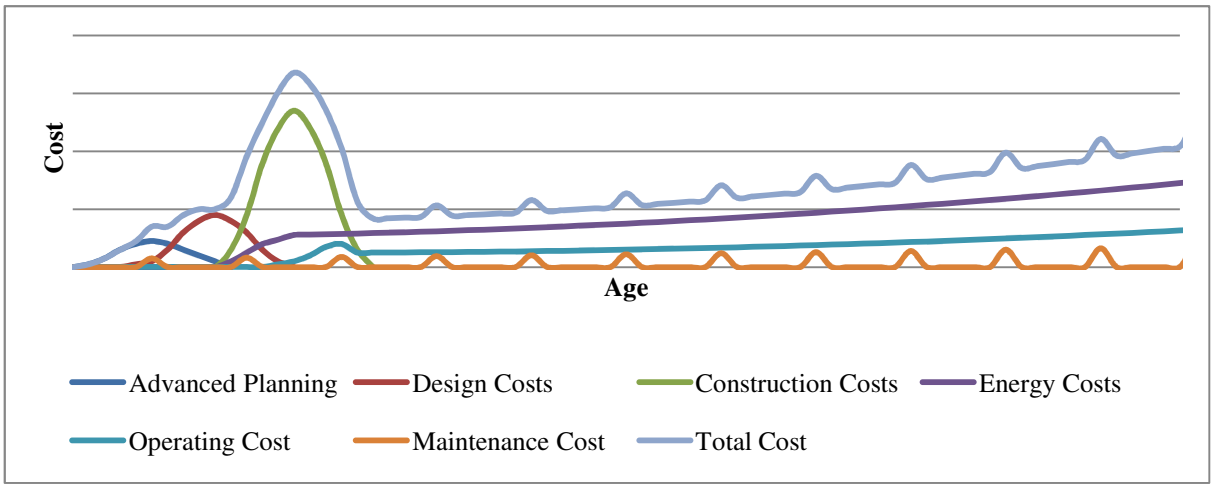

Figure 2.20 - System Component Cost over Operating Life

Upgrading the system as discussed in Section 2.6 will reduce the operating cost of the system but introduce additional costs in the form of design and construction of the upgrade. Figure 2.20 reflects conceptually how these upgrade costs and decreased energy costs may affect the overall cost of the system.

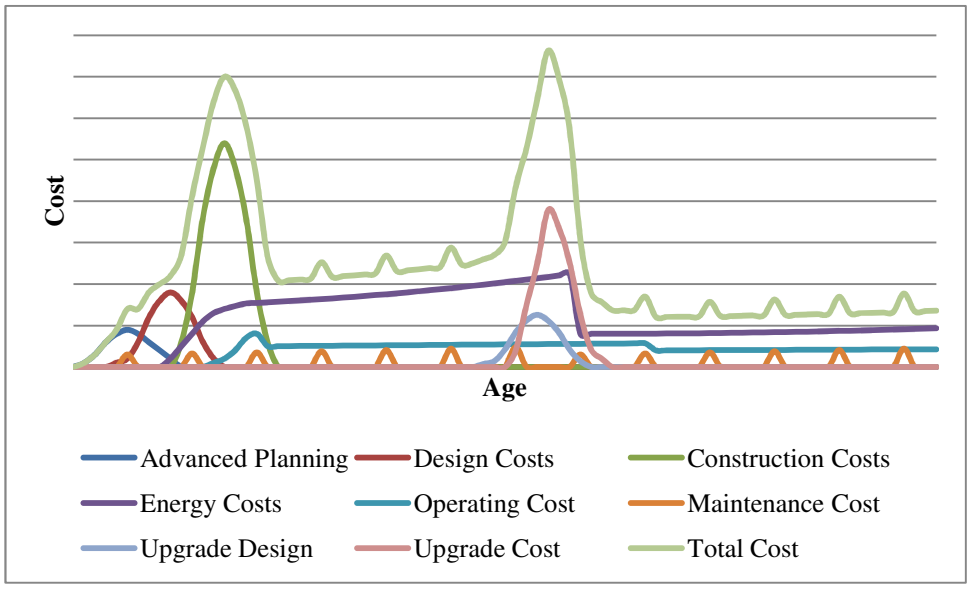

Figure 2.21 - Component Costs of a System with System Upgrade

It is important to consider the value of all the components allowing for the relationship between the value of money and time, which can be evaluated with Life Cycle Cost (LCC) analysis. LCC analysis is an economic tool used to determine the total cost of a system over its lifetime. This is done by utilizing inflation, cost escalation, and discount rates to create a present value associated with each item's cost to determine the Net Present Value (NPV) of

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each item. LCC analysis generally uses both costs and incomes to determine the most cost efficient option; however for pipeline operation it can be assumed that the incomes will be equal for all options, therefore incomes can be excluded

For a pumped pipeline system, the total LCC can be defined as the sum of all the present value of each of the costs associated with an option as show in Equation 2.21 (Hydraulic Institute, 2001).

$$LCC = C_{AP} + C_D + C_C + C_E + C_M + C_O + C_{UD} + C_{UC}$$

Equation 2.21

Where:
C_{AP} = *advanced planning cost*
C_D = *design cost*
C_C = *construction cost*
C_E = *energy cost*
C_M = *maintenance cost*
C_O = *Operating cost*
C_{UD} = *upgrade design cost*
C_{UC} = *upgrade construction cost*

The advanced planning costs are the costs associated with the original planning of a pipeline system. This process includes determining the daily transfer volume needs, the locations of the supply and end demand and how the pipeline system will interact with the rest of the distribution system. These costs are relatively minor in comparison to other system components, occur over a short period, and are relatively predictable.

The design costs are the costs associated with the technical design of the system including route selection, pipe specification, pump selection, pump station design, air, scour and isolating valve location and design, as well as the bid process and other costs inherent to the design process.

The construction costs are the costs associated with building the system including purchase of pipe, valves, and pumps, earthworks, pump station and valve chamber construction, laying of pipe, and installation of pumps and valves, all the associated electrical and control equipment, as well as initial operation, training and testing (US DOE, 2006).

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The energy costs are the single largest factor in a pipeline system's lifetime costs (Hydraulic Institute, 2001). This cost will be incurred every time that the pipeline is pumping, and will vary over the lifetime of the system; however it can be estimated fairly accurately, although the long term costs are difficult to predict (see Section 2.5). Several factors will affect the energy costs of a system including increasing demand, energy price escalation, and the decreasing hydraulic capacity of pipelines as they age. The decreased hydraulic capacity of a pipeline will increase the headloss, decreasing the flow rate along the pumps curve. This decreased flow rate, along with increasing water demands will require longer pumping hours and increased energy use. Additionally, energy prices for most of the world are projected to increase, further raising the electrical costs.

The maintenance costs of a pumped pipeline system include monitoring the system, pump servicing, operation of valves, system flushing, other general maintenance items and system repairs. Repair costs can are often included in maintenance costs, but the can also be included as their own cost item. Efficient maintenance, particularly on the pump itself can prevent breakdowns, reducing repair costs and allow for the pump to operate more efficiently (US DOE, 2006).

The operating costs of a pumped pipeline system include the salaries of the pump station operators and maintenance personnel, the associated offices and vehicle expenses, as well as other related expenses.

The upgrade design costs are the costs associated with the selection and design of an appropriate upgrade option. This includes evaluating operational changes, cleaning, rehabilitating, replacing, or paralleling the pipeline, determining which option is most appropriate for the system, and technical design of the improvement option.

Upgrade construction costs are all the costs associated with operational changes, cleaning, rehabilitating, replacing, or paralleling the pipeline, including material purchase, earthworks, installation, bypass piping, testing, and other construction related costs.

Life cycle cost analysis often includes other cost components (such as repair costs, downtime costs, environmental costs, and decommissioning costs), however, for the purpose of

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analysing the LCC difference between normal operation and improvement options, the cost differences of these additional cost components can assumed to be negligible.

2.8 Available Prioritization Tools

With operating costs of pipeline systems increasing, and municipality's budgets, more often than not, shrinking, as well as the average age of water pipelines increasing, there is a growing backlog of water systems that require renewal and optimization. Pipeline renewal prioritization tools address this growing backlog by determining which pipelines need renewal and how, while system optimization tools determine the most efficient method to operate the system.

2.8.1 Pipeline Renewal Prioritization and Technology Selection

As pipelines age, their structural integrity as well as their hydraulic capacity will decrease. The lowered structural capacity leads to increased rates of breakages, while the hydraulic deterioration can increase pumping costs, decrease delivery, and degrade water quality. To counter the effects of ageing, pipelines are renewed – relined, rehabilitated, or replaced. For a municipality that manages many hundreds, if not thousands, of kilometres of pipelines, choosing which pipelines to replace, and how to replace them, is a daunting task. There are several available decision support systems (DSS) or models (DSM) that range in application from determining the order in which pipelines should be renewed, to reviewing the appropriate renewal technologies that could be used for renewal, to cost assessment and prioritization. The following DSS and DSMs were identified by the US Environmental Protection Agency, (US EPA) to be the most promising processes for pipeline prioritization and renewal process selection (Mathews et al., 2011).

TAG/TAG-R, was developed by the US National Utility Contractor's Association and the Trenchless Technology Centre at Louisiana Tech University, and released in 2008 (Mathews et al., 2011). TAG/TAG-R utilizes project specific inputs, and an internal database of industry vetted data to determine which of 80+ renewal technologies are most appropriate for the specific site. The DSS is not able to perform a cost analysis, has no allowance for the potential change in hydraulic capacity, and does not consider the difficulties of bypassing.

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M-PRAWDS is a simple model focusing not on renewal technology selection, but on minimizing the overall cost associated with pipeline renewals and emergency repairs of breakages (Kliener et al., 2001). The model considers the hydraulic and structural deterioration over time to determine when and how (replacement, relining, or upsizing) to replace specific pipelines. The software was developed as a demonstration project and is currently being incorporated into the Distribution – Water Main Renewal Planner (D-WARP) program developed through the Nation Research Council Canada (Mathews et al., 2011).

The American Water Works Association developed two systems to determine the appropriate technology to renew water distribution lines. The first, Comprehensive Decision Support System (CDSS) determines the appropriate renewal technologies, and then performs a highly detailed cost analysis for each technology to determine which renewal option is most cost efficient (Deb et al., 2002). The software does not incorporate new technologies, nor does it include the flexibility to adjust the cost estimate to site specific conditions. It appears the development and implementation has stopped. The second DSS developed by the AWWA is a series of flow charts to provide a simple method to determine how a specific pipe section should be renewed (AWWA, 2001). The charts include no references to cost analysis, nor do they include a method of prioritization.

The system of asset management contained in CARE-W provides the most in depth method of pipeline evaluation and prioritization and has successfully been applied in several pilot locations in the US and Europe (Le Grauffe et al., 2007). The system first estimates the condition of the water system, and then predicts likely failures, allowing for pipeline prioritization. Additionally, it allows for long term analysis of different prioritization strategies. CARE-W does not include any details on how a pipeline should be renewed; only suggesting which pipelines should be renewed.

In addition to commercially available DSS/DSMs, many consulting companies have developed their own, in-house systems. For example, Hazen and Sawyer, a US based engineering firm developed several systems that are then tailored to the specific application (Bonge and Roberts, 2010). These methods range from weighted matrixes based solely on the pipelines characteristics, to statistical modeling calculating the estimated likelihood of failure, consequence, risk, etc., to produce a pipeline renewal plan.

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Additionally, the US EPA performed a survey of eight major cities in the US to determine what, if any, systems were used to prioritize pipeline renewal and facilitate renewal technology selection (Mathews et al., 2011). The survey found that only two cities out of the eight utilized asset management software, and three out of the eight utilized software for technology selection. The remaining cities relied on engineer's experience and input from consulting engineers for pipeline prioritization and renewal technology selection. Almost all the cities surveyed expressed a desire for a more robust system for pipeline prioritization and renewal process selection.

None of the DSS/DSMs researched account for the energy cost savings associated with renewed pipelines.

2.8.2 Pump Scheduling and System Optimization

Pump scheduling involves improving the efficiency of operating an individual, or system of pumped pipelines, while meeting a variable daily demand, with different combinations of pumps with different operating characteristics. The main difficulty with pump scheduling is the significant number of potential solutions to optimizing a systems operation. For example, pipeline system, powered by three pumps, which can only operate on or off, has to consider $(2^3)^{24}$ or $4.7x10^{21}$different potential pumping combinations for optimization throughout the day (assuming that the operating pumps would change every hour). This number, coupled with different valve settings, VSDs, and other variables will increase the potential number of solutions to approach infinity. The potential number of solutions has been traditionally reduced to manageable solutions with significant assumptions, but with advances in computing technology, proliferation of SCADA systems, and large scale data collection systems, the optimal, or near optimal solution can be calculated in real time.

There are several available pump system optimization programs available to improve the efficiency of operating a pump system. The programs range from cost optimization, deciding operational hours based on the variable price of electricity, to system optimization, where different combinations of pumps or reservoirs are used based on the current and forecasted demand, to data analysis and mining to predict daily demands based on historical trends. Three of the most promising software suites are mentioned below; however there is a wealth

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of publications available to understand the theory behind pump scheduling. Key publications for further understanding of the theory research in the area include:

- Ormsbee and Lansey, (1994) provide a comprehensive survey review of existing optimal control methodologies for water-supply pumping systems, including hydraulic network models, demand forecast models, and optimal control models as well as a discussion on the often overlooked area of operator acceptance issues.
- Balla and Lingireddy (2000) address the difficulties in utilizing personal computers to find optimal pump scheduling solutions and address the problem by utilizing the combined computing power of networked PCs.
- Ulanicki et al. (2007) utilize a dynamic optimization approach to find a near optimal pump scheduling solution in a significantly faster manner by utilizing heuristic assumptions.
- Rao and Salomons (2007) utilized an artificial neural network to determine in real time the near optimal combination of control settings to allow the system to operate at its peak efficiency for the real time conditions. This process serves as the bases for Potable Water Distribution Management (POWADIMA) discussed below.

While there are many different software packages available for optimal pump scheduling, three of the most promising software suites are discussed below.

Aquasuite, created by the engineering consulting firm, Royal Haskoning DHV, is a program that allows for monitoring and control of water purification and transmission systems (Royal Haskoning DHV, 2012). The program evaluates historical data to predict hourly and 2-day demand to allow for the plant to operate more consistently, which improves water quality and allows for energy intensive pumping to be shifted to lower cost hours. The system claims 5-10% energy savings, and the more consistent operation reduces switching, lowering pump wear, resulting in lower maintenance cost (Royal Haskoning DHV, 2012). The system is designed only to be applied to water treatment plants, makes no efforts for wider system modeling, and cannot adapt to potential instrumentation faults.

Several European and Israeli universities have developed a program for system optimization called Potable Water Distribution Management (POWADIMA) (Bunn & Reynolds, 2009).

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Using the existing system's operation and EPANET for hydraulic modelling, POWADIMA was able to find near optimal solutions in a relatively short time. The program was applied to two cities (Haifa, Israel and Valencia, Spain) and was able to achieve an estimated cost savings of 25% for the City of Haifa's A district (Salomons et al., 2007), and a 17% savings for Valencia's water distribution network (Martinez et al., 2007). The software utilizes both genetic algorithms and an artificial neural network to allow the program to optimize the current system in near real time. POWADIMA is unable to account for potential instrumentation failures. It has only been applied to two cities as demonstration projects.

Perhaps the most robust optimization software available is Aquadapt developed by Dereeto LTD (Bunn & Reynolds, 2009). Aquadapt utilizes real time operational data to direct water to customers through the least expensive path in a distribution network. The program is able to predict future demand from historical databases and to account for calculated real time pump efficiency, variable water production costs, and varying electrical costs to reduce the overall system operating cost. Additionally, it can detect and automatically correct faulty data and determine instrument malfunctions to improve the accuracy of its historical database, improving the potential cost savings for future operation. It has been applied to several cities in the US, with energy use reductions ranging from 6 to 8% and cost savings of 13-20% (Bunn & Reynolds, 2009). The software does not consider the increased wear and required maintenance of frequent pump switching and does not account for pipeline deterioration, only pump deterioration.

No program researched was able to make recommendations on improvements that would allow for the system to operate more cost efficiently.

2.9 Summary of Literature Review

This chapter first focused on the components of pumping pipeline system, the hydraulic relationships controlling their energy use. The specific energy losses in both the pump station and pipeline were discussed, including pump efficiency, losses in pump/flow controls, friction, and secondary losses throughout the pipeline. The next section reviewed factors that can affect the hydraulic capacity of a system, including depositions, scaling, corrosion, and biofilm, and how specific pipe materials will react to these influences over time.

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The operational costs were then discussed, focusing on the global sources of electricity and trends for developing/developed countries. Options to lower the operation costs by increasing the efficiency of the pipeline were evaluated next, reviewing changes to the operation of the pumps, rehabilitation options, replacement options, and paralleling the pipeline.

Next, the economic analysis of the operation of a pumping pipeline system was reviewed, focusing on LCC analysis. The review of the hydraulic aspects, the electrical trends, and improvement options coupled with the discussion of LCC analysis will assist in the development of a system to prioritize pipelines of a bulk transfer network for improvements. The prioritization will promote efficient allocation of capital to pipelines where it will provide the greatest benefit.

Finally, a review of the existing prioritization and optimization tools that are available showcased two categories of tools, decision support tools for pipeline renewal prioritization and pumped system operation optimization. The current tools for pipeline renewal are able to review a series of pipelines and determine which pipelines should be renewed, based on minimizing combined repair and renewal costs, and to determine how to replace the prioritized pipelines. The optimization tools are able to filter, store, and mine operational data, predict future demands, and determine the most cost efficient operation system. However they lack the ability to determine where and how system improvements can be implemented to improve the system's operation.

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3 Conceptual Development

A municipality or water board often manages many hundreds of kilometres of bulk water pipelines. The City of Cape Town, for example, operates 596 km of bulk transfer lines in addition to operating many hundreds of kilometres of smaller, distribution lines. Improving all these pipelines to peak efficiency would be impractical, wasteful of capital, as well as being outside the typically limited municipal budgets for capital improvements. A systematic approach based on the potential energy and cost savings versus the cost of improvements was developed to allow for the prioritization and strategic application of capital to where it can provide the greatest improvement in cost-effective management of the water distribution infrastructure.

As discussed in Chapter 2, developing countries are likely to see significant increases in the cost of electricity as demand, regulations, and construction costs continue to grow. South Africa will be used as an example country to illustrate both the growing demands and the increasing electrical cost. South Africa has two new coal power plants, one new pumped storage scheme, and various wind farms under construction to meet this growing demand. To finance this new construction, an 8% annual increase in tariffs has been accepted, as well as time dependent pricing to try to keep pace with and manage the growing demand. As one of the single largest users of electricity, pumps, specifically pumped bulk transfer water lines, should be evaluated and improved to reduce both their electrical demand and the cost of operations.

The conceptual model for prioritization is based on a preliminary evaluation of the two main aspects relating to operational cost: the pipeline's hydraulic characteristics, and the operational control of the system. The preliminary prioritization will determine which pipelines are inefficiently operated and have a potential for cost savings. The hydraulic evaluation will categorize the pipelines based on roughness, velocity, and diameter to determine, hydraulically, which pipelines are in need of improvements. The operational evaluation will categorize the pipelines based again on the velocity and the pumping schedule to determine which pipelines are in need of operational improvements.

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The final step is an economic evaluation of all the potential improvement options, focusing on the cost savings from gains in energy efficiency versus the cost of the improvement(s).

3.1 Hydraulic Evaluation

The hydraulic evaluation examines the energy losses of a pipeline, specifically focusing on the friction head loss. As shown in Equation 2.4, the friction head loss (h_f) is dependent on the velocity squared (v^2), diameter (D), length (L), and the roughness of the pipeline (k_s) - through lambda. Dividing h_f by L calculates the friction slope (S_f), which can be used as an index of how efficiently pipelines are operating. To compare a pipeline's S_f, the ratio of k_s to d, also known as relative roughness (ε) can be graphed versus the operating velocity squared. Since S_f is dependent on the square of the velocity and the roughness, while inversely dependent on the diameter, the further from the origin, the more energy will be required to operate the pipeline as reflected graphically in Figure 3.1.

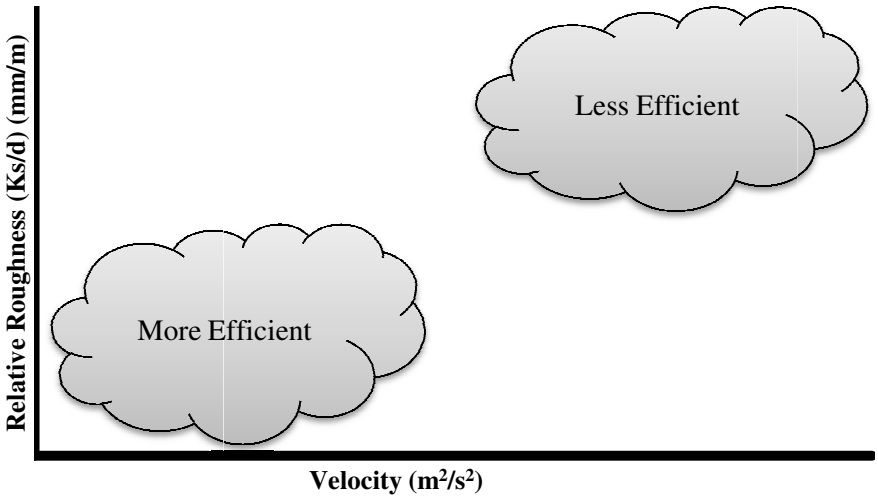

Figure 3.1 - Conceptual Model as Basis for Hydraulic Evaluation

Using the regions of similar efficiency, as reflected in Figure 3.1, the pipelines can be prioritized, purely based on their hydraulic conditions, by multiplying the relative roughness by the operating velocity squared. The pipelines with the higher prioritization value would be ideal, hydraulically, to be improved first. To illustrate how to decrease the friction slope, the operating curves of four example pipelines are shown in Figure 3.2.

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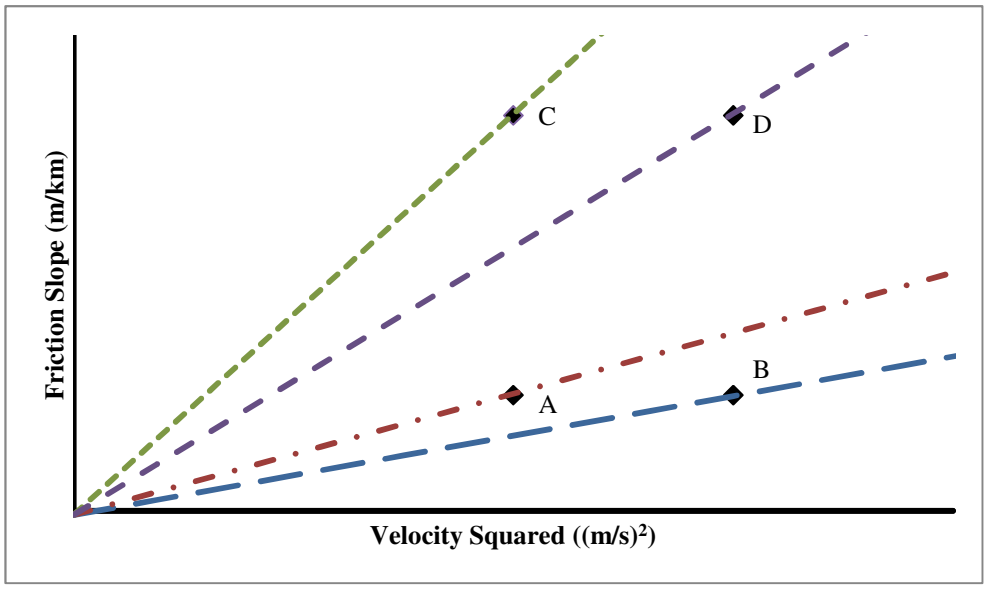

Figure 3.2 - Operating Curves of Example Pipelines

To improve the energy efficiency of a pipeline, the friction slope must be reduced, either by decreasing the roughness or decreasing the velocity. Reducing the velocity moves the operating point of the pipeline left on its relative roughness curve, while reducing the roughness flattens the curve that the pipeline operates along, lowering the friction slope and the energy required to operate the pipeline.

There can be situations when the pipeline itself is in good hydraulic condition, but the presence of biofilm degrades the hydraulic capacity of the pipeline. Biofilm itself requires special investigation to determine what the appropriate improvements are to control the effects of biofilm as cleaning or rehabilitation will only have a short term effect. Biofilm can be controlled through regular cleaning or flushing, filtration prior to pumping, or chemical treatment. An alternative is to replace the pipeline with a pipeline of larger diameter; minimizing the effect that biofilm has on the pipeline's friction headloss.

3.2 Operational Evaluation

While the hydraulic evaluation focuses on the *energy* efficiency of pipelines, the operational evaluation focuses on the *cost* efficiency of operating pumps to power the pipelines. Ideally a pumping system should be operated at the pump's best efficiency point, and at the lowest practical velocity to ensure minimum friction and secondary losses throughout the pipeline. In practice however, most large pumps operate with variable electrical costs, costs that can

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change with respect to the time of day, day of the week, or even the time of year. This section is written specifically focusing on South Africa, but can be applied to any situation where the cost of energy varies hourly, daily and seasonally.

With the variations of electrical price considered, an ideal number of pumping hours can be calculated. This ideal operational schedule exists when the efficiency gains from lowering the velocity are offset by the increase in the average price of electricity. Eskom's electrical tariffs are summarized in Section 2.5.3, specifically in Figure 2.9 which reflects the time periods for Eskom's Peak, Standard and Off-peak categories, and Table 2.4 which reflects the tariffs for electricity. Summarizing these two tables, the total weekly hours and the calculated daily average hours for each cost category, are shown in Table 3.1.

Table 3.1 - Time Ranges and Associated Electricity Tariffs

Categories	Weekly Hours	Daily Average Hours	Example Summer Electrical Tariff (R/kWh)	Example Winter Electrical Tariff (R/kWh)
Off-peak	81	11.6	25.83	30.10
Standard	62	8.8	37.06	56.37
Peak	25	3.6	60.54	216.00

From this cost information, the electrical cost per pumping hour average over a week can be determined for both summer and winter, as reflected in Figure 3.3.

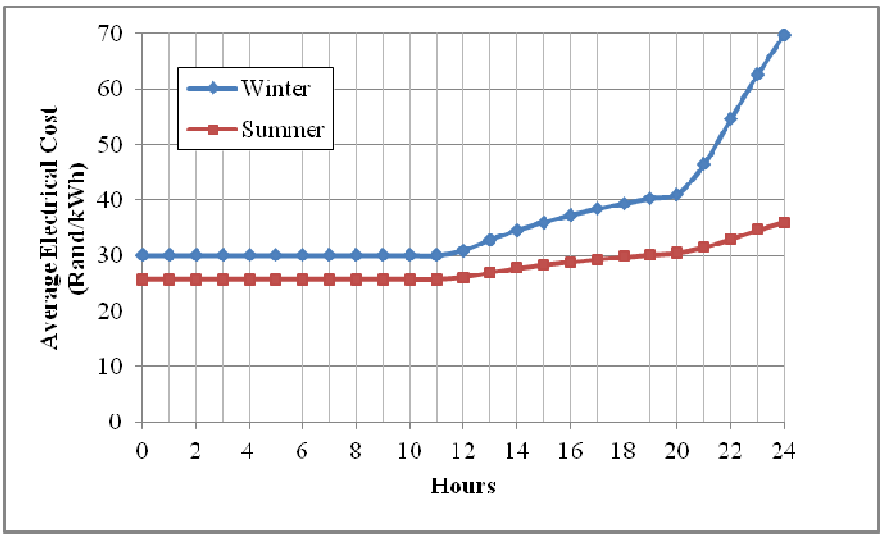

Figure 3.3 - Average Hourly Electrical Cost (for cost logical operation)

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This average electrical cost makes the assumption that the pump operates logically according to electrical price; it assumes that the first 81 hours of pumping a week will all take place in off peak hours; the next 62 hours of operation will take place in standard hours; and the remaining 25 hours will take place in peak hours. This however is not always the case; options for changing the pumping schedule to allow the pump to operate logically are discussed in the next section.

Assuming the pumped pipeline can operate at *any flow rate* (for theoretical calculations), longer pumping hours dictates lower flow velocity, which leads to lower friction losses, which leads to lower energy requirements. The cost structure of electricity, shown in Figure 3.3, means that pumping for fewer hours will lead to lower average electrical costs, a trade-off that requires the ideal pumping hours to be calculated for each pipeline. Assuming the pump is operated cost logically to maximize pumping during the lower cost time periods, a cost curve can be generated to determine the ideal pumping hours, the hours that have the lowest operational cost to convey the system's average annual daily demand (AADD). The variations of energy cost for different pumping hours for three example pipelines are shown in Figure 3.4, below.

