CONSIDERATIONS IN THE HYDRAULIC DESIGN OF PIPELINES

Prof S J van Vuuren

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Considerations in the Hydraulic Design of Pipelines

Report to the
Water Research Commission

by

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Considerations in the Hydraulic Design of Pipelines

Executive Summary

The objective of the research was to investigate the hydraulic capacity of aging pipelines and to relate the reduction in hydraulic capacity to the major contributing factors.

The report summarises the findings of pipe reviews which were conducted during the research project and highlights the following actions which should be considered during the hydraulic design of pipelines:

- Review and incorporate available **recorded hydraulic performance data of pipelines in the region in the design of new infrastructure**;
- Include the **secondary energy loss associated with the dimensional details of the couplings in the calculation of the energy loss in the pipeline**;
- Use the proposed **BRM (biofilm resistance model) to calculate a representative roughness for biofouled pipelines**;
- Implement the proposed procedure to **determine the remaining useful life of pipelines to be able to prioritize the upgrading or replacement** of system components; and
- Provide monitoring points for the **initial, continuous or intermittent hydraulic assessment of the pipeline.**

Table i provides a summary of the calculated roughnesses and the yearly increase in the roughness for the pipelines which were assessed during this research. The pipelines which were severely affected by biofilm growth are highlighted with a hash tag (#).

Table i: Summary indicating calculated changes in the absolute roughness of the pipelines

Location ID	Pipe ID	Water Trans-ferred	Pipe diameter (mm)/ Installation date	Pipe material/ liner	Calculated roughness, k_s (mm)	Yearly roughness increase, α (mm/a)
1	Kloofsig	Sewage	250/1975	Steel/Bitumen	0,541	0,0127
2	Erasmia		358/1978	Steel/Bitumen	0,636	0,0223
3	De Rust ##	Raw water	110/1996	uPVC	1.583 #	0,0914
4	Bergriver Dam to Wemmershoek River Release		1500/2008	Steel/CML	1.7	0.214
5	Blackheath Gravity Pipeline		1500/1980	PCP	0.85	0.019
6	Roodeplaat Dam to Roodeplaat WTW		800/2005	Steel/Epoxy	0.95	0.25
7	Roodeplaat WTW to Montana Reservoir	Treated water	750/2005	Steel/CML	0.38	0.023
8	Lower Blyde Irrigation System Pipeline (Data Review 2012 to 2013) ##	Raw water	1500/2000	Steel/Copon	+4.5 #	+0.318
9	Inyaka ##		700/2012	Steel/Epoxy	3.64 #	1.198
10	Rietspruit to Davel (different sections)		1300/1984	PCP	0.257 to 2.232	0.006 to 0.069

Note:

\# *Roughness influenced by the presence of biofilm which creates residual material build-up (Option 3 biofilm growth – **Section 4**) (k_s calculated on the original internal diameter)*

\#\# *Pipelines which are severely influenced by biofouling.*

During the execution of this project it became apparent that the negative influence of biofilm growth on the hydraulic capacity should be considered by increasing the roughness parameter, λ (**Section 4**). The incorporation of the influence of biofilm on the representative roughness was defined in the BRM (**biofilm resistance model**) (**Sections 4.5** and **4.6**).

When the biofilm resistance model (BRM) is applied for Option 3 biofouling, the roughness is calculated for the recorded flow rate and energy loss for the diameter of the pipe equal to the original **diameter minus 2 times t_b**. **Figure i** reflects the different data sets for the field measurements conducted on the Blyde (LBIS) pipeline and the Inyaka (Bushbuckridge) pipeline, showing how the assumed biofilm thickness will change the representative roughness. In **Figure ii** the range for the vertical axis for the a biofilm thickness varying between **7 and 13 mm in the Blyde pipeline** and **14 to 18 mm in the Inyaka pipeline** is shown in the shaded boxes. Based on the recorded data the "skin" roughness indicated by the dashed lines (minimum and maximum) for these two pipelines varies between 0.93 and 2.60 mm for the review done on a reduced internal diameter of D-2t_b.