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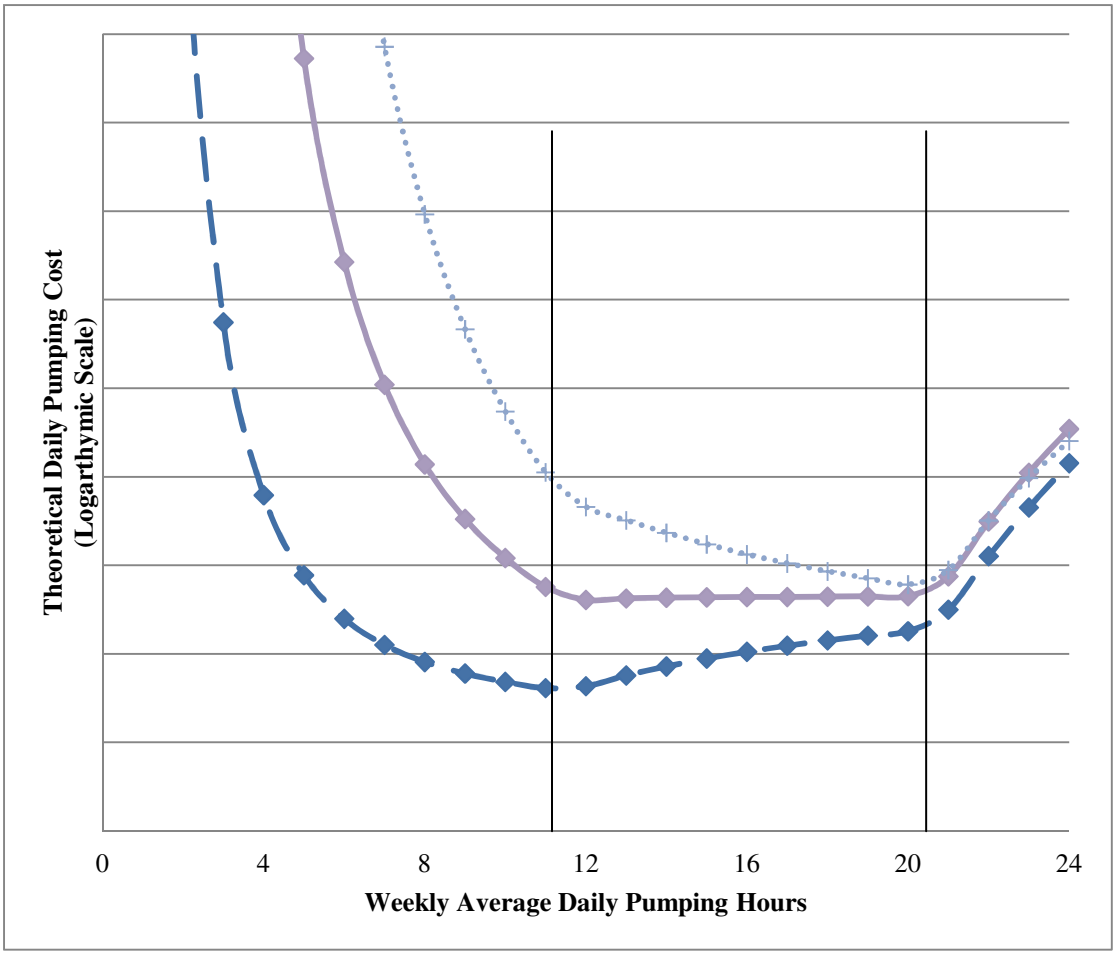

Figure 3.4 - Total Energy Cost with Respect to Variations of Electrical Prices

Note: The total theoretical energy cost curves are based on the assumptions that (1) the pumped pipeline system can operate at any flow rate, and (2) the pumps will operatecost logically, ie in the lowest cost time periods first.

Visible on each of the curves in Figure 3.4 are two points where the slope of line changes, one at 11.6 hours and at 20.4 hours, points at which the pricing structure of electricity changes. The ideal number of pumping hours corresponds to the lowest theoretical daily pumping costs, therefore is it expected the that likely possibilities that the ideal pumping hours are; 12 (off peak only, as indicated by the dashed line), 20 (standard and off peak, as indicated by the dotted line) or a range of hours where the operating cost is relatively equal, as indicated by the solid line.

To prioritize pumping pipeline systems based on their operational cost efficiency, the systems are placed in three categories, the current pumping hours are shorter, equal to, or longer than the ideal hours. This can be visualized by graphing the increase or decrease in pumping hours, versus the ideal velocity as shown in Figure 3.5.

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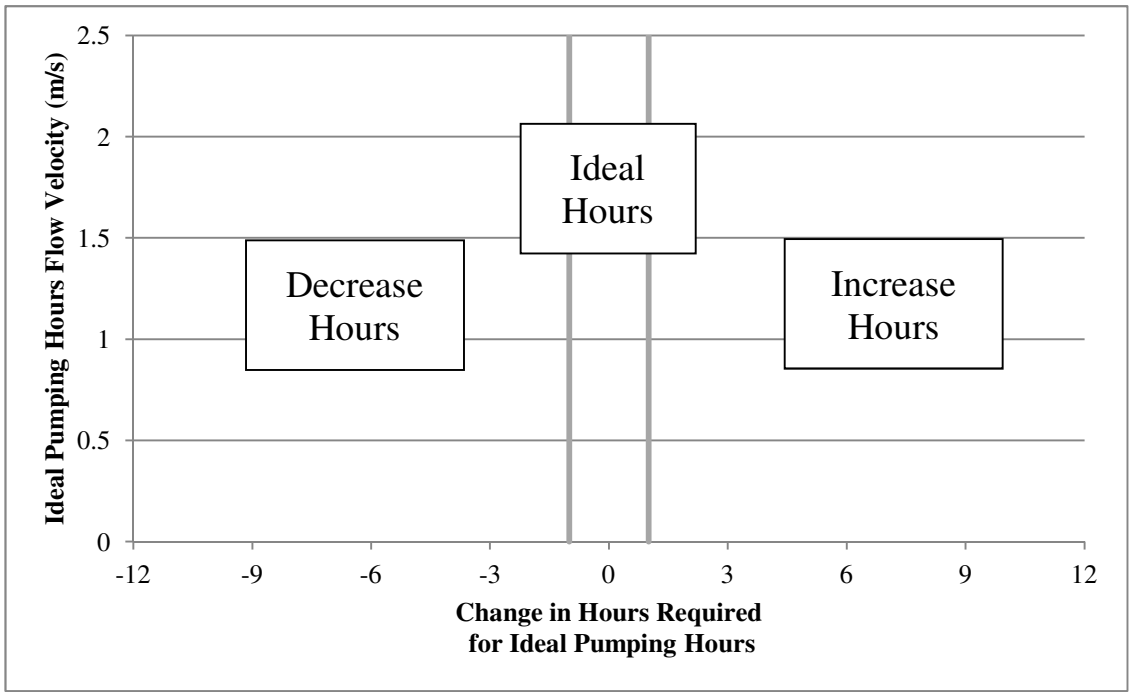

Figure 3.5 - Conceptual Evaluation of Pumping Hours

Additionally, there can be situations when the pipeline is in good hydraulic condition, and the pump station is operating cost efficiently for the existing pipeline, but the system still has to run for long hours at high velocities to convey the AADD volume required. In this situation, the pipeline does not have the cross sectional area to transport the AADD efficiently, and has low redundancy to allow for failures or maintenance. Additional pipeline capacity is required, either through the installation of an additional parallel pipeline, or the replacement of the existing line. This concept can be added to Figure 3.5, using a velocity of 1.5 m/s, the high end of the historical normative flow range (CSIR, 2000) to form the model that will be used as the basis for operational evaluation as shown in Figure 3.6.

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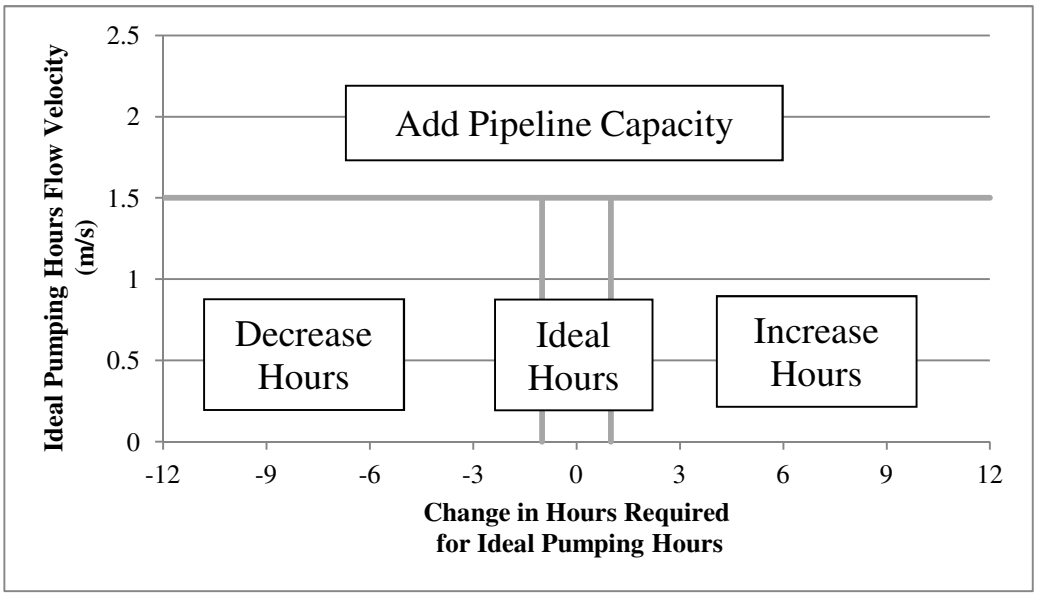

Figure 3.6 -Conceptual Evaluation of System Operation

For systems that require a change in the pumping hours, both the pump and the external system must be examined. The external system would include anything that is directly run before or after the system – water treatment plants, industry users, domestic consumption, power generation, etc. –that would be affected by the change in pumping hours. The pumping hours can be increased by the incorporation of a pump control, such as a variable frequency drive (VFD), or replacing the pump(s) with pumps that operate at a lower flow rate on the system curve. The pumping hours can be decreased either by altering the operation of the existing pumps (running multiple pumps simultaneously), adding additional pumping capacity, or by improving the pipeline, which would decrease the head loss, allowing the current pump to operate at a higher flow rate, therefore decreasing the pumping hours.

However, the external system may dictate the operation of the system, forcing it to operate illogically from a cost perspective, i.e. operating when the cost of electricity is not cheapest. For example, the pump may be required to operate throughout standard hours when a water treatment plant is operating, or to provide water to end users during peak hours. When the external system dictates pump operation, reservoirs, either on the supply side or demand side of the system, can be added to allow for the system to operate more cost efficiently.

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A thorough examination should be undertaken to determine if the energy savings from operational improvements would offset the costs of improvements over the lifetime of the pipeline.

3.3 Economic Evaluation of Improvement Options

The hydraulic and operational evaluations identify the pipelines that are in need of improvements and suggest options that could improve energy and/or cost efficiency. To determine which option(s) is (are) best from an economic point, life cycle cost (LCC) analysis is used. The first step is to use the hydraulic and operation evaluations to determine the combined improvement alternatives that can be considered to improve the system. The categories from the previous evaluations and their associated improvement options are summarized in Table 3.2.

Table 3.2 - Pipeline Improvement Options Included in Analysis

Hydraulic Condition	Improvement options		Operational Conditions	Improvement options
Good	• "Do nothing"		***Good***	• "Do nothing"
Moderate	• Jet cleaning, Foam or Ice Pigging		***Decrease Pumping Hours***	• Add additional pumps • Adjust operation of multiple Pumps • Replace pump / enlarge impellor • Add reservoir(s)
Poor	• Rigid pigging • Intensive cleaning and rehabilitation • Replacement • Paralleling pipeline		***Increase Pumping Hours***	• Install VFD • Adjust operation of multiple pumps • Reduce impellor / replace pump • Add reservoir(s)
Other Operational Issues				
Illogical Operation	• Add demand or supply side reservoir		***Additional Capacity Required***	• Replace pipeline • Paralleling pipeline

Table 3.3 describes the general hydraulic issues that should be evaluated; however, due to the complexities associated with modelling these issues, they are excluded from further analysis.

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Table 3.3 - Pipeline Improvement Options not Included in Analysis

General Hydraulic Issues				
Air in Pipelines	• Additional Air Valves		***Scaling***	• Jet Cleaning • Intensive Cleaning • Water Softening
Presence of Biofilm	• Regular cleaning • Filtering and/or Chemical treatment		***Depositions***	• Jet cleaning, Foam or Ice Pigging • Filtration • Sedimentation Tanks

Note: The general hydraulic issues presented require site specific investigations and are not included in the conceptual design. They are presented here as potential problems that may require additional investigations

For example, for a pipeline with moderate hydraulic conditions, pumping for less than the ideal hours, and with the pumping hours limited by the external system, the operator would consider the following options for improving the systems cost efficiency.

- Pipeline cleaning – moderately aggressive
- Pipeline Rehabilitation
- VFD Installation
- Adjustment of the operation of multiple pumps
- Reducing impellor size / Replace pump
- Add supply or demand side reservoirs

The conceptual effects and potential issues of these improvements are summarized in Table 3.4 and Table 3.5.

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Table 3.4 - Effects of Hydraulic Improvement Options

Hydraulic Improvement Options	Effect on Roughness	Effect on roughness growth rate	Effect on Diameter	Effect on Structural Integrity	Other Issues
"Do nothing"	None	None	None	Continues to degrade	None
Jetting, Foam or Ice pigging	Moderate improvement	Likely to increase	Some increase	Continues to degrade	Requires pipe to be taken out of service, should be repeated every 5-7 years.
Rigid Pigging	Significantly improved	Likely to increase	Moderate increase	Continues to degrade	Requires pipe to be taken out of service for a significant time. Cleaning may damage brittle pipe.
Intensive Cleaning	Significantly improved	Likely to increase	Restored to original	Significantly degrade	Requires pipe to be taken out of service for a significant time. Cleaning may damage brittle pipe.
Rehabilitation	Improved to the roughness of the liner	Likely decreases	Reduced by liner thickness	Liner can provide additional structural support	Requires pipe to be taken out of service for a significant time. Requires cleaning prior to installation.
In Line Replacement	Improved roughness of new pipeline	Significant decreases	Pipeline can be enlarged	Improved to known characteristics of the new pipeline	Requires pipe to be taken out of service for a significant time.
Paralleling Pipeline	Improved roughness of new pipeline	Significant decreases	Pipeline can be enlarged	Improved to known characteristics of the new pipeline	Allows for pipeline to be kept in service until the new pipeline is completed. The additional pipeline provides flexibility for operation and maintenance.

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Table 3.5 - Effects of Operational Improvement Options

Operational Improvement Options	Effect on Pumping Hours	Effect on Flow Velocity	Effect on illogical operation	Other Issues
"Do nothing"	None	None	None	None
Install additional pump	Decrease or remain the same	Increase or remain the same	None	Should be installed in parallel in most cases. Allows for maintenance of pumps.
Adjust operation of multiple Pumps	Increase, decrease or remain the same	Increase, decrease or remain the same	None	Depending on current operation, decrease or increase pump hours, may be used in conjugation with additional pump. Frequency of switching should be examined.
Enlarge impellor / replace pump	Decrease	Increase	None	Consider effects on external system.
Reduce impellor / replace pump	Increase	Decrease	None	Consider effects on external system.
Install VFD	Increase or remain the same	Decrease or remain the same	None	Maintains pumps original capacity but allows for efficient operation under a range of flow rates.
Add supply or demand side reservoir	None	None	Allows for logical operation when supply dictates operation	Requires large space near pump station, consider effect on NPSH, and pump operation.

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In addition to the effects summarized above, there are several external factors that will influence the energy costs of operating a pumping pipeline system, primarily demand growth or loss and the rate that energy prices will increase. The change of demand is highly site specific, while the energy cost increases are often determined for several years into the future.

To quantify the cost savings from each of these options, the yearly energy cost of the unimproved system is first calculated for each year in the analysis period. The net present value (NPV) of the energy cost is then calculated. The baseline NPV is then be used as a baseline for comparisons for the cost of other improvement options.

The energy cost for each year, for each hydraulic and operational improvement, as well as the combination of hydraulic and improvement options can then be calculated. The NPV of energy usage for each option and combination of options is then calculated, and compared to the baseline NPV. The potential cost savings of each option is determined next, and the improvement option with the highest cost savings is prioritized.

3.4 Conceptual Development Summary

This conceptual development chapter consisted of three sections to evaluate a group of pipelines. The sections conceptually develop the process to determine the relative need for hydraulic condition improvements, the need for operational improvements, and finally which improvements are most cost efficient to implement over the course of the lifetime of the systems. The next chapter quantifies this conceptual development in a system that prioritizes the need for improvements over a range of pipelines.

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4 Pipeline Improvement Selection and Prioritization System

Using the conceptual method outlined in Chapter 3, an analytical approach to understanding the nature of pipeline problems and the impact of various improvements was developed. This model uses the state of the existing pipeline, coupled with anticipated or planned improvements in various aspects of the pipeline, to predict the outcome in terms of capacity, throughput, and operating cost. This model is called the Pipeline Improvement Selection and Prioritization (PISP) system. The key feature of this algorithm is that is allows the user to evaluate a group of pipelines and determine the theoretical impact of multiple improvement option(s) for each. This then allows the user to prioritize the order in which the improvements should be implemented based on cost and impact. The system is broken into two main parts, theory (desktop evaluation) and field verification. Together, these steps determine what improvements are ideal for a given pipeline, what improvements are most cost-efficient for a group of pipelines, and verify the assumptions made to determine with certainty which improvements will have the greatest benefits. The PISP process is summarized in Figure 4.1 and summarized below:

- The Data Gathering step involves using system modelling software, built in flow meters, as-built drawings, pump station operators, nameplate data, electric bills, etc. to gather the information needed for the hydraulic and operational analysis.
- The Preliminary Evaluation consists of a theoretical hydraulic and operational evaluation of potential changes to determine the appropriate improvement options.
- The Economic Analysis then uses the results of theoretical hydraulic and operational modifications, coupled with system specific external conditions, to determine the cost efficiency and ideal improvement for each pipeline. As described in Chapter 3, the improvements can then be prioritized on the basis of their potential impact and cost savings for each pipeline.
- Field Verification is then performed on the pipelines prioritized in the economic evaluation, to verify the hydraulic condition and operational characteristics of the pipelines used for the Model.

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- Finally, the Economic Verification utilizes the data gathered in the field verification to perform a final prioritization of improvement options based on their operational impact, the potential cost savings and payback period.

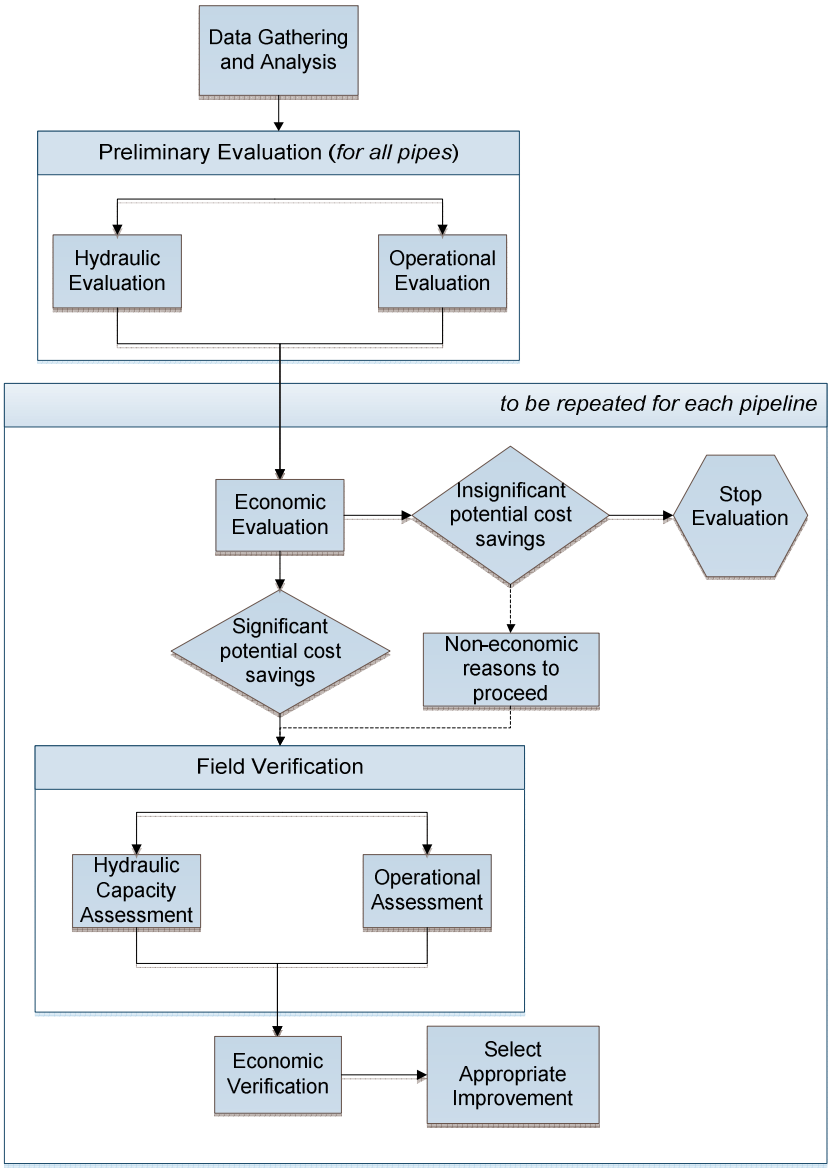

Figure 4.1 - Structure of the PISP System

Similar to Chapter 3, this section is written specifically for South Africa, but can be applied to any country by adjusting the electrical tariff schedule and other assumptions.

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4.1 Step 1 – Data Collection and Analysis

The first step to prioritize improvements for a group of pipelines is to gather the data that will be needed for the hydraulic, operational and economic analyses.

The hydraulic evaluation requires data specific to the pipeline, specifically, the operating flow velocity and relative roughness. The average operating flow velocity ideally should be measured, but can be back calculated from the AADD, pumping hours, and diameter if needed. Information on the AADD can be found by checking inline flow meters, consulting with supply or end users, or calculated using operating flow rate and pumping hours. The pumping hours can be determined by consulting with pump station personnel, measured, or calculated using AADD and operating flow, or reviewing pump nameplate data and electrical bills to determine the number of hours pumps were operating. The internal diameter can be determined by reviewing as-built drawings, measured directly, or calculated using the external circumference, thickness measurements, and liner information.

The internal roughness requires the measurement of the loss of pressure over all or part of the pipeline. This can be measured in several ways, but requires pressure measurements at least at two, ideally more, points along the pipeline to determine friction head loss. The internal roughness can then be back calculated. System modelling software, such as Infrastructure Management Query Station (IMQS) or supervisory control and data acquisition (SCADA) often has pressure, flow, AADD, and pipe information easily accessible. If IMQS or SCADA type modelling software isn't available, then this step must involve field testing.

The operational evaluation requires data specific to the pump station, in addition to some pipeline information. The operational analysis is based on a comparison of the current to ideal pumping hours, and the flow rate for the ideal pumping hours. Calculation of the most efficient, ideal pumping hours requires the electric tariff rates and schedule, which can be found by reviewing the pump stations electric bill or consulting with the electrical supplier. Additionally, the static head, the length, and friction factor for the pipeline must be calculated. The static head can be determined by subtracting the difference in hydraulic grade lines for the supply and demand points. The length can be determined by reviewing as built drawings or other geographic information. The friction factor can be calculated using

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the friction slope measured in the hydraulic analysis. Table 4.1 summarizes the information needed for the preliminary analysis.

Table 4.1 – Example Table of Information Needed for Preliminary Analysis

Variable	Measurement	Unit	Source
Internal Diameter		m	As built drawings
Length		m	As built drawings
Static Head		m	As built drawings
Absolute Roughness		mm	Calculated from friction headloss
Operating Flow Rate		m^3/s	SCADA or flow meters
Operating Velocity		m/s	Calculated from Operating Flow Rate
AADD		m^3	SCADA or flow meters
Pumping Hours		Hrs	SCADA or calculated from AADD

The economic evaluation requires data specific to the larger economic situation as well as quotations or estimates of the cost of improvements and the predicted effects of the improvements. The economic information that is required includes the predicted energy escalation rates and the predicted demand growth rates to calculate energy costs, and the predicted inflation rate, which is used to determine the NPV of the energy costs. The energy escalation rate can be determined by consulting the electrical supplier, International Energy Agency predictions, or other government/economic reports.

The demand growth rate is difficult to determine, but it can be calculated in a number of ways. First and simplest is to review the change in AADD over the course of the life of the pipeline; however, this is only an indication of what happened in the past. A more accurate approach would be to review the development patterns for the areas served, form a prediction for future development, determine the estimated water use for these developments and calculate the increase in demand. In the absence of specific information about development, typically a 2% growth rate is commonly assumed. The cost of improvements can be determined either through estimation or soliciting quotations from contractors. There are a series of cost functions used to estimate prices of improvements that are discussed in the economic analysis section.

With the needed data gathered, the pipelines are then subjected to the hydraulic evaluation.

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4.2 Step 2 – Hydraulic Evaluation

The hydraulic evaluation can be performed as described in the conceptual development chapter. It requires the setup of a relationship between relative roughness vs. operating velocity, divided into three sections. The three sections are created by evaluating the range of prioritization values, to provide relative rankings of poor, moderate, or good hydraulic condition as showing in Figure 4.2.

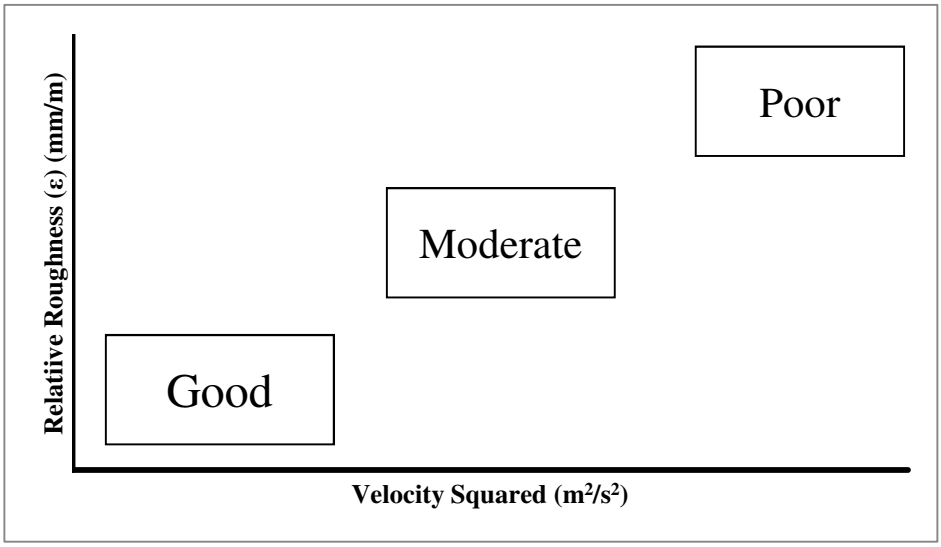

Figure 4.2 - Hydraulic Evaluation

The options to theoretically improve the pipelines' hydraulic condition can be determined based on the pipeline's relative hydraulic condition as discussed in the conceptual development chapter. These potential options are then analysed by the Model for the specific pipeline's external conditions to determine which options are applicable. The hydraulically worst pipelines – the pipelines with the highest values are prioritized.

4.3 Step 3 – Operational Evaluation

The operational analysis requires the calculation of the ideal pumping hours for the pipeline in its current condition. This requires calculating the flow rate, velocity, power used and average electrical price for all 24 hours and determining the lowest energy cost. The ideal pumping hours are then compared to the current pumping hours, and the difference calculated. The velocity corresponding to the ideal pumping hours is also determined. The ideal combination of pump hours and flow velocity is often not possible for the current pump

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configuration, although it can be used as a theoretical point of comparison. The ideal velocity and change in pumping hours is then graphed as shown in Figure 4.3.

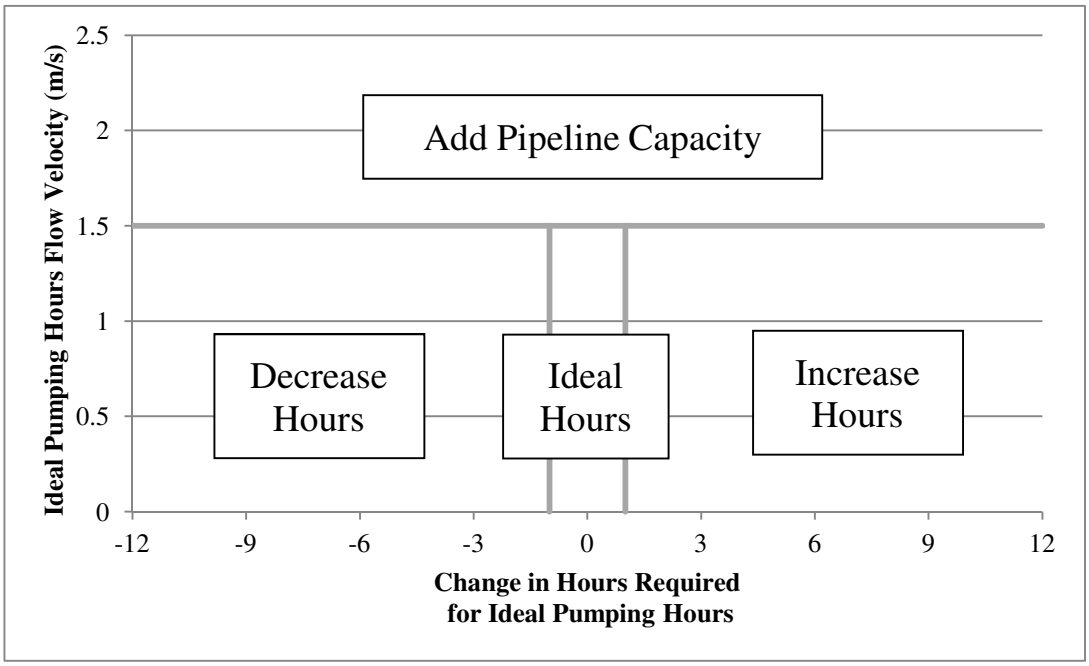

Figure 4.3 - Operational Evaluation

The next step is to investigate external factors that would cause pipelines to operate at cost illogical times, how many hours the pump is operating illogically, and what effect that has on the average electrical price.

With the ideal pumping hours calculated and external factors that would impact those hours identified, improvements to the pumping hours can be investigated as discussed earlier in Section 3-2. The pipelines with the greatest potential cost savings are prioritized.

4.4 Step 4 – Economic Evaluation

The economic analysis calculates the potential energy savings for each potential improvement option applicable to each pipeline. This is done by first calculating operating costs for a baseline condition, the "Do Nothing" option. The NPV of cost savings improvements from each option or combination of options is then predicted by the software model and compared to the baseline to determine the option with the greatest cost savings. Estimates are then generated for the options with the greatest potential savings to determine the total NPV of the improvement.

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4.4.1 Assumptions

Several general assumptions have to be made about the pipeline's operations to determine the baseline operating cost, as well as the improvement savings. These assumptions, shown in Table 4.2, include estimations on demand growth, energy cost escalation, inflation rates, and pipe degradation.

Table 4.2– General Assumption for Pipeline Operations

Assumption	Suggested Range of Values	Notes
Evaluation Period	20-30 Years	Depends on the age of the system, most have a design life of 20-30 years, but often operated for significantly longer
Demand Growth	0-2% per year	Can vary widely
Energy Cost Escalation	6-10% per year	8% increase approved for the next five years
Inflation Rate	4-8%	Available from government or bank outlook reports
Discount Rate	4-6%	Rate selected based on the perceived time value of money
Roughness Growth	0.01-0.4mm per year	Review the original and current roughness to calculate the growth rate specific to the pipeline
Diameter Constriction Growth	0.01-0.4mm per year	Review the original and current diameter to calculate the growth rate specific to the pipeline
Pump Efficiency	60 - 85%	Setting the pump efficiency allows for easier cost comparison, however this should be re-examined where better information is available

Hydraulic Assumptions

The options for hydraulic improvement will decrease friction losses in the pipeline, lowering the power required, therefore, lowering the energy cost. The different options will have different effects on pipelines, depending on the water characteristics, pipeline and liner properties, system age, etc. However, to be used for a theoretical (desktop) comparison, some assumptions must be made to simplify calculations. The assumptions reflected in Table 4.3 are based on the literature reviewed in Section 2.6. These assumptions should be

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modified for specific pipelines where better information is available, however Table 4.3 serves as a basic guideline to be used for desktop evaluations.

Table 4.3 - Hydraulic Improvements and Assumptions

Hydraulic Improvement Option	Estimated Effect on Roughness	Estimated Effect on Roughness Growth Rate	Estimated Effect on Diameter Constrictions	Additional Information
"Do Nothing"	None	None	None	An increased repair cost is expected, however minor compared to energy costs
Foam or Ice Pigging	40% improvement	5% increase#	40% removal	Should be repeated every 5-7 years
Rigid Pigging	60% improvement	5% increase#	80% removal	Should be repeated every 10-15 years
Intensive Cleaning	80% improvement	5% increase#	100% removal	Should be repeated every 15-25 years
Rehabilitation	Improved to roughness of liner	Lowered to 50% of current growth rate*	Original minus liner thickness	Pipe rehabilitation can significantly increase system life
Replacement	Roughness of new pipeline	Lowered to 50% of current growth rate*	Changed to diameter of new pipeline	The replacement pipeline can be designed for minimal losses and for future expansion

* *It is assumed that new pipes and liners will have a lower roughness growth rate as the processes for fabricating pipes and liners have improved.*

\# *It is assumed that after pigging a pipeline without rehabilitation the loss of liner and abrasions to the surface with slightly accelerate corrosion in ferrous pipelines.*

Operational Assumptions

There are far too many operational improvements or combinations of improvements that will depend on highly site specific conditions to generalize for their effects. Instead, eight situations are assumed as described in Table 4.4.

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Table 4.4 - Operating Conditions and Assumptions

Operational Condition	Flow Rate	Pumping Hours	Operational Improvements Required
Continue Current Operation	Constant at current flow rate	Equal to AADD divided by flow rate	None
Use Current pumping hours with cost logical operation	Constant at current flow rate	Equal to AADD divided by flow rate	Supply or demand side reservoirs sized to allow for cost logical operation
20 year average pumping hours fixed to off peak hours only	Predicted Year 10 AADD divided by off peak hours	Varies, 20 year average equal to off peak hours only	Supply or demand side reservoirs and/or pump improvements
20 year average pumping hours fixed to off peak and normal hours only	Predicted Year 10 AADD divided by off peak and normal hours	Varies, 20 year average equal to off peak and normal hours only	Supply or demand side reservoirs and/or pump improvements
Year 20 continuous operation	Predicted Year 20 AADD divided 24	Varies, year 20 equal to 24 hours	Supply or demand side reservoirs and/or pump improvements
Pumping hours fixed to off peak hours only	AADD divided by off peak hours	Equal to off peak hours only	VFD installation and potential Supply or demand side reservoirs
Pumping hours fixed to off peak and normal only	AADD divided by off peak and normal hours	Equal to off peak and normal hours only	VFD installation and potential Supply or demand side reservoirs
Continuous Operation	AADD divided by 24	24 hours	VFD installation and potential Supply or demand side reservoirs

These assumed operating situations will allow for comprehensive analysis to determine the most cost efficient pumping hours. The assumptions will be combined with one of the hydraulic improvements to determine the most cost efficient improvement or combination of improvements for each individual pipeline system.

4.4.2 Economic Calculations

To determine the cost savings from each proposed hydraulic improvement and each operational improvement, as well as combinations, algorithms were built into a Microsoft Excel program. A spread sheet was created to quantify the yearly increases and decreases in AADD, diameter, roughness, electrical costs, etc., as based on the assumptions in Section

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4.4.1. These factors were then used to determine the headlosses and resulting energy requirements for the different operational situations.

4.4.2.1 Data Entry Sections

The economic analysis of PISP System has six sections that require the input of data, the pipeline information, general estimations, electrical tariff, current operation schedule, hydraulic improvement, and operational improvement sections. Screen shots from the entry sections of the PISP software are included in Table 4.5 to Table 4.11.

The first section is general information related to the pipeline itself, as shown in Table 4.5.

Table 4.5 - Pipeline Information Section

Pipeline Specific Information		
	Value	*Units*
Pipeline Name	Example Pipeline	
Age	10	*years*
Water Type	Potable	
Internal Diameter	700	*mm*
Normal Flow Rate	0.715	m^3/s
Velocity	1.62	*m/s*
Length	11 876	*m*
HGL ELV Difference	155	*m*
AADD	46 494.0	m^3
Calculated Lambda	0.0219	
Calculated Roughness	1.083	*mm*

The next section is the General Estimation Section, as shown in Table 4.6. For each variable, an expected range of values is included with the option to enter a value most suited for the pipeline.

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Table 4.6 - General Estimation Sections

General Estimations		
	Range	Selected Value
AADD Growth	0-2% per year	1%
Energy Cost Escalation	6-10% per year	8%
Inflation Rate	4-8% per year	6%
Discount Rate	4-8% per year	6%
Roughness Growth	0.01-0.4 mm per year	0.05
Diameter Reduction Rate	0.5-2 mm per year	0.8
Pump Efficiency	60-85%	75%

However these values will likely not remain constant for the 20 year analysis period. To incorporate the potential differences in year over year changes, an additional table was added for each variable to be used when more detailed information is available. As an example, the Energy Escalation Rate table for year over year changes is shown in Table 4.7.

Table 4.7 - Example Table for Varying Energy Escolation Rates

Energy Escalation Rate	
Year	**Growth**
1	8%
2	8%
3	8%
4	8%
5	8%
6	8%
7	8%
8	8%
9	8%
10	8%
11	7%
12	7%
13	6%
14	6%
15	6%
16	5%
17	5%
18	5%
19	5%
20	5%

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The third section is the electrical tariff section as shown in Table 4.8.

Table 4.8 - Electrical Tariff Section

Summer Electrical Prices (Sep-May) (R/kWh)	
Off Peak	0.258
Normal	0.3706
Peak	0.606
Winter Electrical Prices (Jun-Aug) (R/kWh)	
Off Peak	0.301
Normal	0.5637
Peak	2.1699

The fourth section is the current operational schedule, when the specific operational schedule of the pipeline is entered as shown in Table 4.9. In addition to the current operation schedule, the maximum number of hours for each cost period is entered, allowing for the tool to determine the average electrical price for the current operation and for continuing the current operation into the future.

Table 4.9 - Current Operation Section

Current Operation Schedule		
Weekday Operation Schedule		**Maximum**
Off Peak Hours	3	8
Normal Hours	11	11
Peak Hours	4	5
Saturday Operation Schedule		**Maximum**
Off Peak Hours	11	17
Normal Hours	7	7
Peak Hours	0	0
Sunday Operation Schedule		**Maximum**
Off Peak Hours	18	24
Normal Hours	0	0
Peak Hours	0	0

The fifth section of information needed to be entered into the tool is the hydraulic improvement estimation section as shown in Table 4.10. Values estimated from Section 4.4.1 are included, but can be altered if better information is available.

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The costs of improvement for each item are based on survey that Zhoa et al. (2002) performed in Canada. This is not the best indication of prices in South Africa; however, it can be used as a baseline for comparison until better information is available.

The final section that requires input is the operation improvement section. This section allows for the entry of estimated improvement costs based on the storage volume required and the change in flow rate required for each different operational situation. The operation improvement section is shown in Table 4.11.

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Table 4.10 - Hydraulic Improvement Section

Option	Effect on Ks*	Note	Effect on Ks Growth Rate*	Effect on Diameter*	Note	Cost Function* (R/mm/m)	Est. Cost (in Million Rand)	Repeat every x Years*	Schedule
Foam or Ice Pigging	40%	Reduction	5%	40%	% of restrictions removed[#]	3.00	R 24 939 600	5	5-7 years
Rigid Pigging	60%	Reduction	5%	80%	% of restrictions removed[#]	7.00	R 58 192 400	13	10-15 years
Intensive Cleaning	90%	Reduction	5%	100%	% of restrictions removed[#]	2.00	R 99 758 400	18	15-20
Rehabilitation	0.10	Roughness of liner	-50%	10	liner thickness	10.00	R 83 132 000	25	25+ years
Replacement	0.05	Roughness of new pipeline	-50%	875	Diameter of New pipeline[##]	35.00	R 290 962 000		

Notes: * *Values provided are estimates based on best available information and past experience. These values should be improved anytime that better information is available.*

[#] *Percentage of restrictions removed indicates the estimated percentage of diameter restrictions that would be removed with the selected improvement options.*

[##] *The diameter of the replacement pipeline should be careful calculated utilizing available software. The tool assumes that the diameter of the pipeline will be upsized by 25% for basic analysis; however this should be adjusted for each pipeline.*

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Table 4.11 - Operational Improvement Section

	Pumping Hours Required	Change in Pumping Hours	Storage Volume Needed (m^3)*	Reservoir Cost Function (R/m^3)*	Est. Reservoir Cost (Rand)	Flow Rate Needed (m^3/s)	Change in Flow Needed (m^3/s)*	Pumping Upgrades Cost Function ($R/m^3/s$)	Est. Pumping Improvement Cost (R)	Total Estimated Cost (R)
With Current Operation	**18.1**	**-**		1 250	-	0.715	0.00	5 000 000	-	-
Cost Logical with Current Hours	**18.1**	**-**	-	1 250	-	0.715	0.00	5 000 000	-	-
Cost Logical: 20 year avg. limited to off peak	**11.6**	**3.2**	8 320	1 250	10 400 000	1.218	0.50	5 000 000	2 513 338	12 913 338
Cost Logical: 20 year avg. limited to off peak and Normal	**20.6**	**1.3**	3 270	1 250	-	0.686	0.00	5 000 000	-	-
Year 20 Continuous Operation	**24.0**	**3.0**	7 640	1 250	9 550 000	0.650	0.00	5 000 000	-	9 550 000
Cost Logical: VFD limited to off peak	**11.6**	**3.2**	8 320	1 250	10 400 000	1.345	0.63	5 000 000	3 650 313	14 050 313
Cost Logical: VFD limited to off peak and Normal	**20.6**	**1.3**	3 270	1 250	-	0.757	0.00	5 000 000	500 000	500 000
VFD Limited to Continuous Operation	**24.0**	**3.0**	7 640	1 250	9 550 000	0.650	0.00	5 000 000	500 000	10 050 000

*Notes: * Values provided are estimates based on best available information and past experience. These values should be improved anytime that better information is available.*

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In the operational improvement section, the storage cost is determined from the flow storage required for the change in pumping hours, multiplied by a cost function to determine the estimated reservoir cost. This is a conservative estimate assuming that there is no additional storage available; however it is likely that there is existing storage that can be utilized. Therefore, it is assumed that for storage volumes less than 10% of the AADD, no new storage capacity is required.

The cost of the proposed pumping improvements for the change in flow rate is similarly calculated from a cost function; however it is assumed that flow rates within 10% of the current flow will not require any significant pump improvements.

The information entered in the previous sections now allow for the yearly electrical cost to be calculated under a variety of hydraulic and operational conditions. Additionally, the cost information can then be used to determine the impact of improvements for different options, allowing for a 20 year NPV to be calculated for the electrical and improvement costs.

4.4.2.2 Net Present Value Calculation for Operational Conditions

The first operational condition is to continue to operate the pump as it is currently being operated. This assumes that as the AADD increases the flow rate will remain constant, but the pumping hours will increase to accommodate the increasing AADD. The roughness is assumed to increase, while the diameter is assumed to decrease, causing the energy required to pump the AADD to increase as shown in Table 4.12, a screen shot from the PISP Software.

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Table 4.12 - Example Current Operation Energy Calculations

Year	AADD	Required Daily Pumping Hours	Flow Rate	Diameter	Velocity	Roughness	Lambda	Headloss	Total Head		Daily KWh required
1	46 494	18.06	0.715	693.0	1.896	1.083	0.022	68.1	223.1		37 691
2	46 959	18.24	0.715	692.6	1.898	1.108	0.022	68.7	223.7		38 163
3	47 429	18.43	0.715	692.2	1.900	1.133	0.022	69.2	224.2		38 641
4	47 903	18.61	0.715	691.8	1.902	1.183	0.022	70.2	225.2		39 191
5	48 382	18.80	0.715	691.4	1.904	1.233	0.023	71.1	226.1		39 746
6	48 866	18.98	0.715	691.1	1.906	1.333	0.023	72.7	227.7		40 427
7	49 354	19.17	0.715	690.8	1.908	1.433	0.024	74.2	229.2		41 107
8	49 848	19.37	0.715	690.5	1.909	1.553	0.024	76.0	231.0		41 835
9	50 346	19.56	0.715	690.2	1.911	1.703	0.025	78.1	233.1		42 631
10	50 850	19.76	0.715	690.0	1.912	1.803	0.025	79.4	234.4		43 302
11	51 358	19.95	0.715	689.8	1.913	1.883	0.025	80.4	235.4		43 931
12	51 872	20.15	0.715	689.6	1.914	1.963	0.026	81.5	236.5		44 564
13	52 391	20.35	0.715	689.5	1.915	2.023	0.026	82.2	237.2		45 149
14	52 915	20.56	0.715	689.4	1.916	2.083	0.026	82.9	237.9		45 740
15	53 444	20.76	0.715	689.3	1.916	2.133	0.026	83.5	238.5		46 314
16	53 978	20.97	0.715	689.2	1.917	2.183	0.026	84.1	239.1		46 895
17	54 518	21.18	0.715	689.1	1.917	2.223	0.027	84.6	239.6		47 459
18	55 063	21.39	0.715	689.0	1.918	2.253	0.027	85.0	240.0		48 008
19	55 614	21.61	0.715	688.9	1.918	2.273	0.027	85.2	240.2		48 536
20	56 170	21.82	0.715	688.9	1.918	2.283	0.027	85.3	240.3		49 048

The average electrical cost is then calculated as a weighted value based on the percentage of time spent pumping in each time period, the summer and winter electrical tariffs for each period, and the estimated increase in electrical prices. The calculation of the weekly pumping hours in each time period is shown in Table 4.13, while the calculation of the average electrical cost is shown in Table 4.14.

Table 4.13 - Calculation of Weekly Pumping Hours in Each Time Period

Year	Daily Pumping Hours	Week day Off Peak Hours	Weekday Normal Hours	Weekday Peak Hours	Saturday Off Peak Hours	Saturday Normal Hours	Saturday Peak Hours	Sunday Off Peak Hours	Sunday Normal Hours	Sunday Peak Hours
1	18.1	3.0	11.0	4.0	11.1	7.0	-	18.1	-	-
2	18.2	3.2	11.0	4.1	11.2	7.0	-	18.2	-	-
3	18.4	3.3	11.0	4.1	11.4	7.0	-	18.4	-	-
4	18.6	3.5	11.0	4.1	11.6	7.0	-	18.6	-	-
5	18.8	3.6	11.0	4.2	11.8	7.0	-	18.8	-	-
6	19.0	3.8	11.0	4.2	12.0	7.0	-	19.0	-	-
7	19.2	3.9	11.0	4.3	12.2	7.0	-	19.2	-	-
8	19.4	4.1	11.0	4.3	12.4	7.0	-	19.4	-	-
9	19.6	4.2	11.0	4.3	12.6	7.0	-	19.6	-	-
10	19.8	4.4	11.0	4.4	12.8	7.0	-	19.8	-	-
11	20.0	4.5	11.0	4.4	13.0	7.0	-	20.0	-	-
12	20.2	4.7	11.0	4.5	13.2	7.0	-	20.2	-	-
13	20.4	4.8	11.0	4.5	13.4	7.0	-	20.4	-	-
14	20.6	5.0	11.0	4.6	13.6	7.0	-	20.6	-	-
15	20.8	5.1	11.0	4.6	13.8	7.0	-	20.8	-	-
16	21.0	5.3	11.0	4.7	14.0	7.0	-	21.0	-	-
17	21.2	5.5	11.0	4.7	14.2	7.0	-	21.2	-	-
18	21.4	5.6	11.0	4.8	14.4	7.0	-	21.4	-	-
19	21.6	5.8	11.0	4.8	14.6	7.0	-	21.6	-	-
20	21.8	6.0	11.0	4.8	14.8	7.0	-	21.8	-	-

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Table 4.14 - Calculation of Yearly Average Electrical Price

Year	Weekly Off Peak	Weekly Normal	Weekly Peak	Off Peak	Normal	Peak	Off Peak	Normal	Peak	Average Electrical Price
1	44.4	62.0	20.1	0.258	0.371	0.606	0.301	0.564	2.170	0.458
2	45.4	62.0	20.3	0.279	0.400	0.654	0.325	0.609	2.343	0.494
3	46.5	62.0	20.5	0.301	0.432	0.707	0.351	0.657	2.531	0.532
4	47.6	62.0	20.7	0.325	0.467	0.763	0.379	0.710	2.733	0.574
5	48.7	62.0	20.9	0.351	0.504	0.824	0.410	0.767	2.952	0.619
6	49.8	62.0	21.1	0.379	0.545	0.890	0.442	0.828	3.188	0.667
7	50.9	62.0	21.3	0.425	0.610	0.997	0.495	0.928	3.571	0.746
8	52.0	62.0	21.5	0.476	0.683	1.117	0.555	1.039	3.999	0.834
9	53.2	62.0	21.7	0.533	0.765	1.251	0.621	1.164	4.479	0.933
10	54.3	62.0	22.0	0.597	0.857	1.401	0.696	1.303	5.017	1.044
11	55.5	62.0	22.2	0.668	0.960	1.569	0.779	1.460	5.619	1.167
12	56.7	62.0	22.4	0.735	1.056	1.726	0.857	1.606	6.181	1.282
13	57.9	62.0	22.6	0.808	1.161	1.899	0.943	1.766	6.799	1.408
14	59.1	62.0	22.8	0.889	1.277	2.089	1.037	1.943	7.479	1.547
15	60.3	62.0	23.1	0.978	1.405	2.297	1.141	2.137	8.227	1.699
16	61.5	62.0	23.3	1.076	1.546	2.527	1.255	2.351	9.049	1.866
17	62.7	62.0	23.5	1.162	1.669	2.729	1.356	2.539	9.773	2.013
18	64.0	62.0	23.8	1.243	1.786	2.920	1.451	2.717	10.457	2.151
19	65.2	62.0	24.0	1.318	1.893	3.096	1.538	2.880	11.085	2.277
20	66.5	62.0	24.2	1.384	1.988	3.250	1.615	3.024	11.639	2.387

With the daily kWh needs determined, and the average electric price calculated, the yearly operating cost can be determined for each year as shown in Table 4.15.

Table 4.15 - Yearly Electrical Cost for Continuing Current Operation

	Under Current Operation	
Year	Average Electrical Price	Yearly Electrical Cost
1	0.458	R 6 296 787
2	0.494	R 6 874 813
3	0.532	R 7 505 844
4	0.574	R 8 208 894
5	0.619	R 8 977 127
6	0.667	R 9 846 291
7	0.746	R 11 196 249
8	0.834	R 12 742 574
9	0.933	R 14 521 416
10	1.044	R 16 495 231
11	1.167	R 18 715 331
12	1.282	R 20 853 031
13	1.408	R 23 205 987
14	1.547	R 25 823 325
15	1.699	R 28 721 442
16	1.866	R 31 944 086
17	2.013	R 34 865 940
18	2.151	R 37 685 582
19	2.277	R 40 330 584
20	2.387	R 42 735 466
	NPV Electrical Cost	**R 191 648 497**

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Also shown in Table 4.15 is the NPV of the electrical costs. The NPV is calculated utilizing the discount rate entered in the general estimations section of the tool. The NPV then can be used to compare different hydraulic and operational improvements to determine which option will provide the greatest cost savings – the option with lowest NPV.

The process is repeated for the other seven operational situations. In each situation, the power required, pumping hours and average electrical price are calculated to determine the yearly electrical cost, and the 20 year NPV of the electrical costs for each improvement option. An example calculation for the operational situation of using a VFD and reservoirs to limit operation to only off peak and normal hours is shown in Table 4.16.

Table 4.16 - Example NPV Calculation for Operational Improvements

	Cost logical: 20 Year Avg Limited to Off Peak and Normal Only									
Year	Pumping Hours	Flow Rate	Velocity	Head Loss	Total Head	Daily KWh required	Avg Electrical Cost	Yearly Electrical Cost	Cost of Improvements	Total Cost
1	18.8	0.686	1.818	62.6	217.6	36 766	0.327	R 4 390 268	-	4 390 268
2	19.0	0.686	1.820	63.2	218.2	37 222	0.358	R 4 867 429	-	4 867 429
3	19.2	0.686	1.822	63.7	218.7	37 682	0.387	R 5 321 850	-	5 321 850
4	19.4	0.686	1.824	64.5	219.5	38 210	0.418	R 5 828 066	-	5 828 066
5	19.6	0.686	1.826	65.4	220.4	38 742	0.451	R 6 381 911	-	6 381 911
6	19.8	0.686	1.828	66.9	221.9	39 390	0.487	R 7 007 814	-	7 007 814
7	20.0	0.686	1.829	68.3	223.3	40 038	0.546	R 7 977 781	-	7 977 781
8	20.2	0.686	1.831	69.9	224.9	40 729	0.649	R 9 654 891	-	9 654 891
9	20.4	0.686	1.833	71.8	226.8	41 484	0.727	R 11 013 826	-	11 013 826
10	20.6	0.686	1.834	73.0	228.0	42 124	0.815	R 12 525 634	-	12 525 634
11	20.8	0.686	1.835	74.0	229.0	42 725	0.912	R 14 228 996	-	14 228 996
12	21.0	0.686	1.836	74.9	229.9	43 330	1.087	R 17 191 501	-	17 191 501
13	21.2	0.686	1.836	75.6	230.6	43 892	1.196	R 19 155 884	-	19 155 884
14	21.4	0.686	1.837	76.3	231.3	44 459	1.315	R 21 343 617	-	21 343 617
15	21.7	0.686	1.837	76.8	231.8	45 012	1.447	R 23 769 645	-	23 769 645
16	21.9	0.686	1.838	77.4	232.4	45 569	1.591	R 26 470 564	-	26 470 564
17	22.1	0.686	1.839	77.8	232.8	46 113	1.839	R 30 953 880	-	30 953 880
18	22.3	0.686	1.839	78.1	233.1	46 642	1.968	R 33 500 945	-	33 500 945
19	22.5	0.686	1.839	78.4	233.4	47 153	2.086	R 35 899 819	-	35 899 819
20	22.8	0.686	1.840	78.5	233.5	47 649	2.190	R 38 091 436	-	38 091 436
							LCC Electrical Cost	**R 153 917 601**	**LCC Total Cos**	**153 917 601**

The process is then repeated for all of the hydraulic improvements to determine the NPV of electrical costs for the four hydraulic scenarios and eight operational scenarios, as well as combinations. The calculated NPVs for all the combination of options are then compared to determine which will result in the greatest cost savings as shown in Figure 4.4.

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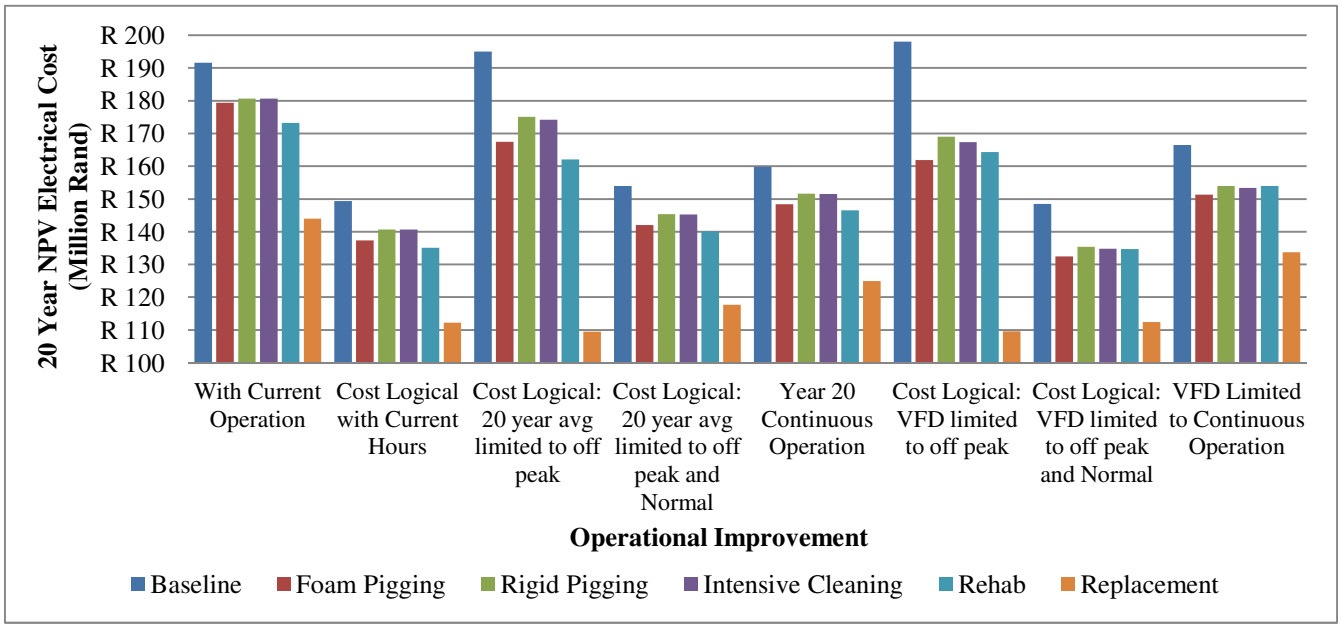

Figure 4.4 – Example Summary Chart of 20 Year NPV of Electrical Cost

The cost of improvements can then be added to the cost of electricity to determine the overall cost of operation. For simplicity, it is assumed that the operational improvements will be paid for in year one, while the hydraulic improvements will be paid for in the year in which they occur.