It is proposed (based on the limited data) that if Option 3 bioufouling occurs, the friction loss can be calculated on the reduced diameter and the **representative roughness be calculated for the biofouled pipeline, using the BRM and specifically the relationships shown on Figure ii and included in Table i. The skin roughness of the biofilm can conservatively be between 1 and 2.75 mm**.

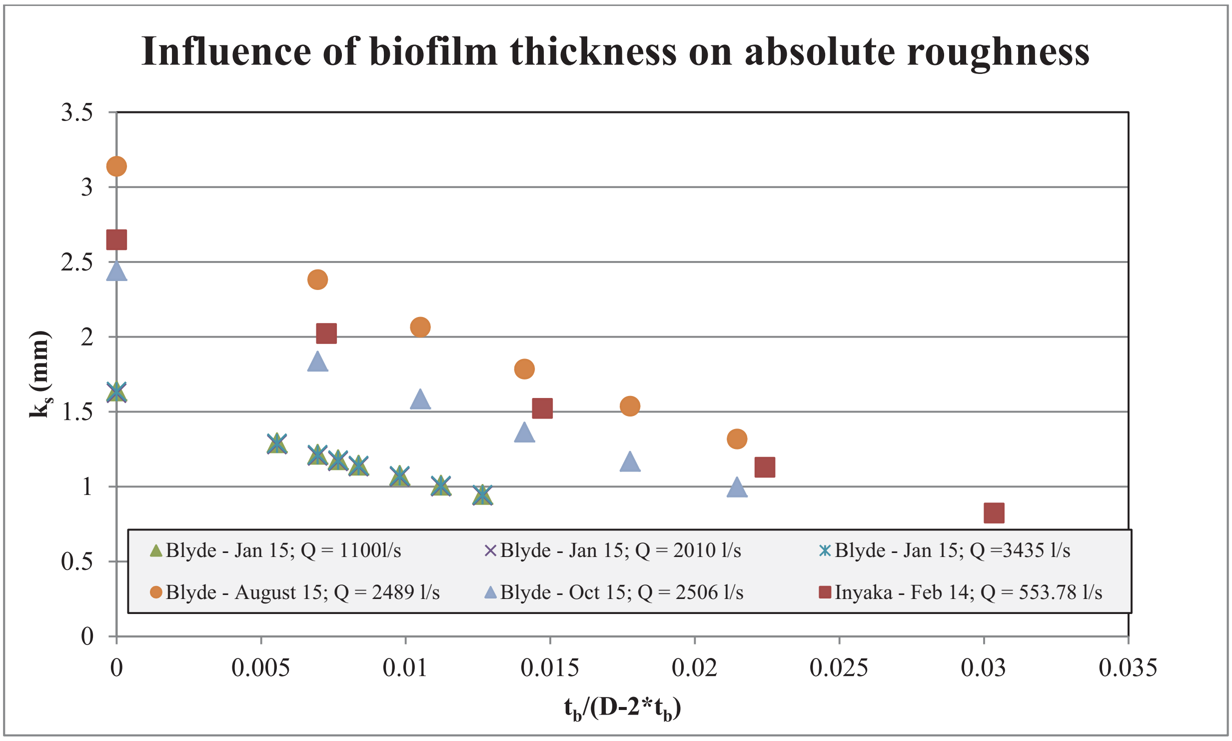

Figure i: Comparing the influence of the biofilm thickness on the calculated roughness – Option 3 biofouling