By including the costs of the improvements for the NPV of each option, a graph similar to Figure 4.4 can be created, which shows the 20 year NPV of total costs for each option as shown in Figure 4.5.

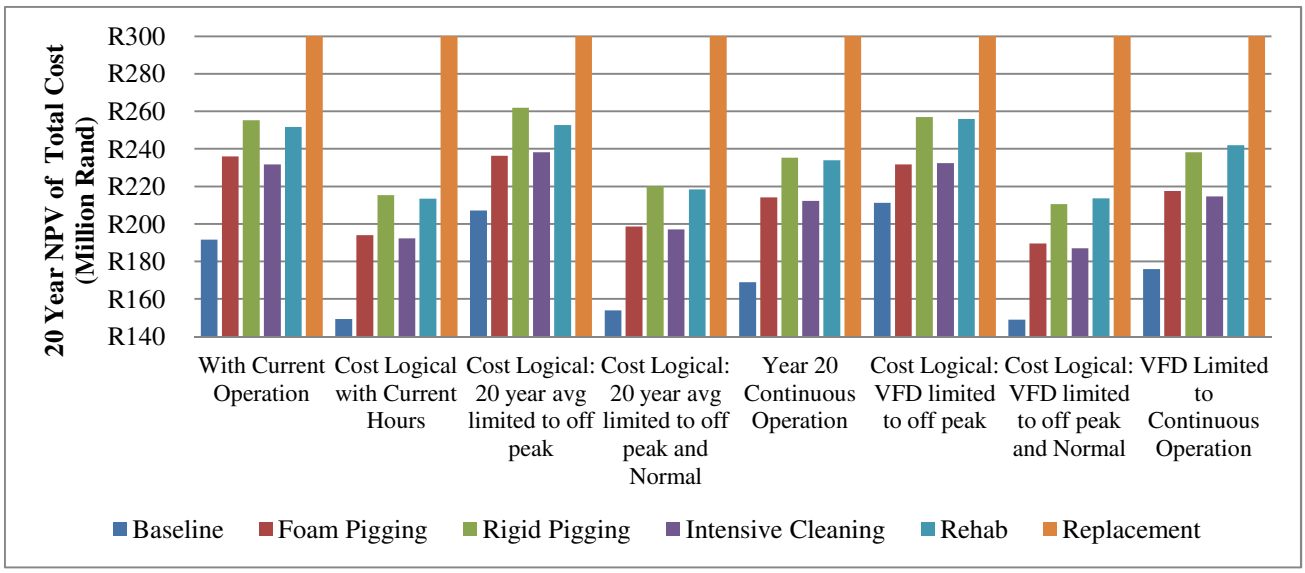

Figure 4.5 - Example 20 Year NPV of Total Costs

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While the total NPV of operation is appropriate to reference when investigating a single pipeline, the cost savings is the most appropriate measure to use as a basis for prioritization. The 20 Year NPV cost savings can be determined for each option as shown in Table 4.17.

Table 4.17 - Example 20 Year NPV Cost Savings for Each Option

20 Year NPV Cost Savings (Million Rand)						
	Hydraulic Improvement					
Operation Improvement	Baseline	Foam Pigging	Rigid Pigging	Intensive Cleaning	Rehab	Replacement
With Current Operation	R 0.0	R -44.3	R -63.7	R -40.1	R -60.0	R -219.1
Cost Logical with Current Hours	R 42.2	R -2.3	R -23.7	R -0.6	R -21.9	R -187.3
Cost Logical: 20 year avg limited to off peak	R -15.5	R -44.6	R -70.3	R -46.5	R -61.0	R -196.8
Cost Logical: 20 year avg limited to off peak and Normal	R 37.7	R -7.0	R -28.4	R -5.4	R -26.8	R -192.7
Year 20 Continuous Operation	R 22.8	R -22.4	R -43.7	R -20.6	R -42.3	R -209.0
Cost Logical: VFD limited to off peak	R -19.6	R -40.1	R -65.3	R -40.8	R -64.4	R -197.9
Cost Logical: VFD limited to off peak and Normal	R 42.7	R 2.0	R -18.9	R 4.6	R -22.0	R -188.0
VFD Limited to Continuous Operation	R 15.7	R -25.9	R -46.5	R -23.0	R -50.2	R -218.3

Note: Where cost savings was not achieved, the increased cost is displayed as a negative cost savings

This process should be repeated for each pipeline identified in the preliminary investigation. The maximum cost savings can then be used to prioritize which pipelines should be improved, as the pipeline improvements with higher cost savings should be examined further.

4.5 Step 5 - Field Verification

With a desktop study completed, it will be necessary to field test the assumptions made in the desktop evaluation. The verification should be performed on the pipelines that are ranked highest priority to determine a more accurate cost of operating the pipeline, verifying or correcting the assumptions made in the desktop evaluation. The field testing will involve elevation surveys, measuring the flow rate and pressure drop to verify the friction slope, and long term flow measurement to verify the AADD, pumping hours and restrictions to the pumping hours.

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4.5.1 Hydraulic Condition Assessment

The purpose of the hydraulic condition assessment is to determine the internal hydraulic characteristics of the pipeline. The procedure to evaluate the hydraulic capacity of pipelines is to establish a flow rate - pressure drop relationship, derived from pressure and flow rate. The flow rate - pressure drop relationship can be used to back calculate the internal roughness of the pipeline. A section of the pipeline, with no off-takes (or off-takes that can be closed) should be selected for the assessment.

4.5.1.1 Pressure Recording

On each of the pipelines at least three positions should be identified where pressure data could be recorded. A minimum of three pressure recordings are required to ensure that the recorded information can be verified with a constant sloped hydraulic gradient. At the pressure recording positions the appropriate pressure transducers and data acquisition systems (loggers) are installed to record the pressure data.

These locations should be surveyed either by means of a dumpy level or GPS system to obtain an accurate elevation of the pressure recording positions to estimate the hydraulic gradient of the system. In restricted cases the elevations can be obtained from the as-built drawings for an estimation of the absolute roughness of the systems.

Low frequency recordings of the pressures are sufficient to establish the pressure loss between two measuring positions along the pipeline, as long as the flow rate is kept constant during the time of the recording. The pressure recordings would be similar to that shown in Figure 4.6. From these recordings, it is possible to determine the changes to the pipeline operation that occurred during the recording period.

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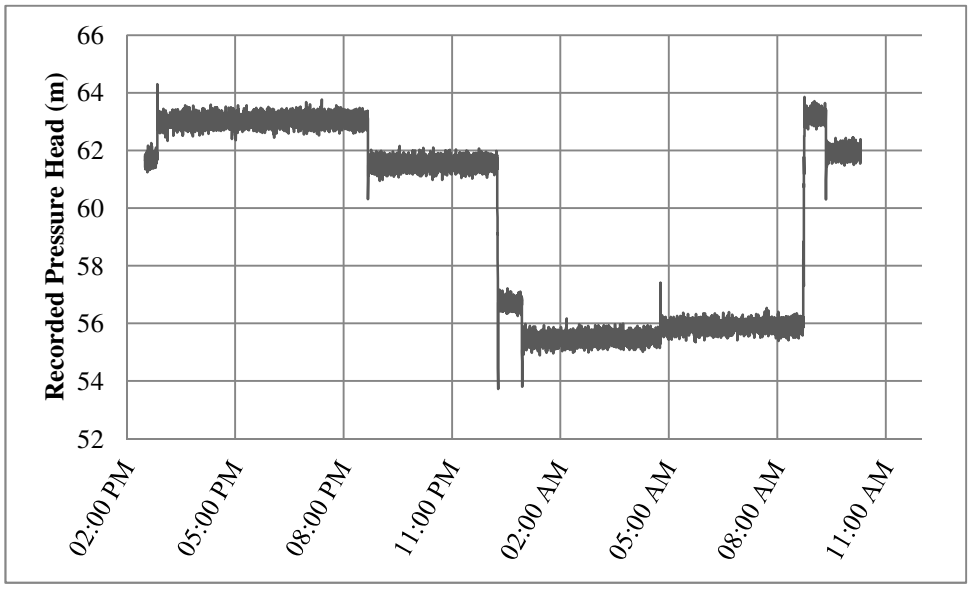

Figure 4.6- Example of Pressure Recordings

The recorded data are captured and used to determine the pressures at the pressure gauging position for the different flow rates during the testing period. This allows for the calculation of the average gauged pressures, the hydraulic grade line, and the energy slope between the recorded positions.

4.5.1.2 Flow Measurement

A critical component of the hydraulic assessment is the accurate measurement of the flow rate. From the pressure recordings, the absolute roughness can be calculated based on the recorded flows and the inclusion of secondary loss components in the system. This roughness is used to determine the decrease in hydraulic capacity,

4.5.1.3 Quantification of Secondary Pressure Losses

Where it is possible, different flow rates should be introduced during the recording of the pressures and flow by operating different pump sets, by the partial closure of the pump control valves, or by the setting of the operational valves in the system. Different flow rates make it possible to determine the influence of other secondary pressure loss factors between the measuring points.

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4.5.1.4 Internal Inspection

Additionally, where possible, an internal inspection of the pipeline should be performed. The internal investigations serve to inspect for the presence of significant biofilm, diameter restrictions, and general internal condition.

Raw water pipelines should undergo internal investigations to determine the presence of biofilm. As discussed in Section 2.4, biofilm can affect the hydraulic operation of a pipeline significantly. An internal investigation for biofilm should record the biofilm thickness, the removal of a sample for chemical analysis, and, if possible, an investigation into the rate in which biofilm will return after cleaning.

Steel pipelines should be investigated for the presence of corrosion. As discussed in Section 2.3.3, corrosion can significantly weaken the structural strength of the pipeline, as well as drastically increase the internal roughness, and through tuberculation, reduce the cross sectional area. An internal investigation for corrosion should record the presence of internal or external corrosion, the presence of tuberculation, and an estimate on reduction of cross sectional area.

4.5.1.5 Status Quo – General Inspection

Every pipeline is different; they operate under different controls with different diameters and with different restrictions. A general assessment of the pipeline to determine the operating philosophy, known problems, restrictions, leakages, pressure losses, etc., should be performed. Often significant losses result from unnecessary pipeline components that have long since out-served their purpose. The following items are typical situations where losses can occur.

- Flow controls
- Throttling valves
- Strainers
- In-line flow meters
- Off-takes
- Partially closed valves
- Entrapped air in pipelines

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These losses can be found through an examination of the as built drawings and a thorough examination of the recorded pressures. The presence of flow losses can be found through the installation of a flow meter at the start and end of the pipeline. This general investigation is highly site specific and will rely on engineering judgement to examine pipeline components, off takes, pressures losses, etc., to determine what, if any, improvements can be made.

4.5.1.6 Summary of Data Required from the Hydraulic Condition Assessment

The summary of the data that are required to be verified in the hydraulic condition assessment is shown in Table 4.18.

Table 4.18 - Data Required from the Hydraulic Condition Assessment

Variable	Measurement	Unit
Length		m
Elevation difference between Hydraulic Grade Lines		m
Diameter		m
Friction Factor		
Roughness Growth Rate		mm/year
Unnecessary Pressure Losses		m
Flow Losses		m^3/s
Additional Information		

4.5.2 Operational Assessment

The purpose of the operational assessment is to investigate the current operation of the pipeline system. The theoretical (desktop) evaluation is meant to perform simple model calculations based on easily accessible data; however, this data may be inaccurate or misleading. The field verification serves to evaluate the specific circumstances of each pumped pipeline system to more accurately predict the cost of operation.

The first step to evaluate the operation of the specific pump station is to gather flow data to verify the DTV and operating flow rates. In ideal situations, the pumped pipeline system is operated through SCADA software, allowing for limitless possibilities of data acquisition. However, these data are not always recorded or available, so alternate options are needed.

The operational schedule can be recorded through the installation of a pressure transducer or flow meter as described in the previous section. This sensor should be installed for a

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minimum of one week, ideally longer. The longer the meter is installed, the more data are available for analysis, resulting in a better estimation of the current cost schedule.

The current operational schedule can be plotted to determine the current pumping hours. An example of the operation of a pumped pipeline, consisting of three pumps, is shown in Figure 4.7. In this figure, the first pump operates continuously at a governed flow of 0.3 m^3/sec, and this is augmented at various times by the second pump, which increases the total flow to 0.70 m^3/sec. The third pump serves as a standby pump.

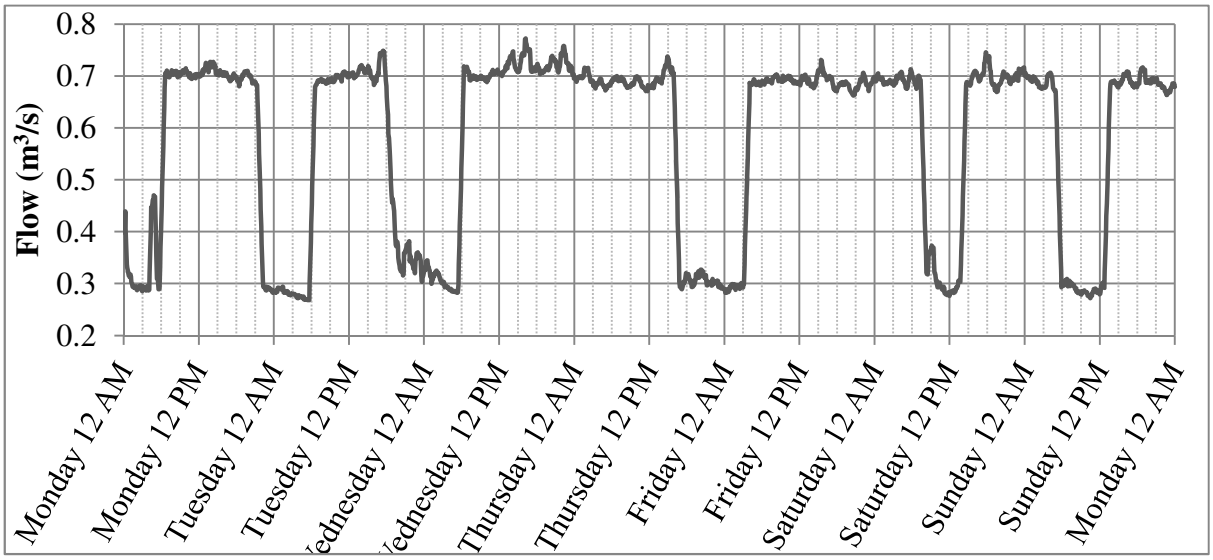

Figure 4.7 - Example Pumping Operation

The total of number of operating hours for the pumps was calculated to be 285, more than the 168 total hours in a week. The extra 117 hours were due to the operation of the two pumps running simultaneously. The breakdown of total pumping hours can be then calculated, and is shown in Table 4.19 below.

Table 4.19- Example Electrical Tariff Calculation

Time Period	Weekly Hours	Summer Cost (R/kWh)	Winter Cost (R/kWh)	Average Electrical Cost (R/kWh)
Off Peak	132	0.25	0.343	0.273
Normal	92.1	0.38	0.56	0.424
Peak	60.8	0.60	2.16	0.988
Average Electrical Cost			0.475	**R/kWh**

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Additionally included in Table 4.19 is the cost of electricity. With the cost of electricity for each period, the average electrical price can be calculated, to accurately determine the current cost of operation.

With the pumping hours, average cost of electricity, flow rates, and AADD verified, the operating restrictions to potential improvements should be explored. This should include evaluating each of the hydraulic and operational improvements to determine what costs would be required for their implementation. A main obstacle for making these hydraulic improvements should be to establish the time restrictions for taking the pipeline out of service, while the main restriction for operational improvements would be to determine what, if any additional storage capacity is available, and how much additional storage would be required for each improvement option.

4.5.2.1 Summary of Data Required from the Operational Assessment

Table 4.20 summarizes the data required to be verified in the operational assessment.

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Table 4.20 – Operational Field Verification Data Required

Variable	Estimated Value (from Desktop Evaluation)	Verified Value	Units	Notes
AADD			m^3	
Number of Operating Pumps			Number	
Pump Efficiency			Percentage	
Daily Pumping Hours			Hours	
Weekly Off Peak			Hours	
Weekly Normal			Hours	
Weekly Peak			Hours	
Average Price			R/kWh	
Operating Flow Rates			m^3/s	
			m^3/s	
Excess Upstream Storage			m^3	
Excess Downstream Storage			m^3	
Minimum Flow Requirement			m^3/s	
Flow Control				
Additional Information				

The verified data from the hydraulic condition and operational assessment can then be used to complete Step 6 which is the economic verification.

4.6 Step 6 - Economic Evaluation Verification

After the hydraulic and operational evaluations have been performed, the results can then be incorporated in the economic evaluation. The hydraulic evaluation provides details on the current capacity of the pipeline, allowing for a more accurate calculation of the friction losses throughout the pipeline system. The operational evaluation verifies the current pumping schedule, the AADD, as well as the average electrical price. The information from these two

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evaluations can be used to more accurately calculate the current cost of operation, as well as the projected baseline for which operational improvements can be compared.

With the information gained from the operational analysis, an additional operational improvement can be quantified. This would utilize the basics of pump scheduling to determine the ideal pump operation given the current operational restrictions. For example, the pipeline in Figure 4.77 has the restriction that one pump always has to be operating, and the second pump can cycle as needed. The flow schedule then can be compared to cost logical operation as shown by the dotted line in Figure 4.8.

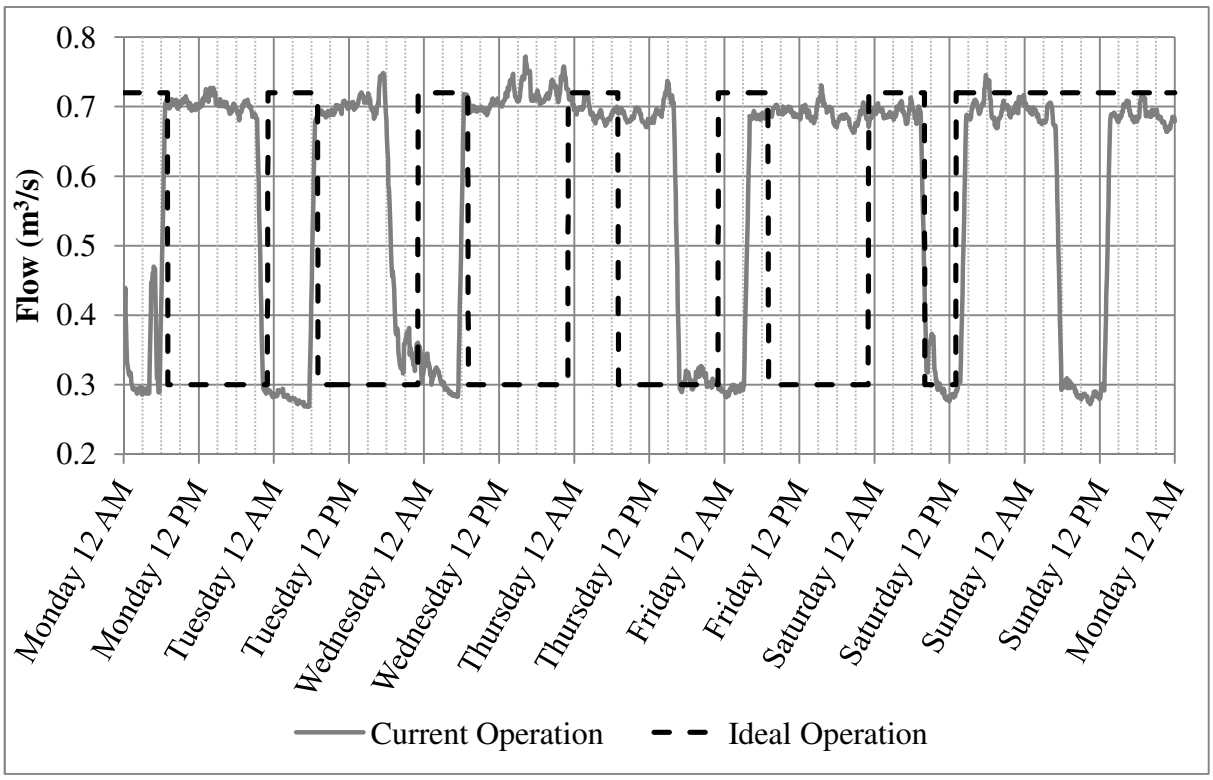

Figure 4.8 – Example Current and Ideal System Operation

The calculation of the breakdown of pumping hours for the ideal operation is shown in Table 4.21.

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Table 4.21 - Average Electrical Cost Calculations Utilizing Pump Scheduling

Time Period	Weekly Hours	Summer Cost (R/kWh)	Winter Cost (R/kWh)	Yearly Average Electrical Cost (R/kWh)
Off Peak	162	0.25	0.34	0.27
Normal	80	0.38	0.56	0.42
Peak	25	0.60	2.16	0.99
Average Electrical Cost			**0.389**	**R/kWh**

In this example, the yearly average electrical cost of the system is decreased from 0.475 R/kWh (as shown in Table 4.19) for the current operation to 0.389 R/kWh, an 18% reduction, by utilizing the basics of pump scheduling.

4.6.1 Economic Calculations

To determine the cost savings from each hydraulic improvement, and each operational improvement, as well as combinations, a Microsoft Excel model was utilized. A spread sheet was created to quantify the yearly increases and decreases in AADD, diameter, roughness, and electrical costs. These factors are then used to determine the headlosses and resulting energy requirements for the different operational situations.

The economic verification tool has five sections that require the input of data: the pipeline information, general estimations, electrical tariff, hydraulic improvement, and operational improvements. Each section is similar to the data entry sections of the economic evaluation described in Section 4.4.2.1. However, the information and insight gained about the operation of the pipelines allows for several of the assumed values to be adjusted.

The information entered in the economic verification now allows for the yearly electrical cost to be calculated under a variety of hydraulic and operational conditions. Additionally, the cost information can then be used to determine the cost of improvements for different options, allowing for a 20 year NPV to be calculated for the electrical and improvement costs.

The 20 year NPV of the different hydraulic and improvement options is calculated as shown in Section 4.4.2.2 with the exception of the current operational and the pump scheduling alternatives. The current operational alternative is based off the average electrical tariff as verified in the operational assessment, with the tariff being inflated yearly based on the

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information contained in the energy escalation section. The pumping-scheduling alternative included in the system times the operation of the pumps to provide the minimum flow rate required, and then schedules the pumps to operate first in the off peak periods, and if more hours are need, then in the normal periods, and then in the peak periods.

An example of the 20 year NPV of cost savings is shown in Table 4.22.

Table 4.22 - 20-Year NPV of Cost Savings

20 Year NPV Cost Savings (Million Rand)						
	Hydraulic Improvement					
Operation Improvement	Baseline	Foam Pigging	Rigid Pigging	Intensive Cleaning	Rehab	Replacement
With Current Operation	R 0.0	R -44.3	R -63.7	R -40.1	R -60.0	R -219.1
Cost Logical with Current Hours	R 42.2	R -2.3	R -23.7	R -0.6	R -21.9	R -187.3
Cost Logical: 20 year avg limited to off peak	R -15.5	R -44.6	R -70.3	R -46.5	R -61.0	R -196.8
Cost Logical: 20 year avg limited to off peak and Normal	R 37.7	R -7.0	R -28.4	R -5.4	R -26.8	R -192.7
Year 20 Continuous Operation	R 22.8	R -22.4	R -43.7	R -20.6	R -42.3	R -209.0
Cost Logical: VFD limited to off peak	R -19.6	R -40.1	R -65.3	R -40.8	R -64.4	R -197.9
Cost Logical: VFD limited to off peak and Normal	R 42.7	R 2.0	R -18.9	R 4.6	R -22.0	R -188.0
VFD Limited to Continuous Operation	R 15.7	R -25.9	R -46.5	R -23.0	R -50.2	R -218.3

Note: Where cost savings was not achieved, the increased cost is displayed as a negative cost savings

4.7 Summary of Pipeline Improvement Selection and Prioritization System

The PISP System discussed in the previous sections outlines the process in which a group of pumped pipelines can be evaluated and potential changes to the pipeline or operation can be theoretically evaluated and prioritized for improvement in performance and cost. The first four steps are relatively simple processes to identify problem pipelines, and these can be accomplished without significant time or money being spent on field work and testing. These steps prioritize the worst pipelines to be examined further, limiting the time and cost of field work. The field verification step reviews the assumptions presented in the first steps, confirming or improving these assumptions. The final step reviews the economics of improvements for the verified pipelines. This step allows for a more accurate estimate of the cost of operations, and the potential savings from improvements.

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4.7.1 Software

To assist in the process of prioritizing pipeline improvements, three different Excel based workbooks were developed, several sections of which are described in the previous sections. A flow diagram illustrating were the workbooks fit into the PISP system

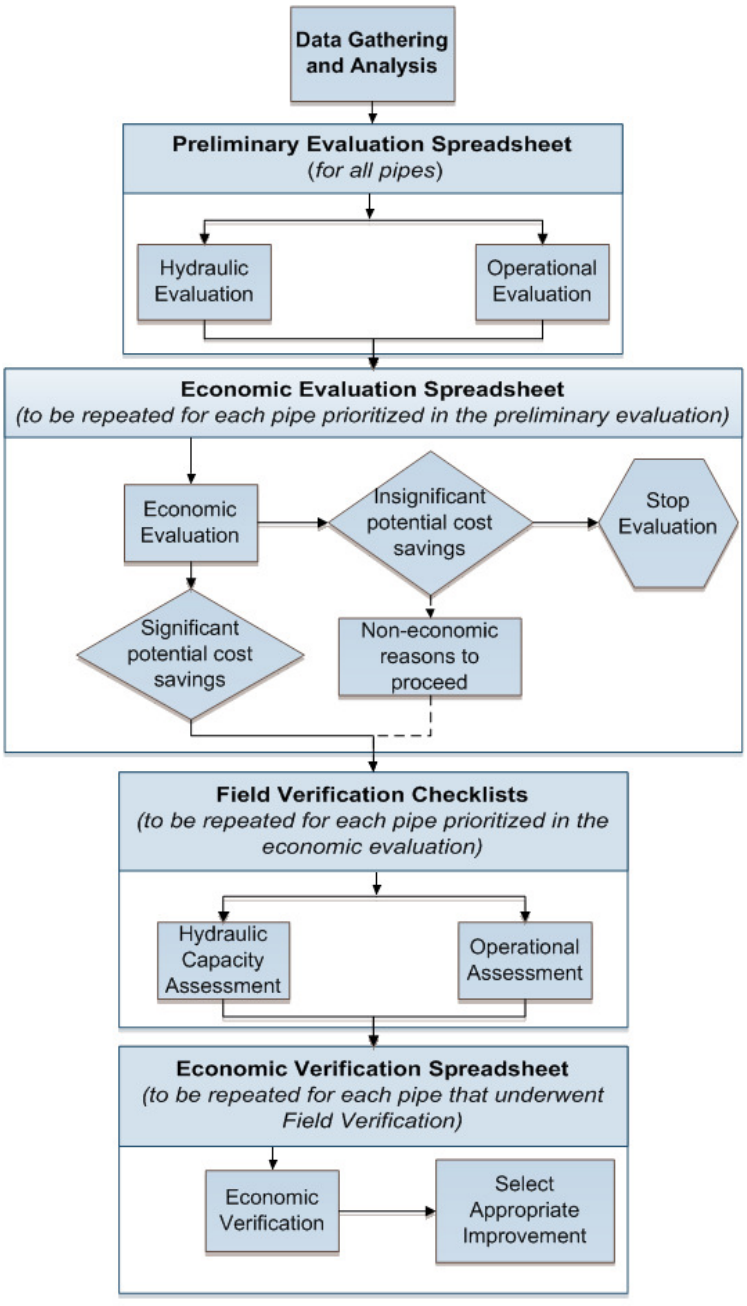

Figure 4.9 - Workbooks of the PISP System

The first workbook, the Preliminary Evaluation, includes the second and third steps, allowing the information for all the pipelines reviewed to be entered, and the prioritized pipelines returned.

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The second workbook includes the Economic Evaluation. This workbook allows for the specifics of a pipeline to be entered and a 20 year simulation to be run. The simulation returns the cost savings for a combination of each of the five hydraulic and seven operational improvement options. This workbook should be applied at least to the pipelines prioritized in the desktop evaluation, but ideally applied to all the pipelines to be reviewed.

Field verification should then be performed on the pipelines with the highest potential cost savings, utilizing the provided checklists, with the additional information put into the Economic Verification.

The Economic Verification workbook should be applied to all of the pipelines that underwent field verification to determine the pipeline improvement option with the greatest potential cost savings. This pipeline system should then be thoroughly evaluated for the recommended improvements.

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5 Tshwane Bulk Water System – Case Study

The city of Tshwane operates hundreds of kilometres of bulk water pipelines, including over 50 pump stations, to bring millions of cubic meters every day to serve 3.5 million people through thousands of kilometres of distribution lines. Of this large water supply network, 9 pumped pipeline systems were selected for evaluation. The pipelines examined were all over 1 km long, over 250 mm in diameter and have pump, flow, and head loss information available. In addition, pipelines were only selected if they were easily accessible and had no splits or off takes en-route to allow for ease of testing.