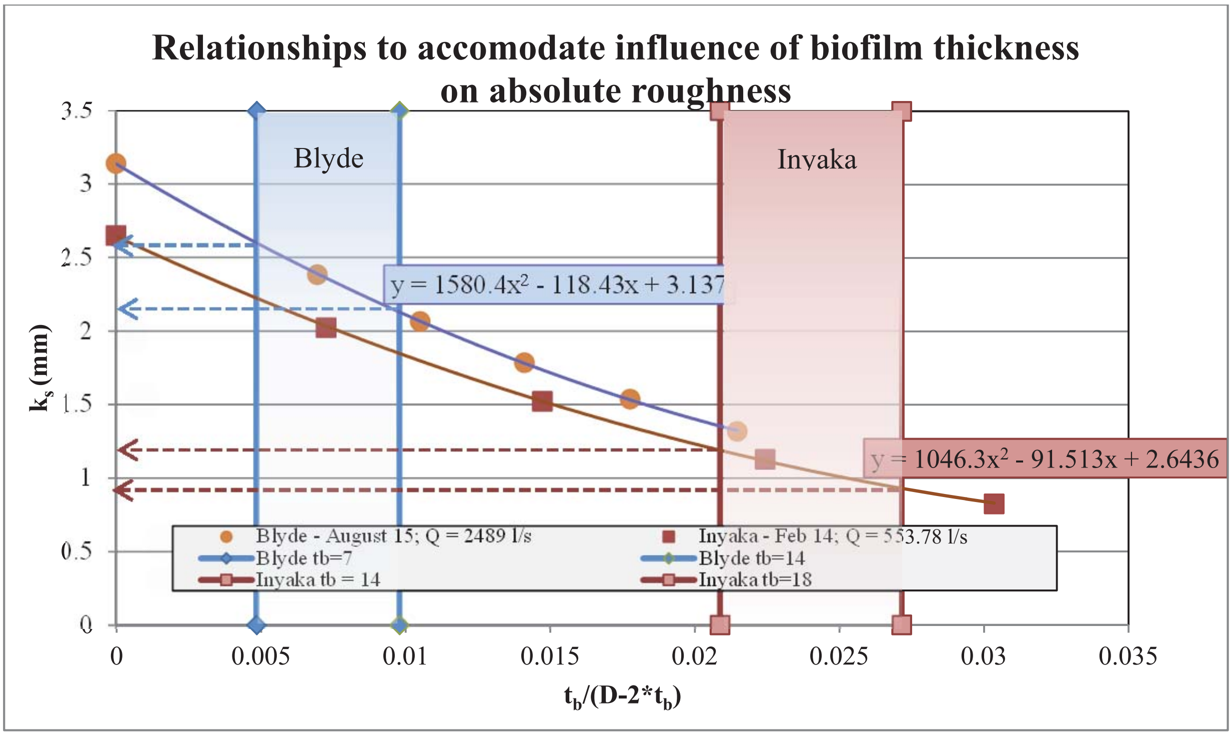

Figure ii: Relationship to include the influence of biofouling on the calculation of the effective roughness – Option 3 biofouling

Based on the limited data defining the influence of biofouling on the hydraulic capacity of pipelines the following relationship is proposed:

$$k_s = aX^2 + bX + c \qquad \ldots(i)$$

Where:

X	=	$t_b/(D-2t_b)$
t_b	=	expected biofilm residual thickness, (mm)
D	=	Internal diameter, (mm)
a	=	Constant
b	=	Constant
c	=	Constant

For the two pipelines which were reviewed (LBIS and Inyaka) the values of the constants (a, b and c) are provided in **Table i**.

Table i: Relationship to calculate the roughness in the pipeline for Option 3 biofouling

Pipeline	Internal diameter (mm)	Relationship #	a	b	c
LBIS	**1458**	$k_s = aX^2 + bX + c$	**1580.0**	**-118.43**	**3.137**
Iyaka	**699**		**1046.3**	**-91.513**	**2.644**

Based on the findings in this report, it is recommended that:

- Field verification tests of the hydraulic performance of water conveyance systems should be implemented as part of the infrastructure management of the water infrastructure in South Africa;
- The monitoring of biofilm growth in pipelines should be expanded to enable the compilation of a "**national biofilm growth production map for pipelines**" for South Africa;
- Further research on the proposed model (BRM) to calculate a representative roughness in biofouled pipelines for Option 3 biofouling is advised;
- A procedure should be developed to establish economic viability of pigging installations on pipelines and the implementation of other anti-microbial growth options; and
- The dataset of pipeline performance reviews should be extended to improve the design guidance for new installations by incorporating the long term expected pipe performance of biofouled pipelines and other capacity reduction factors in the design.