The data on these pipelines were gathered using the City of Tshwane's Infrastructure Management Query Station (IMQS) software. The information in the IMQS software is based on the underlying hydraulic model created in Water Distribution and System Optimization (WADISO). The pipelines are summarized in Table 5.1.

As electrical information was difficult to determine for each pump station, Eskom's Megaflex Local Authority Rates 2012-2013, as summarized in Section 2.5.3, were assumed to apply. This may not be accurate, as the power for some locations are provided from a grid operated by the City of Tshwane, where others are located at a distance where the price may be increased. The assumption that they all operate on the basic Megaflex provides a baseline for comparison and should be adjusted as additional information is gained about the pipelines.

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Table 5.1 - Tshwane Pipelines for Analysis

#	IMQS Pump Station Name	D (mm)	Material	Q (l/s)	V (m/s)	S_f (m/km)	Length (km)	H_S (m)	H (m)	AADD (m^3/day)	Estimated Pumping Hours	λ	k_S (mm)	"C" Value
1	**Bronkhorstspruit WTP to Res PS 1**	700	DI-10	625	1.6	4.2	3,010	151	164	50,304	22.5	0.0203	0.78	110
2	**Elandsfontein PS to Ekanduatria Res**	508	ST-4.5	425	2.1	8.2	18,802	64	218	36,456	24	0.0204	0.58	105
3	**Klipdrift WTP to Babelegi Res PS**	450	AC	160	1.1	3.5	1,294	28	33	6,117	11	0.0230	0.72	99
4	**Rietvlei to Garsfontein PS**	450	ST	240	1.5	6.1	7,427	90	135	13,759	16	0.0215	0.60	110
5	**Rietvlei to Klapperkop PS**	700	ST-B	300	0.8	1.0	12,604	64	77	24,940	23	0.0193	0.68	114
6	**Roodeplaat Raw Water PS**	800	ST	1101	2.2	6.1	3,097	41	59	50,391	13	0.0178	0.65	111
7	**Roodeplaat to Montana PS**	750	ST	500	1.1	2.0	11,876	255	279	43,822	24	0.0219	1.05	109
8	**Roodeplaat to Wallmannsthal PS**	361	GRP	118	1.2	5.7	4,277	41	65	379	1	0.0252	0.77	101
9	**Wilge River PS**	600	Unknown	185	0.7	0.9	36,764	99	132	7,982	12	0.0194	0.59	112

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The PISP software was used to analyse these pipelines and determine if and where significant cost savings can be achieved.

5.1 Preliminary Evaluation

The desktop evaluation followed the steps outlined in Sections 4.2 to 4.3 utilizing the PISP software.

5.1.1 Hydraulic Evaluation

The hydraulic evaluation was performed to rank the pipelines, hydraulically, in order of which should be investigated for improvements first. The results of the hydraulic evaluation are shown in Table 5.2 and displayed graphically in Figure 5.1.

Table 5.2 - Tshwane Hydraulic Evaluation

Ref Number	Pipeline Name	Relative Roughness (mm/m)	Velocity Squared (m^2/s^2)	Prioritization Value	Rank
1	Bronkhorstspruit WTP to Res PS 1	1.121	2.56	2.87	5
2	Elandsfontein PS to Ekanduatria Res	1.134	3.61	4.09	1
3	Klipdrift WTP to Babelegi Res PS	1.603	1.21	1.94	6
4	Rietvlei to Garsfontein PS	1.325	2.25	2.98	4
5	Rietvlei to Klapperkop PS	0.969	0.64	0.62	8
6	Roodeplaat Raw Water PS	0.807	4.84	3.91	2
7	Roodeplaat to Montana PS	1.394	1.21	1.69	7
8	Roodeplaat to Wallmannsthal PS	2.144	1.44	3.09	3
9	Wilge River PS	0.980	0.49	0.48	9

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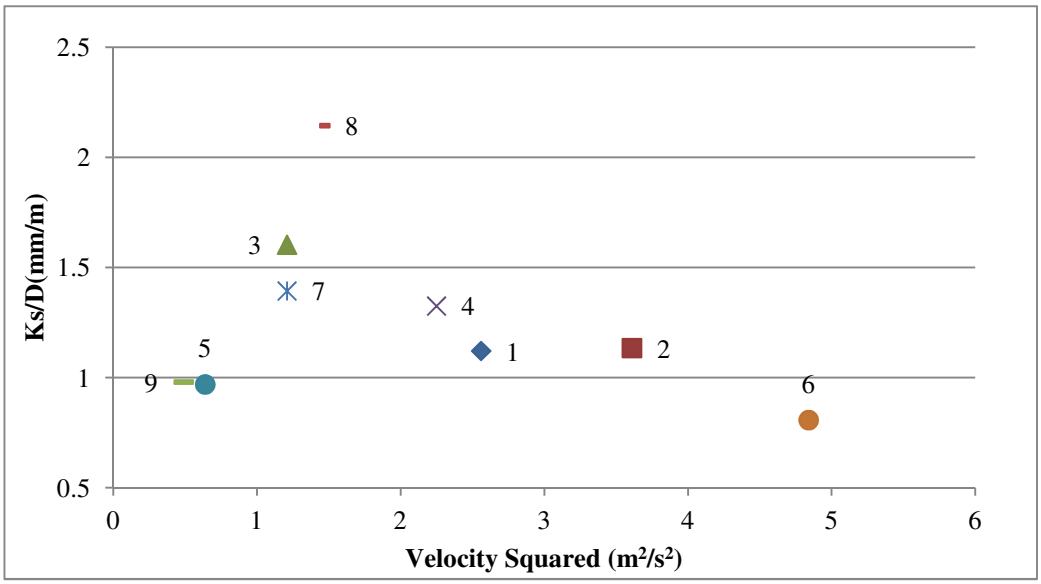

Figure 5.1 - Tshwane Hydraulic Evaluation

Hydraulically, the three worst pipelines are the Elandsfontein PS to Ekanduatria Res (#2), the Roodeplaat Raw Water PS (#6), and the Roodeplaat to Wallmannsthal PS (#8) lines.

5.1.2 Operational Evaluation

The operational evaluation was performed to determine the ideal operating hours, the change in pumping hours required to reach the ideal operating hours, and the potential cost savings of those changes.

The ideal pumping hours were determined for each of the pipelines by determining the power requirements and average electrical cost for average daily pumping hours. This theoretical calculation is based on fixing the daily volume of water to be transferred, and assuming that the pump can operate at any flow rate to alter the pumping hours ranging from 1 to 24. The power requirements and average electrical cost was then used to predict the daily energy cost for the range of pumping hours as shown graphically in Figure 5.2 below. The costs decrease as the flow velocity decreases (lowering the friction losses), but then start to rise again as the increased average electrical price offsets the gains made from lower friction loses.

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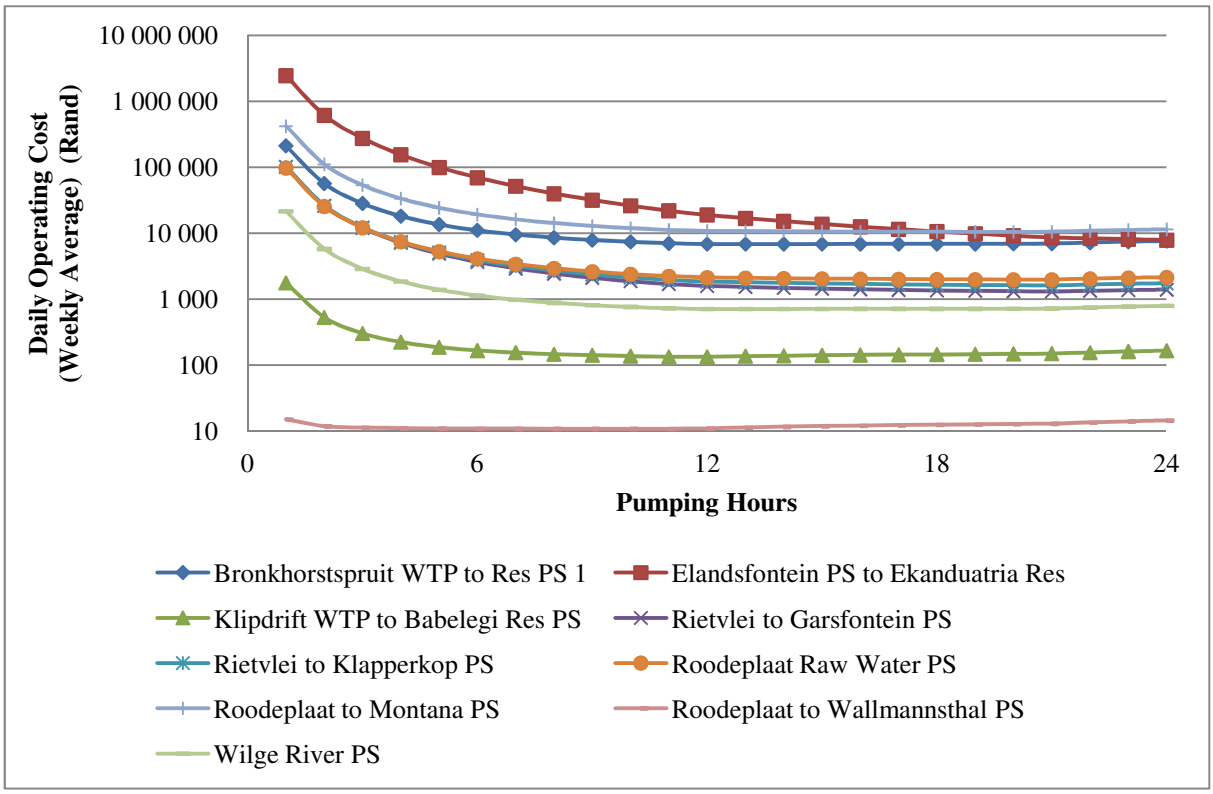

Figure 5.2 – Average Daily Operating Cost

With the ideal pumping hours determined for each pipe, the change in pumping hours and ideal velocity could be determined and graphed, as shown in Figure 5.3.

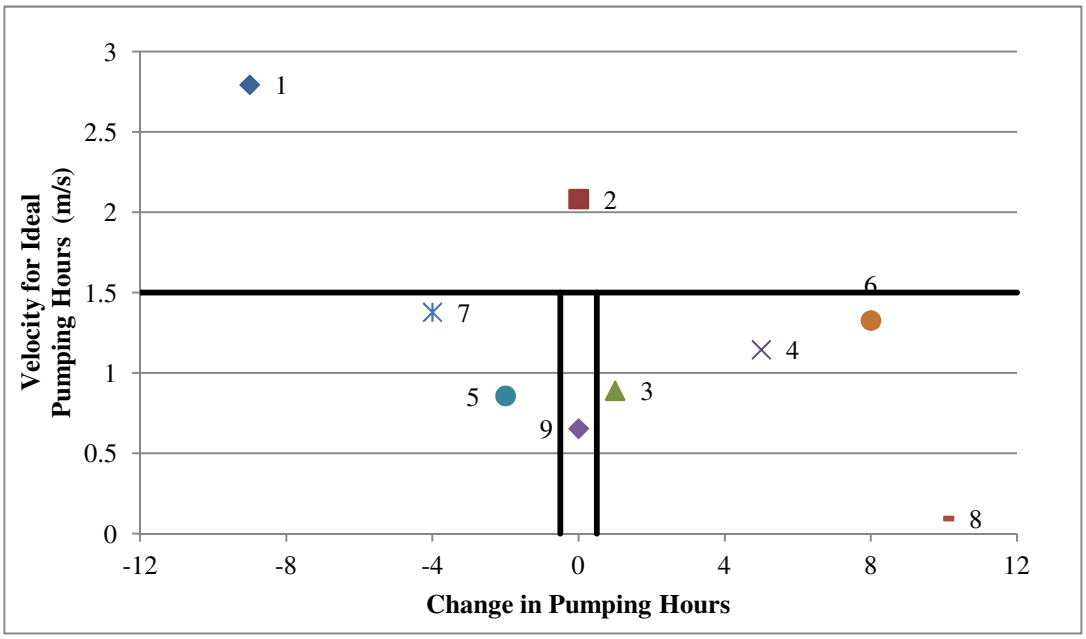

Figure 5.3 - Operational Evaluation

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To prioritize the pipelines, the potential cost savings, the savings gained from changing the pumping hours, was used. As seen in Table 5.3, the three pipelines with the greatest potential cost savings are the Roodeplaat to Montana (#7), the Bronkhorstspruit WTP to Res PS (#1), and the Elandsfontein PS to Ekanduatria Res (#2) pipelines. The 1.5 m/s velocity line is the practical upper limit for a pipeline, as described in Section 3.2, which indicates that pipelines 1 and 2 are operating inefficiently by current design standards.

Table 5.3- Cost Savings from Operational Changes

Pipeline Name	Current Pumping Hours	Current Velocity (m/s)	Ideal Pumping Hours	Ideal Velocity (m/s)	Change in Pumping Hours	Additional Hydraulic Capacity Required?	Current Yearly Operating Cost	Potential Yearly Savings	Rank
Bronkhorstspruit WTP to Res PS 1	22	1.65	13	2.79	-9	Add Capacity	R 3 046 000	R 418 000	2
Elandsfontein PS to Ekanduatria Res	24	2.08	24	2.08	0	Add Capacity	R 3 544 000	R 245 000	3
Klipdrift WTP to Babelegi Res PS	11	0.97	12	0.89	1	Sufficient Capacity	R 51 000	R -	8
Rietvlei to Garsfontein PS	16	1.50	21	1.14	5	Sufficient Capacity	R 554 000	R 31 000	6
Rietvlei to Klapperkop PS	23	0.78	21	0.86	-2	Sufficient Capacity	R 744 000	R 100 000	4
Roodeplaat Raw Water PS	13	2.14	21	1.33	8	Sufficient Capacity	R 808 000	R 35 000	5
Roodeplaat to Montana PS	24	1.15	20	1.38	-4	Sufficient Capacity	R 5 154 000	R 1 097 000	1
Roodeplaat to Wallmannsthal PS	1	1.03	11	0.09	10	Sufficient Capacity	R 6 000	R 2 000	7
Wilge River PS	12	0.65	12	0.65	0	Sufficient Capacity	R 272 000	R -	8

Note: "Additional Capacity Required" refers to pipelines where the ideal pumping hours creates a velocity that is greater than the highest recommended operation velocity of 1.5 m/s.

5.2 Economic Evaluation

An economic analysis was performed for each of the pipelines to determine what, if any, cost savings would result from the combination of different improvement options.

There were significant difficulties in determining how the pipelines were being operated; information was included where possible, however it was unavailable for most pipelines. It was therefore assumed that the pipelines without pumping schedule information were operated when water demand was highest. The periods when demand is the highest corresponds to the electrical peak hour time periods, followed by normal time periods, followed by off peak time periods. This assumption will lead to higher yearly operating costs and greater potential cost savings, but provides an equal baseline for comparison of the pipelines. This assumption is designed to be corrected on the two prioritized pipelines through the operational assessment portion of the field verification step.

While the economic analysis was performed on all pipelines, the summaries of the pipelines prioritized in hydraulic evaluation and operational evaluation are shown in Table 5.4 to Table 5.8. The tables reflect the potential cost savings of each combination of options. In the

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situations where the improvements result in a higher total cost than the baseline, difference is shown as a negative cost savings.

Table 5.4 - Economic Evaluation of Bronkhorstspruit WTP to Res PS (Pipeline #1)

20-Year NPV Cost Savings (Million Rand)						
	Hydraulic Improvement					
Operation Improvement	Baseline	Foam Pigging	Rigid Pigging	Intensive Cleaning	Rehab	Replacement
With Current Operation	R 0.0	R -14.6	R -16.7	R -11.1	R -16.3	R -57.0
Cost Logical with Current Hours	R 1.8	R -9.8	R -15.5	R -9.9	R -15.1	R -55.8
Cost Logical: 20 year avg. limited to off peak	R 8.4	R 2.8	R -4.5	R 1.0	R -2.0	R -31.6
Cost Logical: 20 year avg. limited to off peak and Normal	R 18.5	R 7.9	R 2.2	R 7.8	R 2.6	R -37.4
Year 20 Continuous Operation	R 10.4	R -0.3	R -6.0	R -0.4	R -5.6	R -45.9
Cost Logical: VFD limited to off peak	R 7.3	R 5.7	R -1.5	R 4.4	R -2.9	R -31.8
Cost Logical: VFD limited to off peak and Normal	R 23.1	R 15.3	R 9.7	R 15.5	R 7.2	R -32.9
VFD Limited to Continuous Operation	R 0.0	R -7.7	R -13.3	R -7.4	R -16.3	R -57.1
Pay Back Period (Years)						
With Current Operation	0	>20	>20	>20	>20	>20
Cost Logical with Current Hours	1	>20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak	15	18	>20	20	>20	>20
Cost Logical: 20 year avg. limited to off peak and Normal	1	4	12	10	17	>20
Year 20 Continuous Operation	1	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak	15	18	>20	19	>20	>20
Cost Logical: VFD limited to off peak and Normal	2	12	15	14	17	>20
VFD Limited to Continuous Operation	5	>20	>20	>20	>20	>20

Note: Where cost savings was not achieved, the increased cost is displayed as a negative cost savings

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Table 5.5 - Economic Evaluation of the Elandsfontein PS to Ekanduatria Res (Pipeline #2)

20 Year NPV Cost Savings (Million Rand)						
	Hydraulic Improvement					
Operation Improvement	Baseline	Foam Pigging	Rigid Pigging	Intensive Cleaning	Rehab	Replacement
With Current Operation	R 0.0	R -20.3	R -58.2	R -37.1	R -49.9	R -173.6
Cost Logical with Current Hours	R 0.5	R -20.5	R -58.4	R -37.3	R -50.1	R -173.7
Cost Logical: 20 year avg. limited to off peak	R -297.7	R -248.1	R -312.6	R -296.0	R -281.6	R -256.8
Cost Logical: 20 year avg. limited to off peak and Normal	R -14.9	R -30.6	R -70.1	R -49.0	R -60.1	R -173.8
Year 20 Continuous Operation	R -9.8	R -27.3	R -66.1	R -44.9	R -56.7	R -173.9
Cost Logical: VFD limited to off peak	R -317.2	R -235.0	R -296.9	R -276.4	R -298.2	R -263.4
Cost Logical: VFD limited to off peak and Normal	R -13.3	R -17.8	R -55.4	R -31.4	R -58.8	R -172.7
VFD Limited to Continuous Operation	R -0.8	R -10.9	R -46.8	R -22.6	R -50.6	R -174.1
Pay Back Period (Years)						
With Current Operation	0	>20	>20	>20	>20	>20
Cost Logical with Current Hours	2	>20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak	>20	>20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak and Normal	>20	>20	>20	>20	>20	>20
Year 20 Continuous Operation	>20	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak	>20	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak and Normal	>20	>20	>20	>20	>20	>20
VFD Limited to Continuous Operation	>20	>20	>20	>20	>20	>20

Note: Where cost savings was not achieved, the increased cost is displayed as a negative cost savings

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Table 5.6 – Economic Analysis of Roodeplaat Raw Water Pipeline (Pipeline #6)

20 Year NPV Cost Savings (Million Rand)						
	Hydraulic Improvement					
Operation Improvement	Baseline	Foam Pigging	Rigid Pigging	Intensive Cleaning	Rehab	Replacement
With Current Operation	R 0.0	R -13.4	R -18.9	R -12.5	R -18.2	R -62.2
Cost Logical with Current Hours	R 30.9	R 16.8	R 10.3	R 16.9	R 10.2	R -39.0
Cost Logical: 20 year avg. limited to off peak	R 28.0	R 15.1	R 8.3	R 14.7	R 8.5	R -38.5
Cost Logical: 20 year avg. limited to off peak and Normal	R 12.2	R -3.0	R -9.0	R -2.3	R -9.5	R -61.8
Year 20 Continuous Operation	R 2.2	R -13.1	R -19.0	R -12.4	R -19.6	R -72.0
Cost Logical: VFD limited to off peak	R 25.5	R 14.2	R 7.5	R 14.1	R 6.1	R -40.5
Cost Logical: VFD limited to off peak and Normal	R 13.4	R -0.9	R -6.8	R -0.0	R -8.4	R -60.6
VFD Limited to Continuous Operation	R -0.8	R -15.1	R -21.0	R -14.2	R -22.7	R -75.3
Pay Back Period (Years)						
With Current Operation	0	>20	>20	>20	>20	>20
Cost Logical with Current Hours	1	7	8	11	16	>20
Cost Logical: 20 year avg. limited to off peak	1	8	13	11	16	>20
Cost Logical: 20 year avg. limited to off peak and Normal	14	>20	>20	>20	>20	>20
Year 20 Continuous Operation	19	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak	3	12	15	14	17	>20
Cost Logical: VFD limited to off peak and Normal	14	>20	>20	>20	>20	>20
VFD Limited to Continuous Operation	>20	>20	>20	>20	>20	>20

Note: Where cost savings was not achieved, the increased cost is displayed as a negative cost savings

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Table 5.7 – Economic Analysis of Roodeplaat to Montana PS (Pipeline #7)

20 Year NPV Cost Savings (Million Rand)						
	Hydraulic Improvement					
Operation Improvement	Baseline	Foam Pigging	Rigid Pigging	Intensive Cleaning	Rehab	Replacement
With Current Operation	R 0.0	R -54.0	R -75.2	R -50.5	R -76.1	R -265.3
Cost Logical with Current Hours	R -4.1	R -59.0	R -80.1	R -55.5	R -81.1	R -270.3
Cost Logical: 20 year avg. limited to off peak	R 10.0	R -33.4	R -57.3	R -32.0	R -52.8	R -221.9
Cost Logical: 20 year avg. limited to off peak and Normal	R 24.8	R -28.5	R -49.8	R -25.1	R -50.3	R -238.2
Year 20 Continuous Operation	R 13.3	R -40.3	R -61.5	R -36.8	R -62.1	R -250.5
Cost Logical: VFD limited to off peak	R 8.4	R -28.2	R -51.8	R -26.0	R -53.9	R -221.7
Cost Logical: VFD limited to off peak and Normal	R 32.8	R -16.0	R -37.1	R -12.0	R -42.4	R -230.3
VFD Limited to Continuous Operation	R -1.4	R -50.3	R -71.2	R -46.2	R -77.4	R -266.6
Pay Back Period (Years)						
With Current Operation	0	>20	>20	>20	>20	>20
Cost Logical with Current Hours	>20	>20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak	14	>20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak and Normal	1	>20	>20	>20	>20	>20
Year 20 Continuous Operation	1	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak	14	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak and Normal	2	>20	>20	>20	>20	>20
VFD Limited to Continuous Operation	>20	>20	>20	>20	>20	>20

Note: Where cost savings was not achieved, the increased cost is displayed as a negative cost savings

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Table 5.8 - Economic Analysis of Roodeplaat to Wallmansthall Pipeline (Pipeline #8)

20-Year NPV Cost Savings (Million Rand)						
	Hydraulic Improvement					
Operation Improvement	Baseline	Foam Pigging	Rigid Pigging	Intensive Cleaning	Rehab	Replacement
With Current Operation	R 0.0	R -10.4	R -13.8	R -9.6	R -14.5	R -49.3
Cost Logical with Current Hours	R 0.6	R -9.9	R -13.3	R -9.0	R -14.0	R -48.9
Cost Logical: 20 year avg. limited to off peak	R -2.0	R -12.5	R -15.9	R -11.6	R -16.6	R -51.5
Cost Logical: 20 year avg. limited to off peak and Normal	R -4.3	R -14.8	R -18.2	R -13.9	R -18.9	R -53.9
Year 20 Continuous Operation	R -5.2	R -15.7	R -19.1	R -14.8	R -19.7	R -54.7
Cost Logical: VFD limited to off peak	R -2.5	R -13.0	R -16.3	R -12.1	R -17.0	R -52.0
Cost Logical: VFD limited to off peak and Normal	R -4.8	R -15.3	R -18.6	R -14.4	R -19.3	R -54.3
VFD Limited to Continuous Operation	R -5.7	R -16.2	R -19.5	R -15.3	R -20.2	R -55.2
Pay Back Period (Years)						
With Current Operation	0	>20	>20	>20	>20	>20
Cost Logical with Current Hours	1	>20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak	>20	>20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak and Normal	>20	>20	>20	>20	>20	>20
Year 20 Continuous Operation	>20	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak	>20	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak and Normal	>20	>20	>20	>20	>20	>20
VFD Limited to Continuous Operation	>20	>20	>20	>20	>20	>20

Note: Where cost savings was not achieved, the increased cost is displayed as a negative cost savings

The economic analysis was additionally performed for each of the remaining pipelines and the results are summarized in Table 5.9. The improvements are ranked in two ways, first, the improvement for each pipeline that results in the greatest cost savings, then again by the improvement for each pipeline that results with the shortest pay-back period.

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Table 5.9 - Summary of Economic Analysis for Selected Tshwane Bulk Water Pipelines

Greatest Cost Saving				
Name	Max Cost Savings (20 Year NPV Million Rand)	Pay Back Period	Operational Improvement Option	Rank
Bronkhorstspruit WTP to Res PS 1	R 23.10	2	Cost Logical: VFD limited to off peak and Normal	3
Elandsfontein PS to Ekanduatria Res	R -	0	With Current Operation	9
Klipdrift WTP to Babelegi Res PS	R 2.37	0	Cost Logical with Current Hours	7
Rietvlei to Garsfontein PS	R 14.08	0	Cost Logical with Current Hours	4
Rietvlei to Klapperkop PS	R 3.66	6	Cost Logical: VFD limited to off peak and Normal	6
Roodeplaat Raw Water PS	R 30.93	0	Cost Logical with Current Hours	2
Roodeplaat to Montana PS	R 32.81	2	Cost Logical: VFD limited to off peak and Normal	1
Roodeplaat to Wallmannsthal PS	R 0.58	0	Cost Logical with Current Hours	8
Wilge River PS	R 11.41	0	Cost Logical with Current Hours	5
Shortest Pay Back Period				
Name	Fastest Pay Back Period (years)	Cost Savings (million Rand)	Operational Improvement Option	Rank
Bronkhorstspruit WTP to Res PS 1	0	R 18.53	Cost Logical: 20 year avg limited to off peak and Normal	3
Elandsfontein PS to Ekanduatria Res	0	R -	With Current Operation	9
Klipdrift WTP to Babelegi Res PS	0	R 2.37	Cost Logical with Current Hours	7
Rietvlei to Garsfontein PS	0	R 14.08	Cost Logical with Current Hours	4
Rietvlei to Klapperkop PS	0	R 3.05	Cost Logical: 20 year avg limited to off peak and Normal	6
Roodeplaat Raw Water PS	0	R 30.93	Cost Logical with Current Hours	1
Roodeplaat to Montana PS	0	R 24.79	Cost Logical: 20 year avg limited to off peak and Normal	2
Roodeplaat to Wallmannsthal PS	0	R 0.58	Cost Logical with Current Hours	8
Wilge River PS	0	R 11.41	Cost Logical with Current Hours	5

Note: A payback period of "0" years indicates that the cost of the improvements required to achieve this cost savings are negligible.

As can be seen in Table 5.9, there is significant cost savings that can result from operational changes, however, despite the "common knowledge" here in South Africa that a poorly operating pipe should just be replaced, none of the hydraulic improvement options resulted in a long term cost savings. The focus of pipeline improvements should fall onto operational improvements. The operational improvement options that yield significant cost savings

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require a minimal capital investment to implement, resulting in short pay back periods. The two pipelines with the greatest potential cost savings – Roodeplaat Raw Water PS and Roodeplaat to Montana PS should be prioritized for potential improvements and these two pipelines were selected for field verification.

5.3 Field Verification - Roodeplaat Water Treatment Plant

The Desktop Evaluation determined that the raw water pipeline leading to and the potable water pipeline leading away from Roodeplaat Water Treatment Plant (WTP) were the two pipelines with the greatest potential for cost savings. Field testing was performed on each pipeline to determine the hydraulic capacity as well as the current operational schedule.

5.3.1 Hydraulic Condition Assessment

The hydraulic evaluation was performed as discussed in Section 4.5.1.

5.3.1.1 Raw Water Pipeline Hydraulic Condition Assessment

The Roodeplaat Raw Water Pipeline runs from the Raw Water Pump Station, located adjacent to Roodeplaat Dam, to Roodeplaat WTP inlet works. The 813 mm diameter pipeline is a little over three kilometres long and is a welded steel pipe with an epoxy liner. It was built in 2005 as part of the improvements to the dam off-takes and WTP upgrades. The pipeline profile, as well as the location of the pump station, air valves, and scour valves, is shown in Figure 5.4.

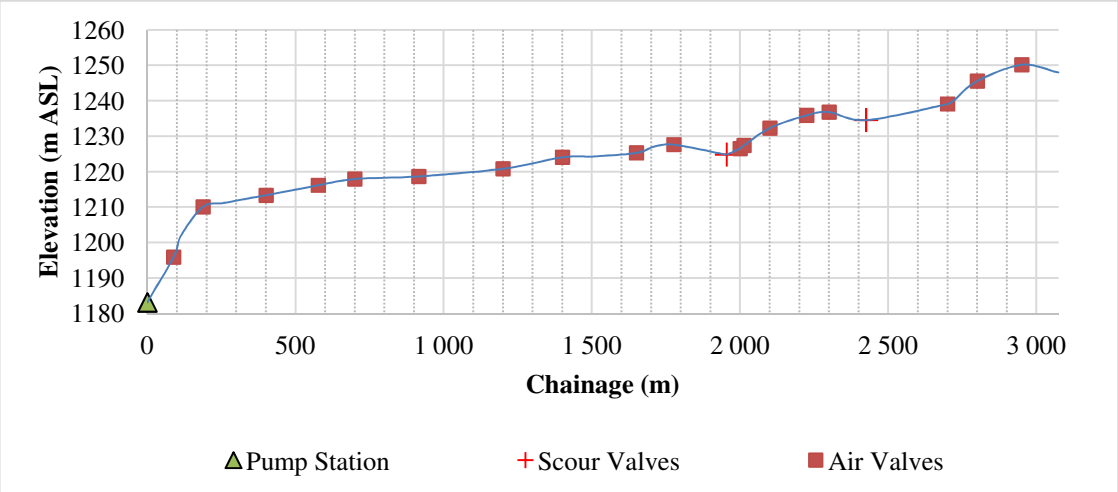

Figure 5.4 - Elevation profile of the Roodeplaat Raw Water Pipeline

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Recording positions on the Raw Water Pipeline

The selection of pressure recording locations on the Roodeplaat Raw Water Pipeline was performed in a manner to allow for accurate computation of the capacity of the pipeline, as well as to accurately calculate secondary losses along the pipeline. Table 5.10 reflects details of the pressure recording locations. All the measuring points were surveyed with a Trimble Geo Explorer 3000 Series GPS; however the GPS was unable to provide an accurate elevation reading at several points.

Table 5.10 - Pressure Recording Positions on the Raw Water Pipeline

Pressure Recording Position:	Pipeline Location:	Maximum Expected Pressure (m)	Chainage#:	Coordinates:	As Built Invert Elevation (m)
1	Inside Raw Water PS	85 m	0.00	25°37'11.15"S 28°22'15.91"E	1180.40
2	RW 1A	70 m	88.070	25°37'10.94"S 28°22'12.44"E	1195.93
3	RW 8	25 m	1176.58	25°36'56.42"S 28°21'16.54"E	1227.84
4	WTP Inlet Works	0 m	3116.33	25°37'3.01"S 28°20'35.93"E	1258.63

Notes: # Chainages were obtained from the As Built Drawings

The final testing point is the known elevation of invert of the weir of the inlet structure where the pipeline discharges to atmospheric conditions, and therefore there is no residual pressure. The inlet structure is shown in Figure 5.5.

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Figure 5.5 - Inlet Works of the Roodeplaat WTP

The locations of these measuring points are shown in Figure 5.6.

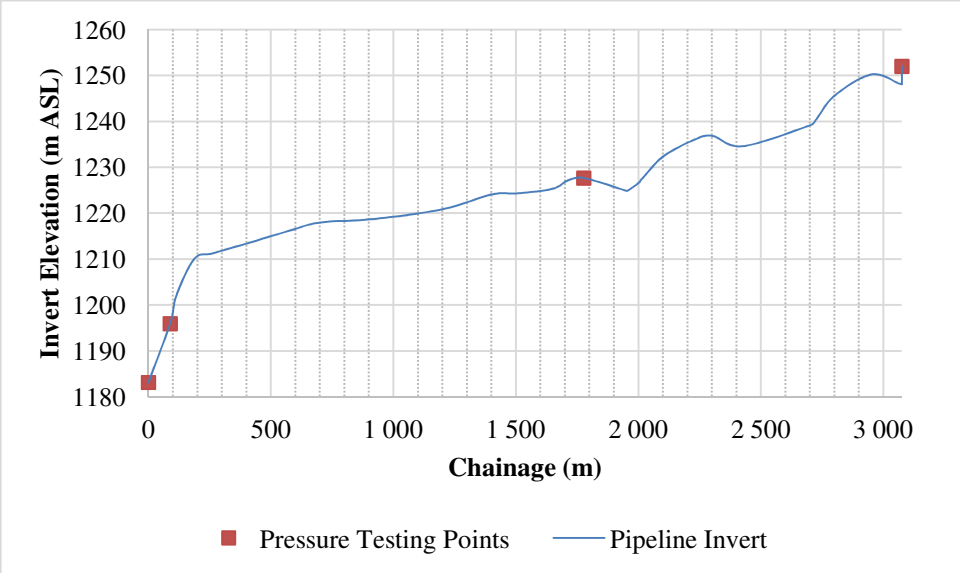

Figure 5.6 : Location of the pressure recording positions on the Roodeplaat Raw Water Pipeline

Details of the pressure recording equipment and the pressure transducers are shown in Table 5.11. The first pressure testing point utilized the WTP's SCADA system for data acquisition and recording.

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Table 5.11 : Details of the pressure transducers and data loggers used on the Raw Water Pipeline

Pressure Recording Position:	Pipeline Location:	Pressure Transducers		Recording Accuracy (m)*	Recording Frequency (Hz)	Data Logger Serial #
		Channel 1	Channel 2			
1	Inside Raw Water PS	SCADA System Sensors		N/A	N/A	N/A
2	RW 1A	10	16	0.025	0.20	2229541
3	RW 8	4	10	0.010	0.20	784505
4	WTP Inlet Works	No Installation Required		±0.050	N/A	N/A

*Note: *The data logger is a 12 bit logger*

Recordings from both pressure transducers were captured on a data logger, which measured the pressure as milliamps. These values of the current were converted into pressure based on the specific pressure transducers' range installed at the measuring point. Two pressure transducers were installed at each location.

An example pressure testing point, PT 2, is shown Figure 5.7.

Figure 5.7 - Pressure Testing Point 2 on the Roodeplaat Raw Water Pipeline

Figure 5.8 graphically reflects the calculated hydraulic grade lines (HGL) for the measuring points for the recording period. The HGL is the sum of the recorded pressure at the measuring point plus the measuring point elevation as provided by the as-built drawings, as the Trimble Geo Explorer 3000 Series GPS was not able to provide an accurate elevation

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reading at several locations. The as-built elevation for testing point 2 was adjusted to provide for a straighter hydraulic grade line. The elevations of all points should be verified when a survey is performed in the future.

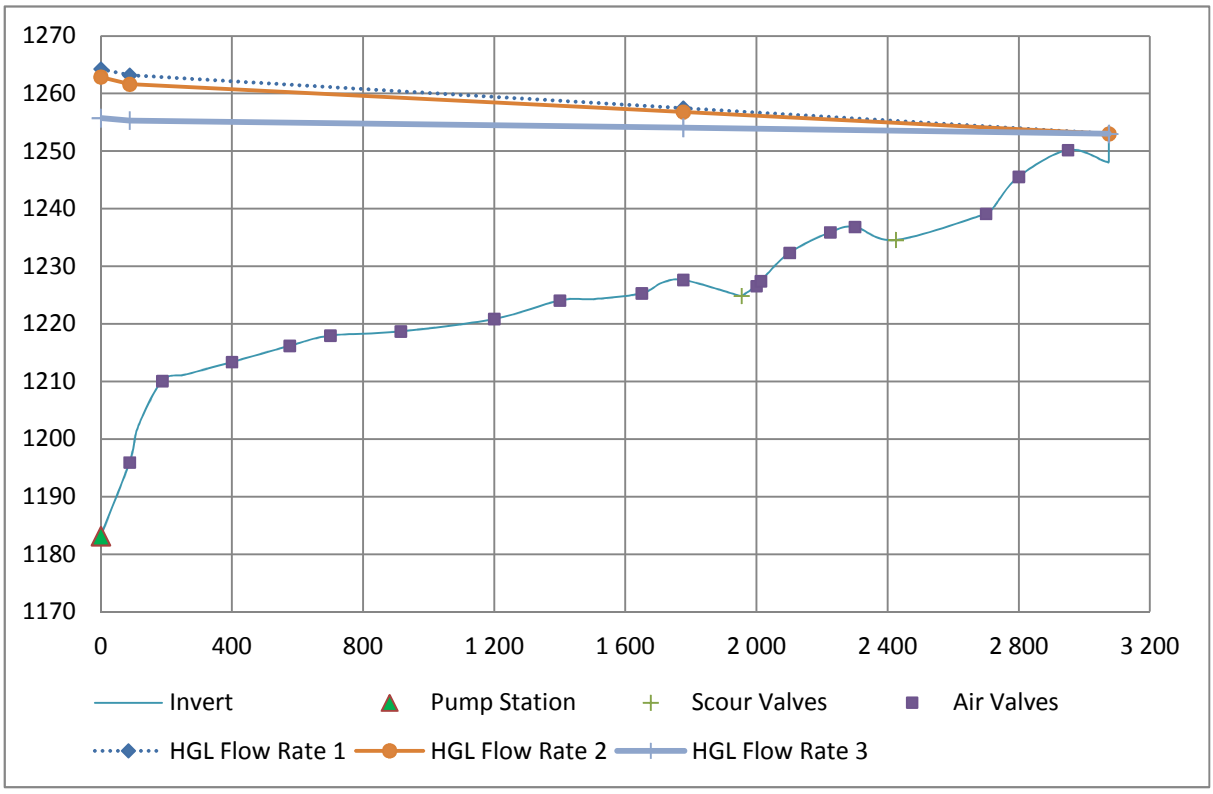

Figure 5.8 - Hydraulic Grade Lines for Roodeplaat Raw Water Pipeline

Selection of Flow Periods for Roughness Calculation

From the recorded flow and pressure recordings, 3 distinct time periods were selected where pressures and flow could be compared between all the measuring points. These 3 periods start at times 15:00, 21:00, and 00:40 where stable flow and pressure conditions prevailed as shown in Figure 5.9.

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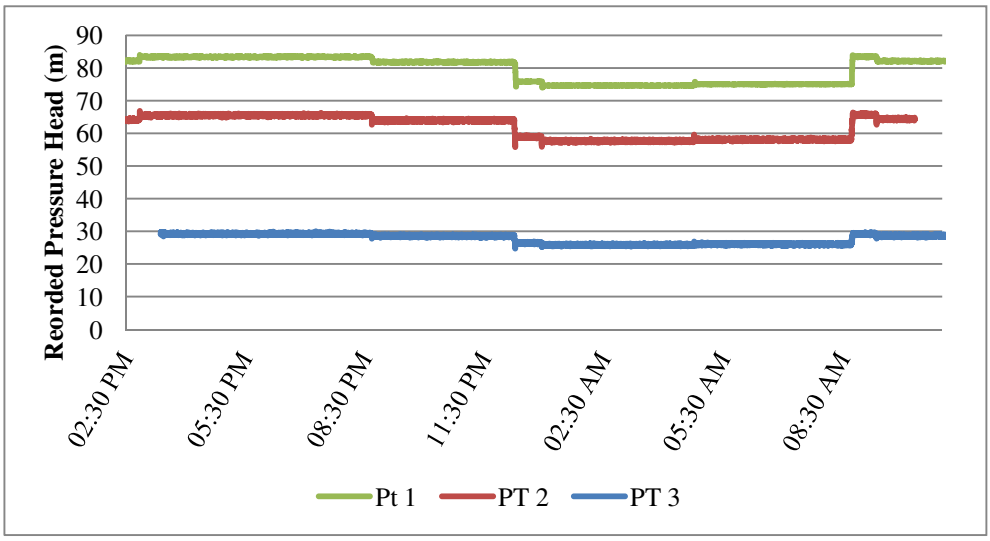

Figure 5.9 - Selection of Flow Periods for Roughness Calculation of the Roodeplaat Raw Water Pipeline – Measured on 27 February 2014

Flow Rate

The Water Treatment Plant's SCADA system was used for flow metering. Figure 5.10 shows the recorded flow, overlaid with the recorded pressures at each testing point.

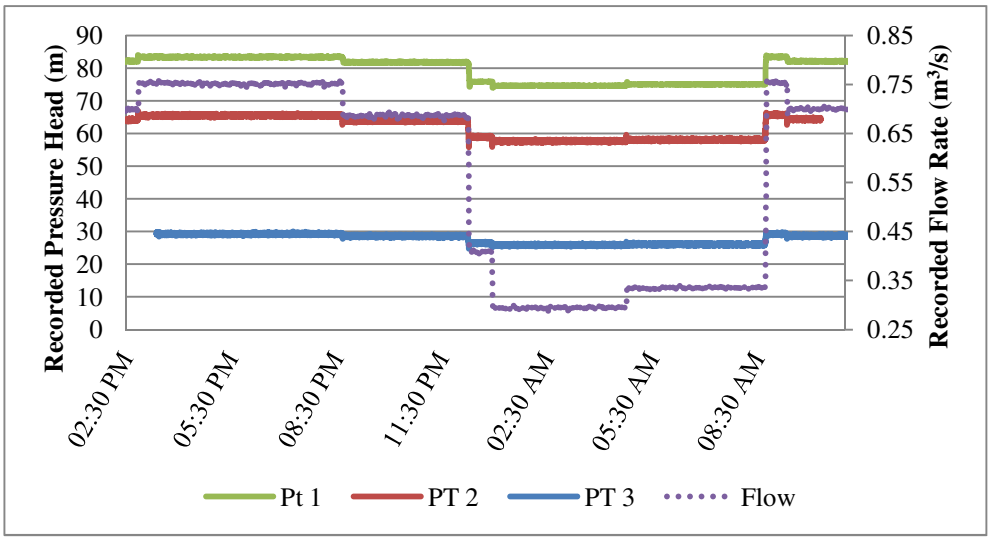

Figure 5.10 - Recorded Flow and Recorded Pressures of the Roodeplaat Raw Water Pipeline – Measured on 27 February 2014

Table 5.12 reflects the recorded flow rates for each time period and the corresponding velocities.

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Table 5.12 - Recorded Flow Rates on the Raw Water Pipeline

	Flow 1	Flow 2	Flow 3
Flow Rate (m^3/s)	0.75	0.69	0.29
Velocity (m/s)	1.50	1.37	0.59
	Recorded Pressures (m)		
PT 1	83.17	81.79	74.64
PT 2	65.52	63.94	57.64
PT 3	16.82	16.16	13.43
PT 4	0	0	0

Quantification of Secondary Losses

In order to accurately quantify the calculation of roughness, the secondary losses should be quantified and included in the assessment. The calculation of the secondary loss coefficient (K-values) for specific elements of the system is shown in Table 5.13. The extent of the secondary losses falls within the expected range of 6-10% of the total head loss in the system.

Table 5.13 - Initial K Values for the Roodeplaat Raw Water Pipeline

Section	Air Valves	Scour Valves	Isolating Valves	Non Return Valves	Soft Bends <45°	Significant bends 45°<x<90°	>90° Bends	Initial total K value
K Value	**0.30**	**0.1**	**2**	**3**	**0.1**	**0.4**	**1**	
1-2	1	0	1	1	1	2	2	8.2
2-3	9	0	0	0	2	4	0	4.5
3-4	7	2	0	0	2	2	1	3.3
Total	17	2	1	1	5	8	3	17

Note: K values were selected from the ranges recommended in Chadwick et al, (2004)

The three flow rates were used for the calculation of the absolute roughness. The sections between pressure recording positions 1 and 4 were analyzed individually to provide details of the variation of the roughness in the individual pipe sections. Table 5.14 reflects the calculated friction coefficients for the different flow rates.

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Table 5.14 - Friction Coefficients for Flow Rates in Pipe Sections of the Roodeplaat Raw Water Pipeline

Section	Length (m)	Flow (m^3/s)	Change in HGL (m)	Average Velocity (m/s)	Secondary pressure loss (m)	Friction head loss (m)	Friction coefficient (λ)
1-2	88	0.75	1.07	1.50	0.69	0.38	0.030
		0.69	1.26	1.37	0.58	0.69	0.066
		0.29	0.42	0.59	0.11	0.31	0.163
2-3	1689	0.75	5.72	1.50	0.51	5.21	0.022
		0.69	4.82	1.37	0.43	4.39	0.022
		0.29	1.24	0.59	0.08	1.16	0.031
3-4	1298	0.75	4.46	1.50	0.49	3.97	0.022
		0.69	3.80	1.37	0.41	3.39	0.022
		0.29	1.07	0.59	0.08	1.00	0.033
2-4	2987	0.75	10.19	1.50	1.00	9.18	0.022
		0.69	8.62	1.37	0.84	7.78	0.022
		0.29	2.73	0.59	0.15	2.16	0.033
Overall	3075	0.75	11.26	1.50	1.69	9.57	0.022
		0.69	9.88	1.37	1.41	8.47	0.023
		0.29	2.73	0.59	0.26	2.47	0.037

The lowest flow rate, flow regime 3 produced an operating velocity of 0.59 m/s, a velocity that did not create enough of a pressure drop to accurately quantify the losses. The results from this flow rate were calculated; however the results are potentially questionable.

Determination of Hydraulic Capacity and Internal Roughness

The friction factor, λ, of the Roodeplaat Raw Water Pipeline was first calculated based on recorded pressure and flow data, followed by the calculation of the roughness using the different well-known roughness formulae. The various roughness values are shown in Table 5.15. The variation of absolute roughness (k_S-values) with respect to flow could be related to the secondary loss contributions.

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Table 5.15 - Calculated Roughness Values in Roodeplaat Raw Water Pipeline

Section	Flow Regime	Flow Rate (m^3/s)	von Kármán & Prandtl, k_s (mm)	Colebrook-White Transition, k_s (mm)	Barr, k_s (mm)	Moody, k_s (mm)
1-2	1	0.75	**3.097**	**2.944**	**2.949**	**2.732**
	2	0.69	**28.427**	**28.387**	**28.356**	**42.080**
	3	0.29	**157.293**	**157.191**	**157.226**	**784.597**
2-3	1	0.75	0.949	0.966	1.036	0.841
	2	0.69	0.951	0.936	1.026	0.842
	3	0.29	**3.736**	**3.669**	**3.833**	**3.428**
3-4	1	0.75	0.937	0.939	0.875	0.780
	2	0.69	1.034	0.994	1.036	0.856
	3	0.29	**5.311**	**5.413**	**5.288**	**5.105**
2-4	1	0.75	0.955	1.023	0.923	0.798
	2	0.69	1.083	0.982	0.956	0.848
	3	0.29	**4.414**	**4.331**	**4.366**	**4.102**
Overall	1	0.75	0.888	1.029	0.956	0.833
	2	0.69	1.285	1.303	1.185	1.058
	3	0.29	**6.118**	**6.071**	**6.125**	**6.020**
Median			0.955	0.994	1.026	0.842
Suggested Value			**0.95**			

Note: *Values marked in* **bold red** *(greater than 3mm) have been disregarded in the overall calculation of the roughness of the system. These values were identified to be suspect as the flow velocity didn't create the required pressure drop to accurately record the friction losses with the accuracy of the elevation data provided.*

The recorded data produced an average roughness 0.95 mm which is high, considering a new epoxy lined steel pipeline would exhibit a roughness ranging from 0.03 to 0.15 mm. Equation 2.20 was used to calculate the roughness growth rate, which was found to be in the range of 0.25 mm/year. However, raw water pipelines often contain biofilm growth, which could affect the roughness and the roughness growth rate. The presence of biofilm could not be investigated.

General Evaluation

The presence of significant biofilm growth (which could not be reviewed) could have a significant influence on the energy loss. The presence of biofilm is expected for multiple reasons, including:

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- Most raw water pipelines exhibit some form of biofilm growth
- There is biofilm on the adjacent channel, containing the same raw water
- There is biofilm growth on the inlet structure at the water treatment plant.

With the assumption of a 5 mm biofilm growth inside the pipeline, the average roughness is decreased to 1.2 mm accounting for the decreased cross sectional area alone; the biofilm itself could be resulting in an even greater effect. An investigation into the potential biofilm growth inside the pipeline should be undertaken to more accurately quantify the high absolute roughness. Prior to the Raw Water Pump Station, there is a dosage facility to treat the raw water with potassium permanganate under certain water quality conditions; however according to the plant manager, it is rarely operated. This facility could be altered to provide chemical dosing to control the biofilm growth at little cost.

5.3.1.2 Montana Pipeline Hydraulic Condition Assessment

The Roodeplaat to Montana Pipeline runs from the High Lift Pump Station, located at the Roodeplaat WTP, to the Montana Reservoir. The 750 mm diameter pipeline is a little less than twelve kilometres long, and is a welded steel pipeline with a cement mortar liner. It was built in 2005 as part of the improvements to the dam off-takes and WTP upgrades. The pipeline profile, as well as the location of the pump station, air valves, and scour valves, is shown in Figure 5.11.

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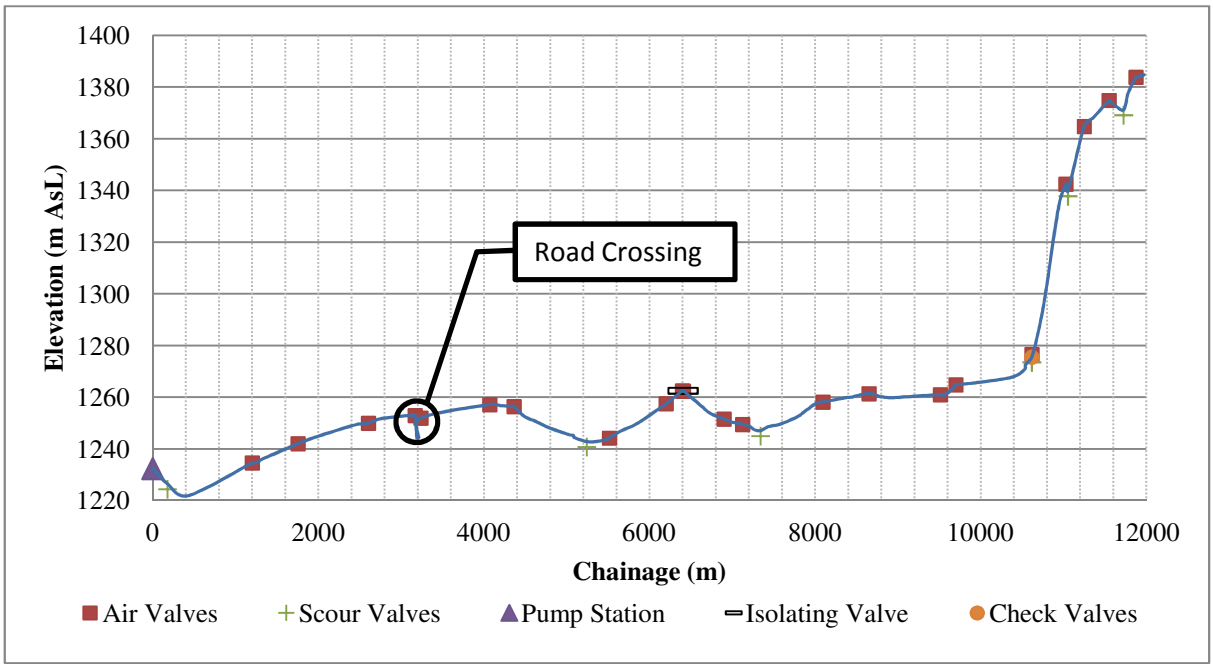

Figure 5.11 - Elevation profile of the Roodeplaat to Montana Pipeline

Recording positions on the Roodeplaat to Montana Pipeline

The selection of pressure recording locations on the Roodeplaat to Montana Pipeline was performed in a manner to allow for accurate computation of the capacity of the pipeline, as well as to accurately calculate secondary losses along the pipeline. Table 5.16 reflects details of the pressure recording locations. All the measuring points were surveyed with a Trimble Geo Explorer 3000 Series GPS. However the GPS was unable to provide an accurate elevation reading at several points.

Table 5.16 - Pressure Recording Positions on the Roodeplaat to Montana Pipeline

Pressure Recording Position:	Pipeline Location:	Maximum Expected Pressure (m)	Chainage#:	Coordinates:	As Built Invert Elevation (m)
1	Inside High Lift PS	210 m	-20.00	25°37'11.79"S 28°20'29.72"E	1232.4
2	Strainer	205 m	0	25°37'12.39" S 28°20'29.93"E	1235.63
3	Isolating Valve	160 m	6,200	25°39'21.42"S 28°18'10.58"E	1257.48
4	Roodeplaat Reservoir	20 m	11,971	25°41'38.18"S 28°16'18.07"E	1384.70

Notes: # Chainages were obtained from the As Built Drawings

The locations of these measuring points are shown in Figure 5.12

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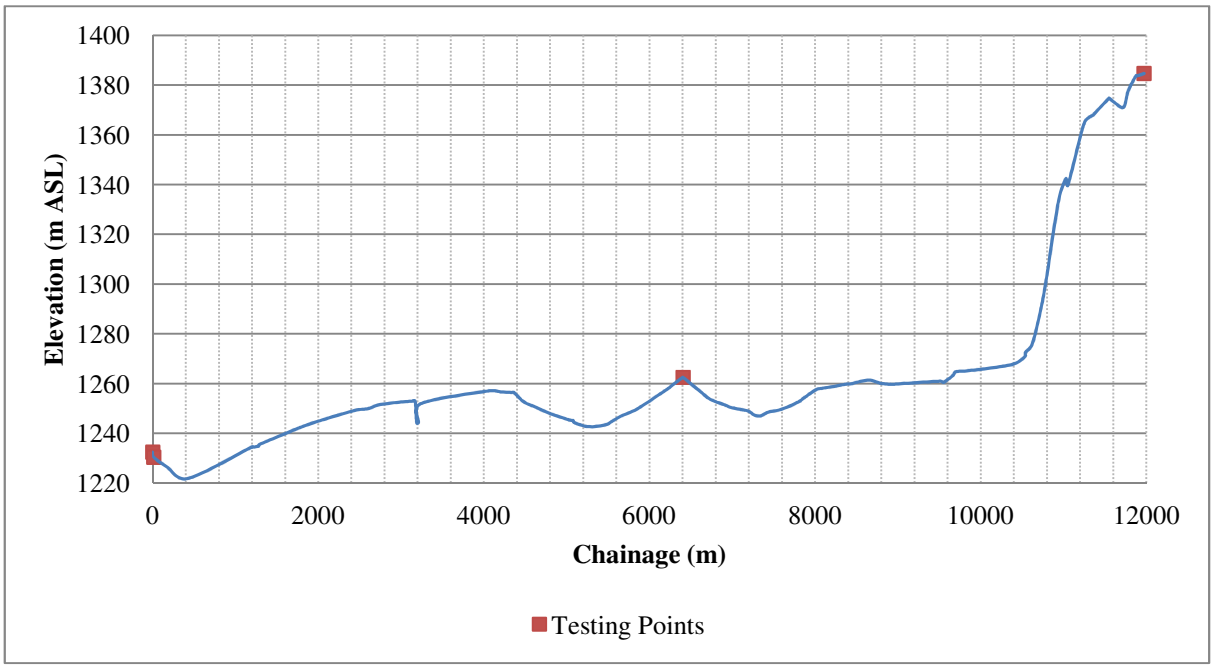

Figure 5.12 : Location of the pressure recording positions on the Roodeplaat to Montana Pipeline

Details of the pressure transducers and data loggers are shown in Table 5.17. The first pressure testing point utilized the WTP's SCADA system for data acquisition and recording.

Table 5.17 - Details of the pressure transducers and data loggers used on the Roodeplaat to Montana Pipeline

Pressure Recording Position:	Pipeline Location:	Pressure Transducers		Recording accuracy (m)	Recording frequency (Hz)	Data logger
		Channel 1	Channel 2			
1	Inside High Lift PS	SCADA System Sensors		N/A	N/A	N/A
2	Strainer	25	40	0.06*	0.2	1025537
3	Isolating Valve	16	25	0.04*	0.2	784504
4	Montana Reservoir	4	16	0.01*	0.2	784503

Note: *The data logger is a 12 bit logger

Recordings from both these pressure transducers were captured on a data logger, which measured the pressure as milliamps. These values of the current were converted into pressure based on the specific pressure transducers' range installed at the measuring points. Two pressure transducers were installed at each location.

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An example testing point, Pt. 3 at the isolating valve on the Roodeplaat to Montana Pipeline is shown in Figure 5.13.

Figure 5.13 - Pressure Testing Point 3 on the Roodeplaat to Montana Pipeline

Figure 5.14 graphically reflects the calculated hydraulic grade lines (HGL) for the measuring points for the recording period. The HGL is the sum of the recorded pressure at the measuring point plus the measuring point elevation as provided by the as-built drawings as the Trimble Geo Explorer 3000 Series GPS was not able to provide an accurate reading at several locations.

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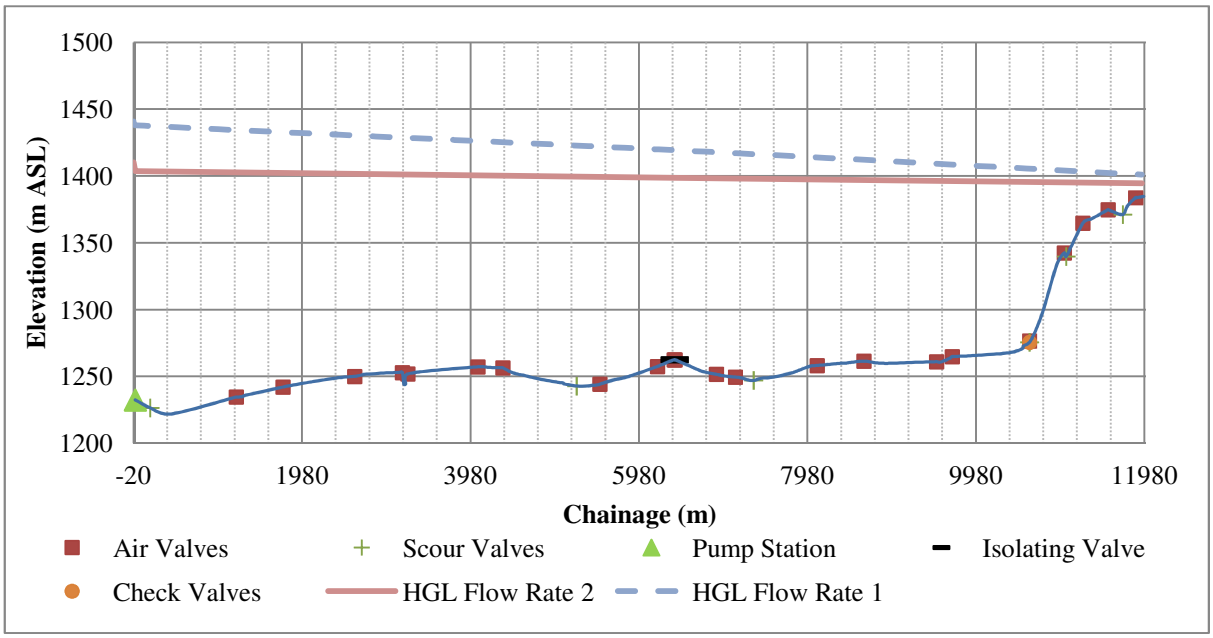

Figure 5.14 - Hydraulic grade lines for three selected flow rates of the Roodeplaat to Montana Pipeline

Selection of Flow Periods to for Roughness Calculate

From the recorded flow and pressure recordings, 3 distinct time periods were selected where pressures and flow could be compared between all the measuring points. These 3 periods start at times 18:00, 01:00, and 10:00 where stable flow and pressure conditions prevailed as shown in Figure 5.15.

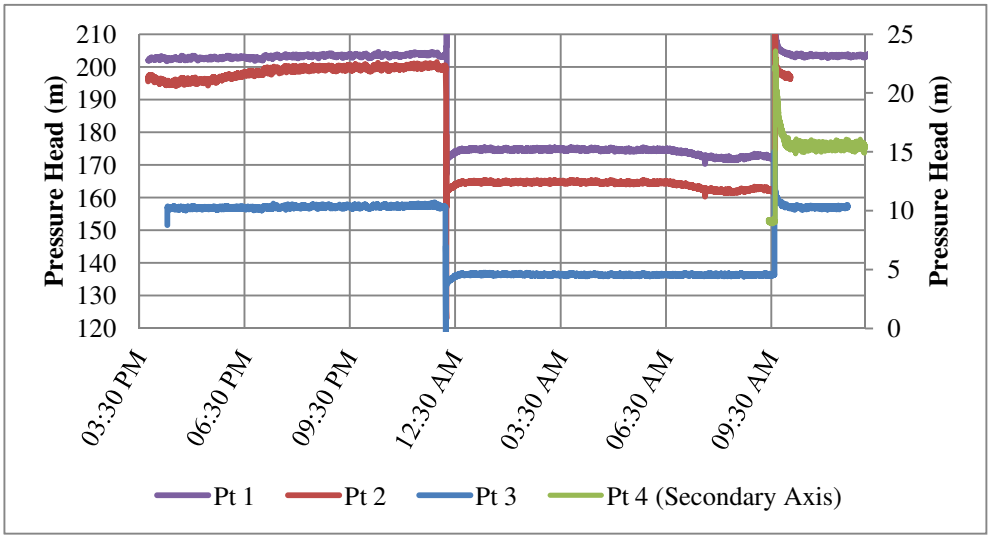

Figure 5.15 - Selection of flow periods for roughness calculation of the Roodeplaat to Montana Pipeline – Measured on 27 February 2014

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Flow Rate

The WTP's SCADA system was to be used for flow recording: however the flow meter failed just prior to testing. The flow was then back calculated from previously recorded flows and pressures recorded at Pt. 1. Figure 5.16 shows the recorded flow, overlaid with the recorded pressures.

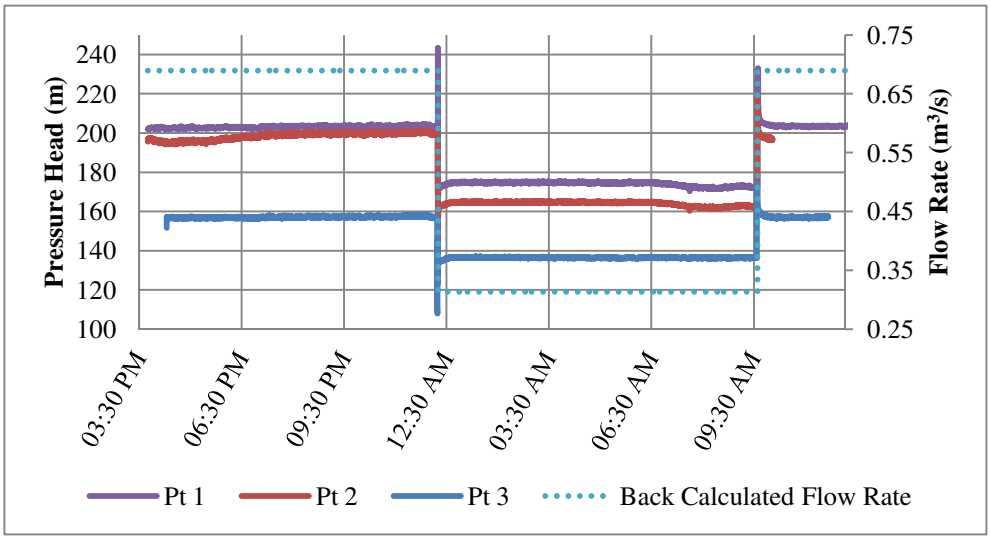

Figure 5.16 - Selection of flow periods for roughness calculation of the Roodeplaat to Montana Pipeline – Measured on 27 February 2014

Table 5.18 reflects the recorded flow rates for each time period and the corresponding velocities.

Table 5.18 : Recorded flow rates and velocities on the Roodeplaat to Montana Pipeline

	Flow 1	Flow 2
Flow	0.745	0.313
Velocity	1.67	0.71
Recorded Pressure		
Pt. 1	203.2	168.9
Pt. 2	193.2	159.0
Pt. 3	151.1	131.2
Pt. 4	24.3	14.2

Quantification of Secondary Losses

In order to accurately quantify the calculation of roughness, the secondary losses should be quantified and included in the assessment. The calculation of the secondary loss coefficient (K-values) for specific elements of the system is shown in Table 5.19. These secondary loss

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coefficients were further refined in order to ensure that in the fully rough domain on the Moody Diagram and the calculation of the absolute roughness provides a consistent value. The extent of the secondary losses falls within the expected range of 6-10 % of the total head loss in the system. The final K-values for each pipe section are shown in Table 5.19.

Table 5.19 - Initial K Values for the Roodeplaat to Montana Pipeline

Pipeline Section	Air Valves	Scour Valves	Isolating Valves	Non Return Valves	Soft Bends <45°	Significant bends 45°<x<90°	>90° Bends	Initial total K value
K Value	**0.30**	**0.1**	**2**	**3**	**0.1**	**0.4**	**0.6**	
1-2	0	0	1	1	2	2	1	6.6
2-3	11	3	1	0	11	12	4	13.9
3-4	12	3	0	1	17	11	0	13
Total	23	6	2	2	30	25	5	33.5

Note: K values were selected from the ranges recommended in Chadwick et al, (2004)

In addition to the secondary losses described in Table 5.19 there is a strainer located downstream of the high life pump station, in pipeline section 1-2. The strainer is shown in Figure 5.17.

Figure 5.17 - Strainer at Pressure Testing Point 2 on the Roodeplaat to Montana Pipeline

Pressure testing was performed both upstream and downstream of the strainer, with the change in pressure graphically displayed in Figure 5.18.

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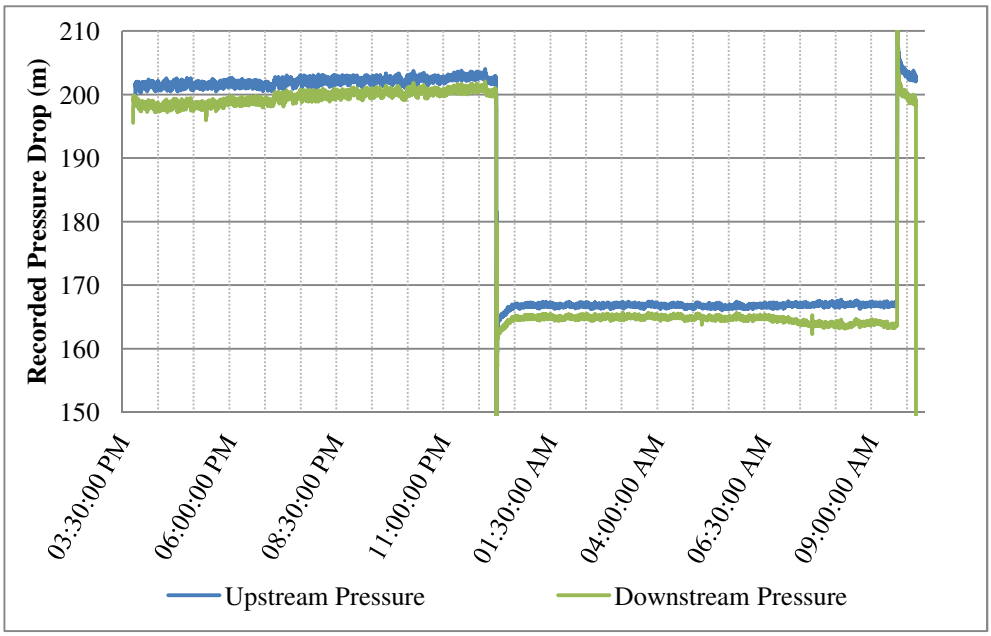

Figure 5.18 - Pressure Losses across Strainer at Pressure Testing Point 2 on the Roodeplaat to Montana Pipeline

The head loss for the two operating velocities and the calculated K values are shown in Table 5.20 below.

Table 5.20 - Pressure Loss across Strainer and Calculated K Values for the Roodeplaat to Montana Pipeline

Head Loss (m)	Flow Rate (m^3/s)	Velocity (m/s)	Calculated K Value
1.75	0.350	0.792	54.7
2.5	0.700	1.584	19.5

As the K values are significantly different, it was decided to remove the head loss of the strainer from the secondary losses and account for the pressure losses created by it separately.

Two different flow rates were recorded; however, the lower flow rate didn't provide the needed velocity to accurately measure the change in HGL. The sections between pressure recording positions 1 and 4 were analyzed individually to provide details of the variation of the roughness in the measured pipe sections. Table 5.21 reflects the calculated friction coefficients for the different flow rates.

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Table 5.21 - Friction Coefficients for Flow Rates in Pipe Sections of the Roodeplaat to Montana Pipeline

Section	Length (m)	Flow (m^3/s)	Change in HGL (m)	Average Velocity (m/s)	Secondary pressure loss (m)	Friction head loss (m)	Friction coefficient (λ)
1-2	20	0.69	2.8	1.56	2.71	0.07	0.0204
2-3	6 403	0.69	18.6	1.56	1.43	17.19	0.0162
3-4	5 547	0.69	18.2	1.56	2.81	15.43	0.0168
2-4	11 950	0.69	36.9	1.56	4.30	32.56	0.0165
Overall	11 970	0.69	39.6	1.56	6.95	32.69	0.0165

Determination of Hydraulic Capacity and Internal Roughness

The friction factor, λ, of the Roodeplaat to Montana Pipeline was first calculated based on recorded pressure and flow data, followed by the calculation of the roughness using the different well known roughness formulae as described in Section 2.3.1. The variation of absolute roughness (k_s-values) with respect to flow could be related to the secondary loss contributions, as shown in Table 5.22.

Table 5.22 - Calculated Roughness Values for the Roodeplaat to Montana Pipeline

Section	Flow rate (m^3/s)	von Kármán & Prandtl, k_s (mm)	Colebrook-White transition, k_s (mm)	Barr, k_s (mm)	Moody, k_s (mm)
1-2	0.69	**0.93**	**0.93**	**0.93**	**0.79**
2-3	0.69	0.35	0.35	0.35	0.30
3-4	0.69	0.41	0.41	0.41	0.35
2-4	0.69	0.37	0.37	0.37	0.32
Overall	0.69	0.38	0.38	0.38	0.32
Average		0.38	0.38	0.38	0.32
Suggested value		**0.38**			

Note: *Values marked in **Bold Red** has been disregarded in the overall calculation of the roughness of the system. These values were identified to be suspect.*

Since the flow rate could not be directly recorded and was back calculated, a sensitivity analysis was performed to evaluate the effect that a ±5% discrepancy would have on the roughness, as shown in Table 5.23.

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Table 5.23 - Sensitivity Analysis of Roughness Values for the Roodeplaat to Montana Pipeline

Section	von Kármán & Prandtl, k_s (mm)		Colebrook-White Transition, k_s (mm)		Barr, k_s (mm)		Moody, k_s (mm)	
Flow Rate (m^3/s)	**.724**	**.655**	**.724**	**.655**	**.724**	**.655**	**.724**	**.655**
1-2	0.10	3.64	0.10	3.64	0.10	3.64	0.08	3.33
2-3	0.21	0.57	0.21	0.57	0.21	0.57	0.18	0.48
3-4	0.26	0.66	0.26	0.66	0.26	0.66	0.22	0.56
2-4	0.23	0.60	0.23	0.60	0.23	0.60	0.19	0.51
Overall	0.23	0.61	0.23	0.61	0.23	0.61	0.20	0.52
Average	.23	.61	.23	0.61	.23	0.61	.20	0.52

When the flow meter is repaired, the operating flow rates should be verified to determine the correct roughness value.

The average roughness value of 0.38 from the recorded data is expected, because new CML steel pipeline would exhibit a roughness ranging from 0.03 to 0.15 mm degrading at a 0.05 mm/year, and therefore a value of 0.38 is logical. Equation 2.20 was used to calculate the roughness growth rate, which was found to be in the range of 0.04-0.10 mm/year.

General Evaluation

In a general evaluation of the pipeline, the presence of two strainers in the pipeline, located just downstream of the High Lift Pump Station, and just upstream of the entrance to Montana Reservoir add significant (±2 m) head loss each. These strainers serve no justifiable purpose and should be removed. Removal of the strainer would result in a yearly cost savings in the range of R80 000 to R100 000.

5.3.2 Roodeplaat Water Treatment Plant Operational Assessment

The operation of the raw water pipeline leading to and the potable water pipeline leading away from the Roodeplaat Water Treatment Plant is relatively synchronized as shown in Figure 5.19.

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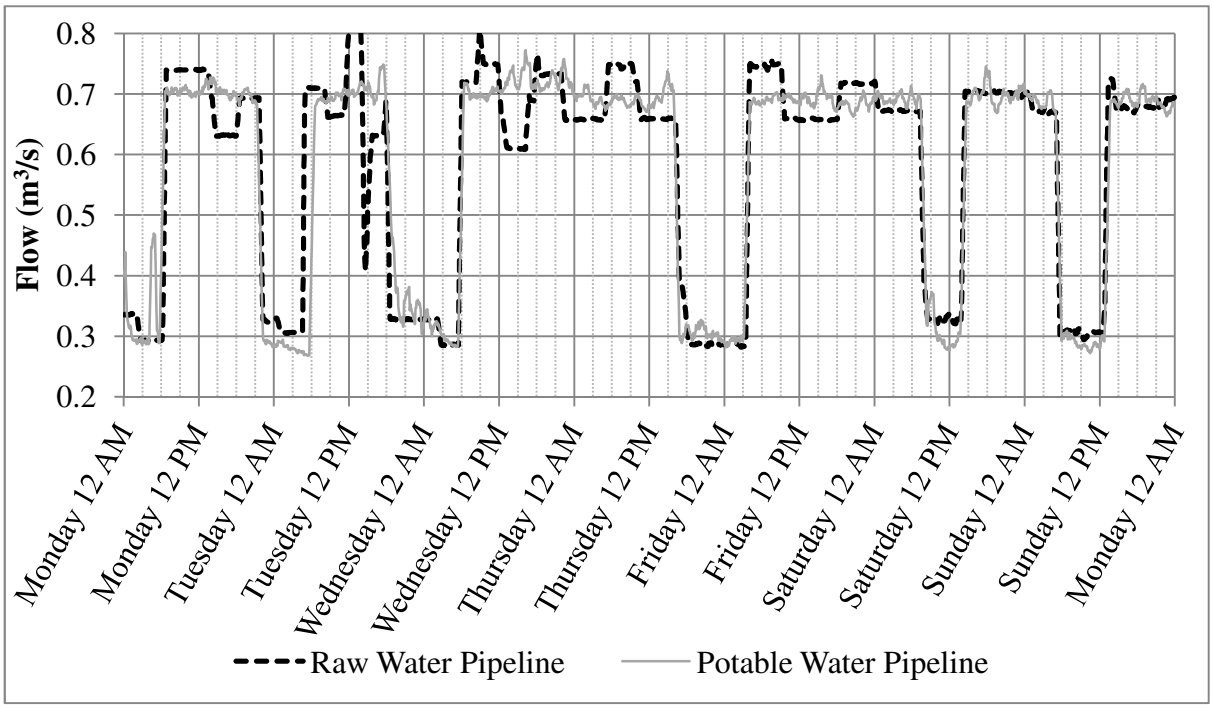

Figure 5.19 - Pumping Operation of Roodeplaat WTP

Although the operation is synchronized, the pipelines themselves have different operational restrictions, upstream and downstream storage, and flow controls. For example, the raw water pipeline runs from Roodeplaat dam (which provides several years of storage) to Roodeplaat WTP, with no downstream storage, while the potable water line connects the clear water reservoir of Roodeplaat WTP (which provides ±2 hours of storage) to Montana reservoir (providing ±18 hours of storage). The differences in the storage schemes, the flow controls, and downstream demands require the evaluation of the Roodeplaat WTP system to be broken into two parts for operational assessment.

5.3.2.1 Roodeplaat Raw Water Pipeline Operational Assessment

The operational assessment of the raw water pipeline was conducted based on data obtained from the SCADA system for a period from 19-December 2013 to 17-February 2014, as well as reviews of pipeline drawings, discussions with plant personnel, and site visits. The flow rate was downloaded in five-minute intervals from the plant's SCADA system and used to determine the AADD and the operating flow rates. There are three pumps in the raw water pump station, during normal operation; one pump is always running, one on standby and one alternating with demand requirements. The pumps are controlled via VFD. The three pumps in the raw water pump station are shown in Figure 5.20.

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Figure 5.20 – The Roodeplaat Raw Water Pump Station

The 60-day monitoring period was broken down into eight weeklong intervals. These weeklong periods were analysed to determine the total number of pumping hours, and the breakdown of those hours into each electrical cost period. The operation for an example week, the week of January 20th is shown in Figure 5.20.

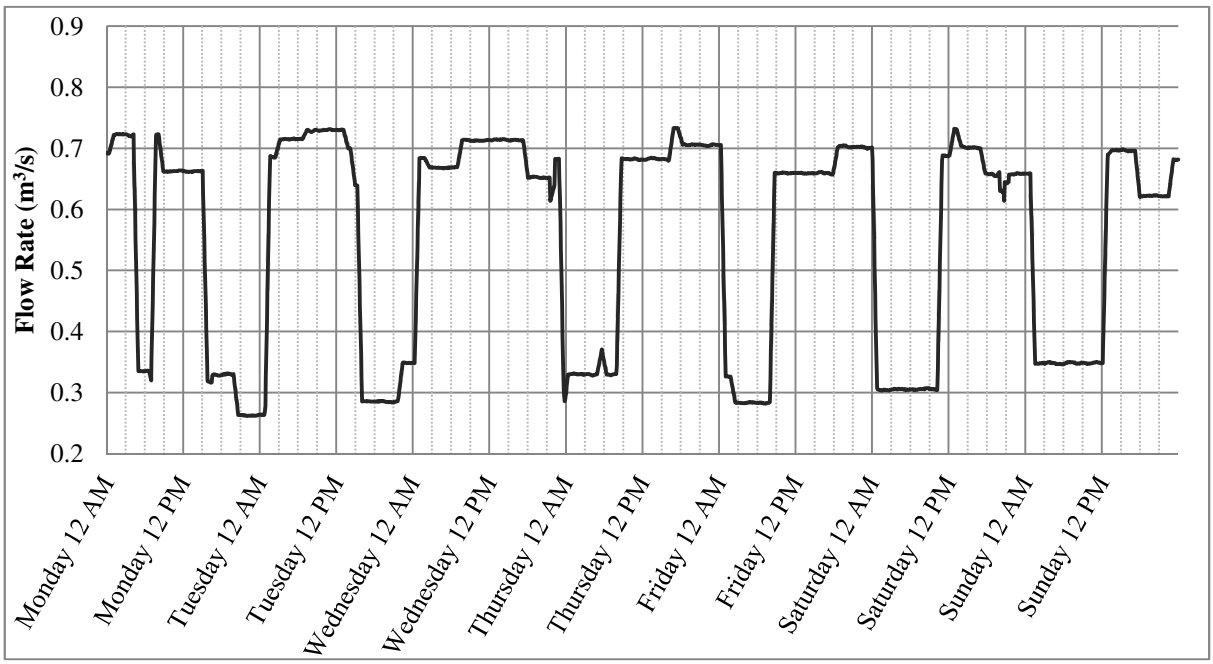

Figure 5.21 - Pumping Operation of Roodeplaat Raw Water Pipeline

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The operating restrictions and system storage were then further evaluated. Table 5.24 provides a summary of the operational assessment on the Roodeplaat Raw Water Pipeline.

Table 5.24 -Summary of Raw Water Pipeline Operational Assessment

Variable	Estimated Value (from Economic Evaluation)	Verified Value	Units
AADD	50,391	48,580	m^3
Number of Operating Pumps	1	2	number
Pump Efficiency	70%	85%	percentage
Daily Pumping Hours *	12.8	35.2	Hrs
Weekly Off Peak	18.4	114.4	Hrs
Weekly Normal	45.6	93.4	Hrs
Weekly Peak	25	38.9	Hrs
Average Electrical Cost	0.55	0.443	R/kWh
Operating Flow Rates	1.10	0.71	m^3/s
		0.36	m^3/s
Excess Upstream Storage	2,500	43,472,000	m^3
Excess Downstream Storage	2,500	0	m^3
Flow Control	Variable Frequency Drives		
Operating Restrictions	Must provide a minimum of 0.36m^3/s to Roodeplaat WTP		

*Note: * The daily pump hours includes the total runtime of both pumps, therefore it can be more than 24 hours.*

The information used in the economic was taken from the City of Tshwane's IMQS software. However this displays significant discrepancies when compared to the data verified by the operational analysis. This information verified by both the operational and field testing should be used to update the City's hydraulic model.

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5.3.2.2 Montana Pipeline Operational Assessment

The operational assessment of the Roodeplaat to Montana Pipeline was conducted based on data obtained from the SCADA system for a period from 19-December 2013 to 17-February 2014, as well as reviews of pipeline drawings, discussions with plant personnel, and site visits. The flow rate was downloaded in five-minute intervals from the plant's SCADA system and used to determine the AADD and the operating flow rates. There are three pumps in the high lift pump station, one of which is always running, one on standby and one alternating with demand requirements. There is no additional flow control. One of the three pumps, Pump #3 for the Roodeplaat to Montana Pipeline is shown in Figure 5.22.

Figure 5.22 – Pump #3 on the Roodeplaat to Montana Pipeline

The 60-day monitoring period was broken down into 7 weeklong intervals, with the remaining days being discarded because of a flow meter failure. These weeklong periods were analysed to determine the total number of pumping hours, and the breakdown of those hours into each electrical cost period. The operation over an example week, the week of January 20th is shown in Figure 5.23.

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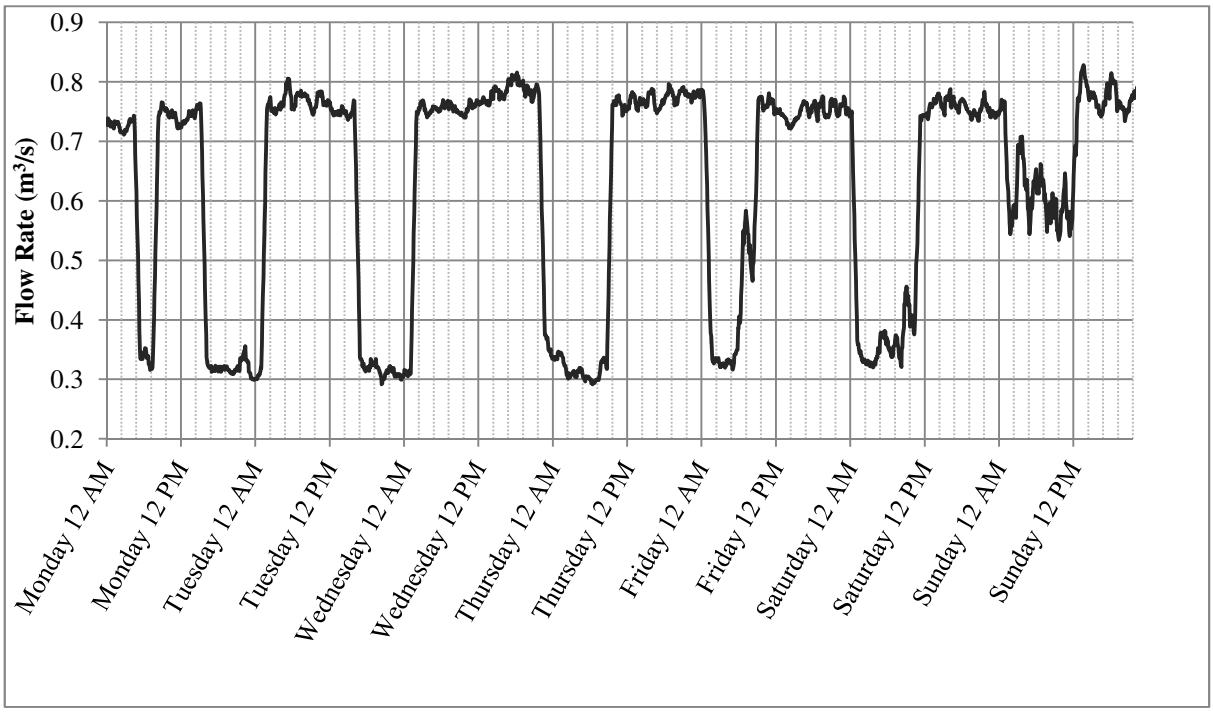

Figure 5.23 -Pumping operation of Roodeplaat to Montana pipeline

The operating restrictions and system storage were then further evaluated. Table 5.25 provides a summary of the operational assessment on the Roodeplaat to Montana Pipeline.

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Table 5.25 - Summary of Operational Assessment on the Roodeplaat to Montana Pipeline

Variable	Estimated Value (from Desktop Evaluation)	Verified Value	Units	Source
AADD	43,822	57,802	m^3	SCADA Recorded Flow
Number of Operating Pumps	1	2	number	SCADA
Pump Efficiency	70%	85% at 0.35m^3/s	Percentage	Efficiency Test Report
Daily Pumping Hours	24	37.4	Hrs	SCADA
Weekly Off Peak	81	126.4	Hrs	SCADA
Weekly Normal	62	80.6	Hrs	SCADA
Weekly Peak	25	54.7	Hrs	SCADA
Average Electrical Cost	0.43	0.470	R/kWh	SCADA and Eskom Rates
Operating Flow Rates	0.5	0.75	m^3/s	SCADA Recorded Flow
		0.33	m^3/s	SCADA Recorded Flow
Excess Upstream Storage	2,200	2,000	m^3	SCADA Recorded Res Levels
Excess Downstream Storage	2,200	15,000	m^3	SCADA Recorded Res Levels
Flow Control	Number of pumps running			Plant Personnel
Operating Restrictions	Must convey a minimum of 0.3 m^3/s from Roodeplaat WTP			Plant Personnel

5.4 Economic Verification

The data created and verified by the operational assessment and field verification were used to perform a more detailed economic analysis for each of the pipelines.

5.4.1 Raw Water Pipeline Economic Verification

An economic verification was performed with the data collected in the hydraulic condition and operational assessments. The economic analysis was performed as described in Section

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4.5.2 utilizing the developed software. The 20-year NPV of cost savings, and payback period for each improvement option is summarized in Table 5.26.

Table 5.26 - Roodeplaat Raw Water Pipeline Potential Cost Savings

NPV of 20-Year Cost Savings (Million Rand)						
	Hydraulic Improvement					
Operation Improvement	Baseline	Foam Pigging	Rigid Pigging	Intensive Cleanin	Rehab	Replacement
With Current Operation	R 0.0	R -12.2	R -20.7	R -13.9	R -21.2	R -71.3
Pump Scheduling	R 0.4	R -11.8	R -20.3	R -13.6	R -20.8	R -70.9
Cost Logical with Current Hours	R 12.9	R 0.5	R -8.0	R -1.3	R -8.6	R -59.7
Cost Logical: 20 year avg. limited to off peak	R 8.0	R -7.4	R -16.3	R -9.4	R -15.6	R -57.4
Cost Logical: 20 year avg. limited to off peak and Normal	R 12.2	R -2.3	R -10.8	R -4.0	R -11.2	R -61.0
Year 20 Continuous Operation	R 8.6	R -5.8	R -14.3	R -7.6	R -14.8	R -64.8
Cost Logical: VFD limited to off peak	R 6.2	R -9.2	R -18.1	R -11.4	R -17.5	R -58.6
Cost Logical: VFD limited to off peak and Normal	R 13.5	R -0.9	R -9.5	R -2.7	R -9.9	R -59.6
VFD Limited to Continuous Operation	R 3.0	R -11.4	R -19.9	R -13.2	R -20.4	R -70.7
Payback Period (Years)						
With Current Operation	0	>20	>20	>20	>20	>20
Pump Scheduling	0	>20	>20	>20	>20	>20
Cost Logical with Current Hours	0	20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak	9	>20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak and Normal	0	>20	>20	>20	>20	>20
Year 20 Continuous Operation	0	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak	10	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak and Normal	2	>20	>20	>20	>20	>20
VFD Limited to Continuous Operation	7	>20	>20	>20	>20	>20

The variable that is probably most difficult to estimate is the energy escalation rate. The analysis used an educated estimate of the yearly rate staying fixed at 8% for the next five years, then increasing to 12% for the next five years to account for the increasing demand, then decreasing by 0.5% a year for the remaining 10 years. A sensitivity analysis was performed, altering the energy escalation rate from 4% to 12%, in intervals of 2%. At no rate did any of the hydraulic improvement options produce a cost savings alone; however, the change of escalation rate did alter the cost savings from the operational improvements as reflected in Figure 5.24.

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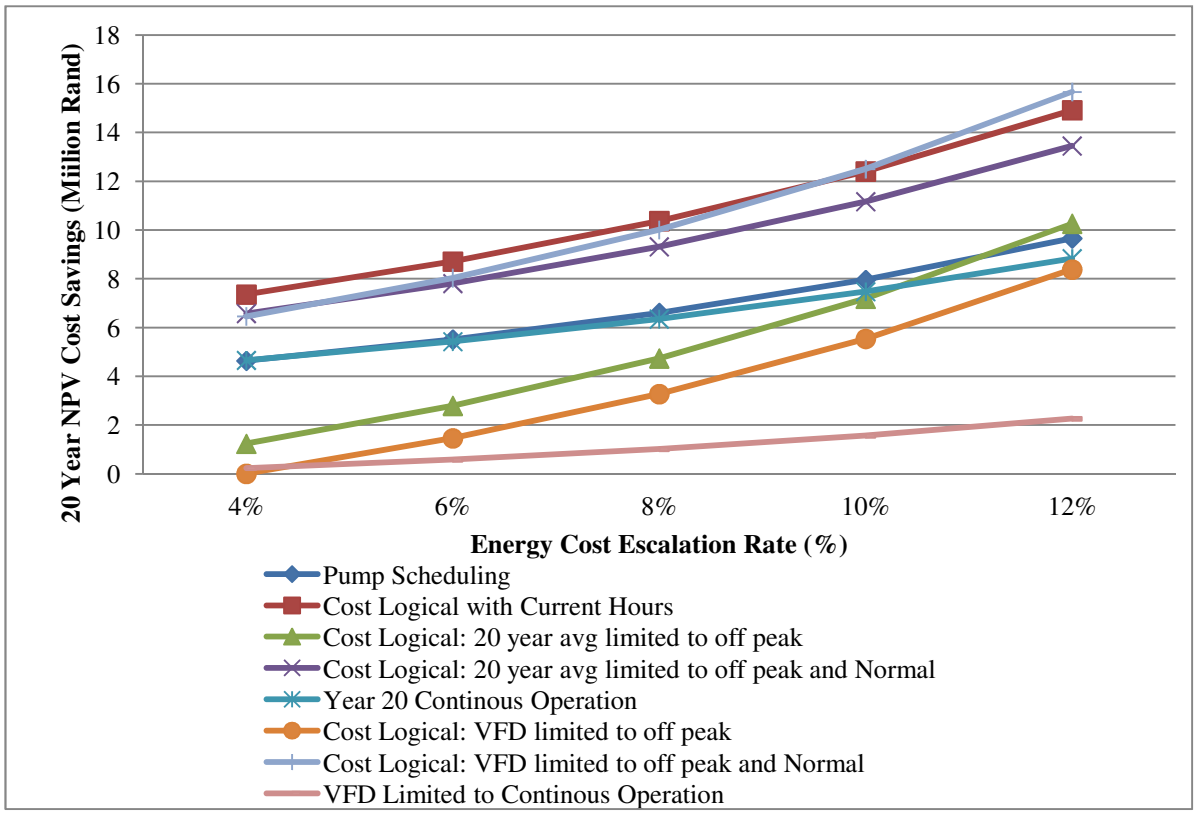

Figure 5.24 - Sensitivity Analysis for Varying Energy Escalation Rates for Roodeplaat Raw Water Pipeline

Utilizing pump scheduling based on the varying electrical prices, with little to no capital expense, could reduce the cost of operation by R 288 000 a year. This 12% savings would only continue to grow as electricity prices continue to rise.

The potential presence of biofilm represents a significant energy loss. The raw water pipeline was built at the same time as the Roodeplaat to Montana pipeline; however it exhibits a roughness that is five times higher, leading to a friction slope that is ten percent higher. There already is equipment in place to dose the raw water with potassium permanganate, this same equipment could be used to dose the pipeline with chlorine or other chemicals that have been shown to be effective at biofilm growth control. Assuming that the treatment results in a pipeline that is hydraulically similar to the Roodeplaat to Montana pipeline, a R 3.8 million savings would be achieved over the next 20 years, a yearly cost savings of 3-5%.

5.4.2 Montana Pipeline Economic Verification

An economic verification was performed with the data collected in the hydraulic condition and operational assessments. The economic analysis was performed as described in Section

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4.6 utilizing the developed software. The 20 year NPV of cost savings, and the 20 year return on investment is summarized in Table 5.27.

NPV of 20-Year Cost Savings (Million Rand)						
	Hydraulic Improvement					
Operation Improvement	Baseline	Foam Pigging	Rigid Pigging	Intensive Cleanin	Rehab	Replacement
With Current Operation	R 0.0	R -45.8	R -64.3	R -41.6	R -79.8	R -265.6
Pump Scheduling	R 20.3	R -26.0	R -44.6	R -22.1	R -60.0	R -247.8
Cost Logical with Current Hours	R 33.3	R -13.3	R -31.8	R -9.5	R -47.4	R -236.2
Cost Logical: 20 year avg. limited to off peak	R 11.7	R -34.6	R -53.1	R -27.8	R -68.1	R -227.2
Cost Logical: 20 year avg. limited to off peak and Normal	R 27.5	R -21.2	R -39.7	R -16.9	R -55.1	R -239.8
Year 20 Continuous Operation	R 19.1	R -29.7	R -48.3	R -25.5	R -63.7	R -249.0
Cost Logical: VFD limited to off peak	R 8.2	R -37.8	R -56.3	R -31.1	R -71.5	R -228.6
Cost Logical: VFD limited to off peak and Normal	R 31.4	R -17.3	R -35.8	R -13.0	R -51.3	R -235.7
VFD Limited to Continuous Operation	R 6.3	R -42.5	R -61.1	R -38.4	R -76.5	R -262.8
Pay Back Period (Years)						
With Current Operation	0	>20	>20	>20	>20	>20
Pump Scheduling	0	>20	>20	>20	>20	>20
Cost Logical with Current Hours	0	>20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak	7	>20	>20	>20	>20	>20
Cost Logical: 20 year avg. limited to off peak and Normal	0	>20	>20	>20	>20	>20
Year 20 Continuous Operation	0	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak	7	>20	>20	>20	>20	>20
Cost Logical: VFD limited to off peak and Normal	0	>20	>20	>20	>20	>20
VFD Limited to Continuous Operation	4	>20	>20	>20	>20	>20

Table 5.27 - Roodeplaat to Montana Pipeline Potential Cost Savings

The energy escalation rate is the variable most difficult to estimate. The analysis used an educated estimate of the yearly rate staying fixed at 8% for the next five years, then increasing to 12% for the next five years account the increasing demand, then decreasing by 0.5% a year for the remaining 10 years. A sensitivity analysis was performed, altering the energy escalation rate from 4% to 12%, in intervals of 2%. At no rate did any of the hydraulic improvement options produce a cost savings; however, the change of escalation rate did alter the cost savings from the operational improvements as reflected in Figure 5.25.

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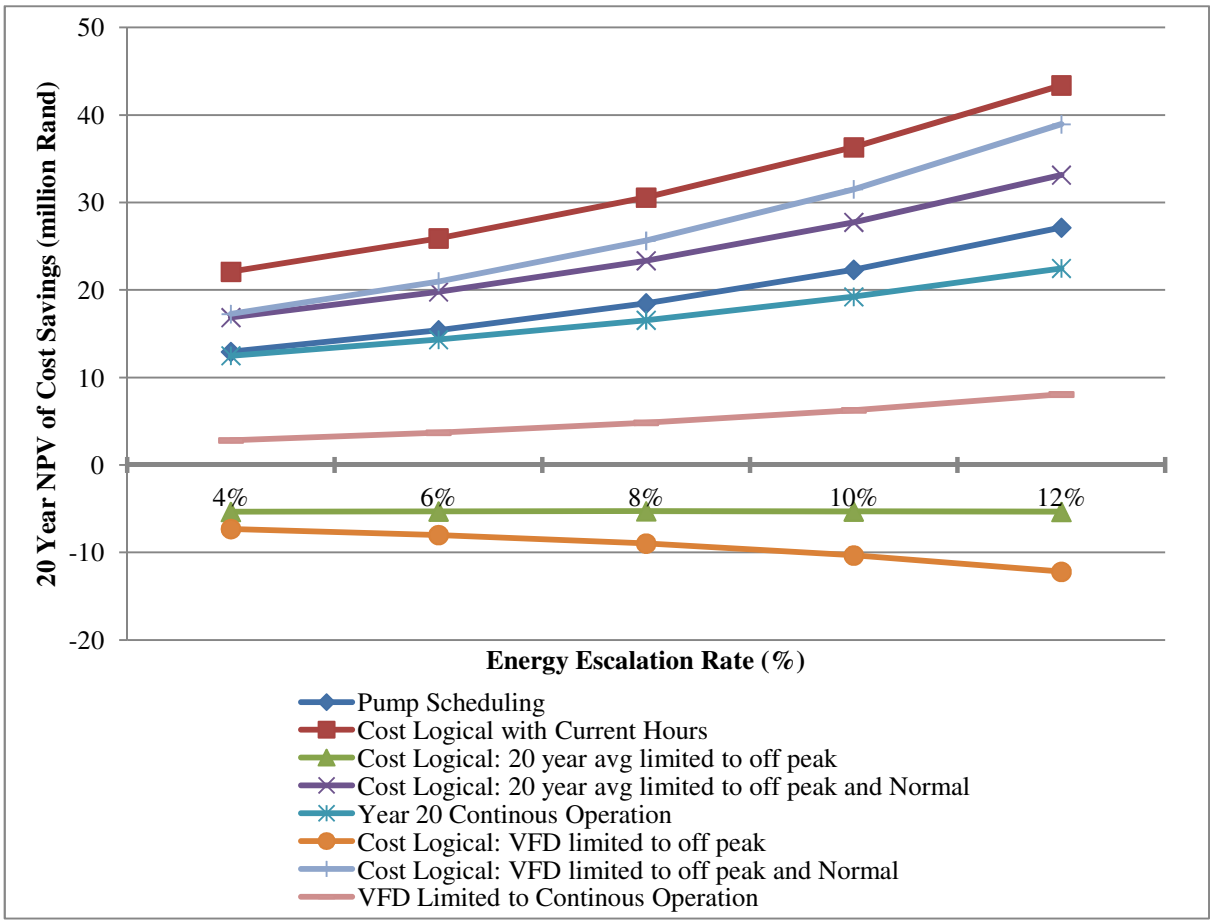

Figure 5.25 - Sensitivity Analysis for Varying Energy Escalation Rates for the Roodeplaat to Montana Pipeline

Utilizing pump scheduling based on the varying electrical prices, with little to no capital expense, could reduce the cost of operation by R 750 000 a year. This 13% savings would only continue to grow as electricity prices continue to rise. In addition to rescheduling the operation of the pumps, removing the strainers from the pipeline would remove a 4 meter energy loss, resulting in an additional cost savings of approximately R 100 000 a year.

5.5 Tshwane Bulk Water System – Summary

The PISP system was applied to nine pipelines selected from the city of Tshwane's bulk water transfer system. The PISP system operated well, showing significant potential cost savings from relatively inexpensive improvements.

The hydraulic evaluation prioritized the Elandsfontein PS to Ekanduatria Res, the Roodeplaat Raw Water PS, and the Roodeplaat to Wallmannsthal PS pipelines, while the operational evaluation prioritized the Roodeplaat to Montana, the Bronkhorstspruit WTP to Res PS, and

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the Elandsfontein PS to Ekanduatria Res pipelines. These pipelines were then analysed in the economic evaluation. The remaining pipelines were evaluated as well to demonstrate the effectiveness of the preliminary evaluation. As will be further discussed in Section 6.1, not including the AADD in the preliminary prioritization caused two pipelines, the Elandsfontein PS to Ekanduatria Res, and the Roodeplaat to Wallmannsthal PS pipelines, to be prioritized even though they are rarely used.

All the pipelines underwent cost analysis utilizing the economic evaluation of the PISP software. The potential 20 year NPV cost savings, recommended improvements, and ranking of pipelines are shown in Table 5.28.

Table 5.28 - Summary of Potential Cost Savings for Selected Tshwane Pipelines

Name	Maximum NPV Cost Savings (million Rand)	Pay Back Period	Operational Improvement Option	Rank
Bronkhorstspruit WTP to Res PS 1	23.10	2	Cost Logical: VFD limited to off peak and Normal	3
Elandsfontein PS to Ekanduatria Res	-	0	With Current Operation	9
Klipdrift WTP to Babelegi Res PS	2.37	0	Cost Logical with Current Hours	7
Rietvlei to Garsfontein PS	14.08	0	Cost Logical with Current Hours	4
Rietvlei to Klapperkop PS	3.66	6	Cost Logical: VFD limited to off peak and Normal	6
Roodeplaat Raw Water PS	30.93	0	Cost Logical with Current Hours	2
Roodeplaat to Montana PS	32.81	2	Cost Logical: VFD limited to off peak and Normal	1
Roodeplaat to Wallmannsthal PS	0.58	0	Cost Logical with Current Hours	8
Wilge River PS	11.41	0	Cost Logical with Current Hours	5

None of the hydraulic improvements showed potential cost savings, as the roughness re-growth and associated diameter constrictions caused the hydraulic capacity improvements to be short lived. Using the example of the Roodeplaat raw water pipeline, rehabilitation of the

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pipeline would result in a 28.7% decrease in headloss, which would reduce the yearly operating cost by 9%. This improvement however would not be cost effective, as the cost of rehabilitating the pipeline would far exceed the cost savings. However, using the current pumping hours, but operating the pump cost logically, would result in the average electrical price decreasing from 0.55 R/kWh to 0.28 R/kWh, inducing a yearly operating cost savings of almost 50%. This was based on the assumption that the pump would operate when the demand for water were highest, coinciding with the peak and normal electrical cost periods.

5.5.1 Field Testing and Economic Verification – Roodeplaat WTP

Field verification was performed on the two pipelines that the economic analysis determined to have the most potential cost savings, the pipeline to and from the Roodeplaat WTP. The verification first examined the hydraulic characteristics of the pipeline, determining that the raw water pipeline has an absolute roughness of 1.5 mm and the potable water line has an absolute roughness of 0.3 mm. The corresponding roughness growth rates were also determined, all of which were included in the economic verification. The field verification also examined the operational characteristics and restrictions of the WTP and pipeline systems, confirming the pumping hours, flow rates, daily transfer volumes, etc. and included them in the economic verification. The general inspection of the pipelines found the presence of two strainers on the potable water line from the treatment plant to Montana reservoirs. The pressure drop across one of the strainers was tested and found to be around 2 meters.

The economic verification on the Roodeplaat Raw Water Pipeline found that pump scheduling, with minimal upfront costs, would create yearly savings of 8-15% for the first 8 years. However, as the AADD increases, the lack of downstream reservoir storage and increasing pumping hours would decrease the potential cost savings. The option with the greatest potential for cost savings would be utilizing the installed VSDs and adding downstream storage to remove pump operation during peak hours. Table 5.29 provides a summary of the potential cost savings for each of the examined options.

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Table 5.29 - Potential Cost Saving for Roodeplaat Raw Water Pipeline

NPV of 20 Year Cost Savings (Million Rand)						
	Hydraulic Improvement					
Operation Improvement	**Baseline**	**Foam Pigging**	**Rigid Pigging**	**Intensive Cleaning**	**Rehab**	**Replacement**
With Current Operation	R 0.0	R -12.2	R -20.7	R -13.9	R -21.2	R -71.3
Pump Scheduling	R 0.4	R -11.8	R -20.3	R -13.6	R -20.8	R -70.9
Cost Logical with Current Hours	R 12.9	R 0.5	R -8.0	R -1.3	R -8.6	R -59.7
Cost Logical: 20 year avg. limited to off peak	R 8.0	R -7.4	R -16.3	R -9.4	R -15.6	R -57.4
Cost Logical: 20 year avg. limited to off peak and Normal	R 12.2	R -2.3	R -10.8	R -4.0	R -11.2	R -61.0
Year 20 Continuous Operation	R 8.6	R -5.8	R -14.3	R -7.6	R -14.8	R -64.8
Cost Logical: VFD limited to off peak	R 6.2	R -9.2	R -18.1	R -11.4	R -17.5	R -58.6
Cost Logical: VFD limited to off peak and Normal	R 13.5	R -0.9	R -9.5	R -2.7	R -9.9	R -59.6
VFD Limited to Continuous Operation	R 3.0	R -11.4	R -19.9	R -13.2	R -20.4	R -70.7

Note: Where cost savings was not achieved, the increased cost is displayed as a negative cost savings

The economic verification on the Roodeplaat to Montana Pipeline found that pump scheduling, with zero upfront costs, would create a yearly savings of 10-12% for the next twenty years. The option with the greatest potential for cost savings would be utilizing the current pumps and available storage to operate the system cost logically. Table 5.30 provides a summary of the potential cost savings for each of the examined options.

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Table 5.30 - Potential Cost Savings for the Roodeplaat to Montana Pipeline

NPV of 20 Year Cost Savings (Million Rand)						
Operation Improvement	**Hydraulic Improvement**					
	Baseline	**Foam Pigging**	**Rigid Pigging**	**Intensive Cleaning**	**Rehab**	**Replacement**
With Current Operation	R 0.0	R -45.8	R -64.3	R -41.6	R -79.8	R -265.6
Pump Scheduling	R 20.3	R -26.0	R -44.6	R -22.1	R -60.0	R -247.8
Cost Logical with Current Hours	R 33.3	R -13.3	R -31.8	R -9.5	R -47.4	R -236.2
Cost Logical: 20 year avg. limited to off peak	R 11.7	R -34.6	R -53.1	R -27.8	R -68.1	R -227.2
Cost Logical: 20 year avg. limited to off peak and Normal	R 27.5	R -21.2	R -39.7	R -16.9	R -55.1	R -239.8
Year 20 Continuous Operation	R 19.1	R -29.7	R -48.3	R -25.5	R -63.7	R -249.0
Cost Logical: VFD limited to off peak	R 8.2	R -37.8	R -56.3	R -31.1	R -71.5	R -228.6
Cost Logical: VFD limited to off peak and Normal	R 31.4	R -17.3	R -35.8	R -13.0	R -51.3	R -235.7
VFD Limited to Continuous Operation	R 6.3	R -42.5	R -61.1	R -38.4	R -76.5	R -262.8

Note: Where cost savings was not achieved, the increased cost is displayed as a negative cost savings

Additional to the potential savings from improving the system operation, removal of the two strainers on the pipeline would result in a savings of approximately R100 000 for the first year, with the yearly savings continuing to grow as the price of energy increases.

5.5.2 Recommended Implementation Schedule

The application of the PISP system to the city of Tshwane's bulk water transfer system showed there are significant cost savings that can be achieved with minimal capital expense. The field testing on Roodeplaat WTP showed that a cost savings of approximately 12% could be achieved by optimizing the operation of the plant's existing facilities. Pump scheduling, either through commercially available software, such as Aquadapt, or through utilizing the city's engineering expertise, should first be implemented to achieve the potential cost savings. Additionally, the strainers on the Roodeplaat to Montana Pipeline should be examined, to determine what, if any purpose they serve. A cost analysis of the purpose of the strainers versus the long term energy cost should be undertaken, and most likely, the strainers

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should be removed. The 2016 planned upgrade of the WTP should consider the addition of a reservoir upstream of the plant, as well as an expansion of the current clear water reservoir to allow for future operations to exclude pumping during the peak electrical periods.

The data extracted from the City of Tshwane's hydraulic modelling software showed significant errors. For example, IMQS showed the static head on the Roodeplaat to Montana pipeline as 255 meters, where in actuality, it was closer to 150 meters. Discrepancies were also found on the operating flow rates, pumping hours, and AADD. The City of Tshwane should review the data input to their hydraulic model, as these discrepancies affect the accuracy of the hydraulic model, as well as the long term planning that is done based on this modelling.

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6 Conclusion and Recommendations

The original hypothesis that the cost of hydraulic and operational improvements will be offset by the decreased energy cost was both confirmed and rejected. As seen in Chapter 5, the cost of hydraulic improvements for the pipelines investigated was not offset by the energy cost savings achieved; however, the cost of operational improvements was offset by the significant energy cost savings achieved.

These results can be expanded to state that energy savings alone does not justify the cost of pipeline renewals. There are other factors, such as high repair costs, excessive leakages, structural deterioration, potential failure, water quality degradation, etc. will determine when a pipeline should be hydraulically renewed. The cost benefit analysis of the inclusion of these factors can be calculated using the software discussed in Section 2.8.

6.1 Pipeline Improvement Selection and Prioritization System

The preliminary evaluation of the PISP system showed that a relatively simple system could be developed; using easily accessible data to determine which pipelines should receive further analysis. The initial selection process requires further refinement, as pipelines that are not regularly operated, only serving as emergency backup capacity, were included. The purpose of the preliminary evaluation was to quickly identify problem pipelines; however it prioritized pipelines without significant potential cost savings.

The economic analysis showed that hydraulic improvements to the pipelines resulted in short term energy efficiency gains, but as the pipeline continued to age, the effect of the improvements decreased, confirming the importance of a thorough cost analysis. The effect of the hydraulic improvements, namely the reduction of the roughness parameter and removal of diameter constrictions, was estimated as there is little literature to discuss how these improvements will affect a specific pipeline. If the PISP system were to be applied by a municipality, both the estimate of the savings gained from hydraulic improvements and the estimated cost of those improvements would be improved by the municipality's experience from past projects.

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Compared to the analysis of the hydraulic improvements, the effect of the operational improvements was more accurately quantified, resulting in more accurate cost savings estimations. The cost of operational improvements was also based on cost functions, but the functions provided reasonably accurate estimates of the cost of the improvements.

The field testing of the PISP system allowed for a more detailed analysis of the pipelines that the economic evaluation had prioritized. The hydraulic assessment allowed the roughness, roughness growth rate, elevations, and pipeline condition to be confirmed, while the operational assessment verified the daily transfer volumes, pumping schedule, and electrical costs. The corroborated data was then used in the economic verification, which provided a more accurate analysis of the operation of the pipeline and the potential cost savings. Thorough a series of applications, the estimated potential cost savings from each of the improvements was calculated and summarized in Table 6.1.

Table 6.1- Estimated Cost Savings from Pipeline Improvements

Cost Savings (%)						
	Hydraulic Improvement					
Operation Improvement	**Baseline**	**Foam Pigging**	**Rigid Pigging**	**Intensive Cleaning**	**Rehab**	**Replacement**
With Current Operation	0%	-126%	-168%	-116%	-174%	-594%
Cost Logical with Current Hours	18%	-107%	-151%	-99%	-158%	-581%
Cost Logical: 20 year avg. limited to off peak	-8%	-125%	-172%	-120%	-176%	-582%
Cost Logical: 20 year avg. limited to off peak and Normal	14%	-111%	-155%	-103%	-162%	-585%
Year 20 Continuous Operation	8%	-117%	-161%	-109%	-168%	-592%
Cost Logical: VFD limited to off peak	-11%	-124%	-170%	-118%	-179%	-584%
Cost Logical: VFD limited to off peak and Normal	16%	-107%	-151%	-98%	-160%	-583%
VFD Limited to Continuous Operation	4%	-120%	-163%	-110%	-173%	-597%

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6.1.1 Recommended Improvements to the PISP System

Several assumptions and negations had to be made in order to develop the PISP system with the current time and resources available. Several improvements to the system are recommended including:

- Reviewing the initial selection of pipelines, to exclude pumped pipeline systems that are not regularly operated or serve only as backup capacity.
- Improving the flexibility of the system to account for user specified situations.
- Including the pump's curve and efficiency in the economic verification, as well as including efficiency degradation over the analysis period.
- Improving the accuracy of the cost functions for hydraulic and operational improvements by incorporating real project costs.

In spite of these shortcomings, the PISP system was applied to analyse nine selected pipelines from the City of Tshwane's bulk water system. The following results were generated through the case study:

- The preliminary evaluation prioritized three pipelines that were in relatively poor hydraulic condition, and three pipelines that were likely to see significant cost savings from operational changes. However, two pipelines serve only as backups and are not regularly used; they did not see significant potential cost savings.
- The economic evaluation found a potential of approximately R100 million savings for the remaining seven pipelines over the next twenty years.
- The economic analysis also determined that the Roodeplat Raw Water Pipeline – supplying water to the Roodeplaat WTP – and the Roodeplat to Montana Pipeline – conveying water from the Roodeplaat WTP to the Montana Reservoir – would have the greatest potential cost savings.
- The field verification on these two pipelines corrected the assumptions of the initial economic evaluation, allowing for a more thorough economic analysis to be performed.
- There were significant discrepancies between the information collected from the City of Tshwane's hydraulic model and the field verified values.

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- The final results suggest that utilizing pump scheduling a 12-15% reduction in yearly electrical cost can be achieved through operational improvements with minimal capital investment.
- With the addition of a reservoir upstream of the WTP and the expansion of the WTP's clear water reservoir, the cost savings could be increased to approximately 25%.
- Additionally, two unnecessary strainers were found, the removal of which would result in an additional savings of an estimated R100 000 each year.
- No hydraulic improvements to the pipeline resulted in a cost savings for the 20 year analysis period.

6.2 Recommendations for Future Work

From this report, areas of additional research that should be performed can be identified. The potential areas recommended for further research include:

- Utilizing the Roodeplaat Raw Water Pipeline dosage facilities to experiment with different chemicals or treatments to control the growth of biofilm.
- Installing additional pressure transducers on the Roodeplaat Raw Water Pipeline to quantify the variations in friction loss caused by seasonal biofilm growth.
- As access inside an operating pipeline is problematic, there is a need to develop a method for determining the nature of the inside of the pipeline without requiring the pipeline to be removed from service.

From the processes developed and results of the case study, several recommendations can be made to the City of Tshwane.

- The PISP system developed in this report should be applied to all 50+ pump stations and their associated pipelines in City of Tshwane's system to investigate potential cost savings.
- The principles of the PISP system should also be applied to the water treatment plants to investigate if cost savings would result from changes to their operation.

Additionally, the effect on Eskom and the greater electrical situation should be examined. Shifting the operating time periods of the 50+ pump stations of the city of Tshwane would result in a loss of income from the high cost electrical periods; however this is likely negated by the lower peak load factor for Eskom. There is also the potential of utilizing some of the

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city's pump stations to allow for demand side management of the electrical system, allowing Eskom to dictate the operation of the pump stations to remove potential "load shedding" that has been necessary recently.

The development of the PISP system highlighted the need to include potential additional reservoir storage to optimize pump system operation. The additional storage allows for the pumps to be operated only when the electrical cost is lowest. Additional work in this field would suggest that future pump scheduling and system optimization programs include potential storage near pumped pipeline systems to facilitate optimal operation, as it was shown to be cost effective in the Tshwane case study. Building on these results is an important step in developing a complete system for optimal pumped pipeline operation.

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