Acknowledgements

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Dr Mike Shand	Aurecon
Mr Walther van der Westhuizen	Department of Water Affairs and Forestry
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Mr Stephen Burke	Umgeni Water
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Mr Anton de Klerk, Mr Louis Coetzee, Mr Abri van Rooyen, Mr Tom Howard and Mr Derik van Eyk from the University of Pretoria assisted in the execution of the field work.

Considerations in the Hydraulic Design of Pipelines

Table of Contents

Considerations in the Hydraulic Design of Pipelines

Table of Figures

List of Tables

Nomenclature

$\Delta\lambda$	=	Change in the value of λ due to the influence of the couplings
A_g	=	Projected area of the air bubble in a plane normal to the direction of the velocity, (m^2)
C_D	=	Drag coefficient
D	=	Internal diameter of the pipeline, (m)
Ds	=	Depth of the step, (m)
F_C	=	Adjustment factor to be used to determine λ_c which can be obtained from Figure 2-4.
g	=	Gravitational acceleration, (m/s^2)
h_f	=	Friction loss, (m)
h_l	=	Secondary loss, (m)
k	=	Secondary loss factor
k_s	=	Absolute roughness of the pipe wall, (mm)
k_t	=	k-value at the end of period 't' (mm)
k_0	=	k-value at start of period, (mm)
L	=	Length of pipe between points being considered, (m)
Ls	=	Length of the discontinuity, (m)
R_e	=	Reynolds number defined as $R_e = \frac{VD}{\nu}$
V	=	Average velocity of the liquid (m/s)
Vol	=	Volume of the gas bubble (m^3)
α	=	Yearly increase in the roughness (mm/a)
λ	=	Value of the calculated pipe friction factor (lambda) with the inclusion of the skin friction and the inherent resistance of the fluid
λ_C	=	Effective pipe friction factor (lambda) that includes the effect of the couplings, i.e. defined as the design friction factor
ν	=	Kinematic viscosity of water, 1.101E-06 at 20°C, (m^2/s)
ρ_g	=	Density of the gas (kg/m^3)
ρ_L	=	Density of the liquid (kg/m^3)

Considerations in the Hydraulic Design of Pipelines

1 Introduction and objectives

1.1 Background

The motivation for the project was based on the findings from a previous investigation research project in which the hydraulic capacity of pipelines was reviewed (van Vuuren & van Dijk, 2012), which concluded that:

- Installation of appropriate flow and pressure recording positions on pipelines should be incorporated during the design phase (with a detailed description of the position, equipment and recording details);
- The current database on roughness values in pipelines should be extended;
- All new pipelines should be hydraulically assessed soon after the installation to obtain the initial hydraulic capacity; and
- Research on the change in hydraulic capacity resulting from biofilm growth in pipelines, needed to be undertaken.

The results from this research improved the understanding of the complexities related to the hydraulic behaviour of pipelines.

The specific aspects which will be highlighted in this document include:

- Review of the factors which influence the hydraulic capacity of pipelines;
- Calculated roughness and roughness changes obtained from field tests; and
- The development of relationships to consider the influence of biofilm growth on the hydraulic capacity of pipelines.

1.2 Layout of the report

This Summary Report provides an overview of the applicable literature, refers to the methodology used in the field tests, discusses the research findings, and refers to supporting material related to the hydraulic capacity of pipelines.

The Summary Report is structured as is shown in **Table 1-1**.

Table 1-1: Layout of the report

Chapter	Description
2	Review of the factors which influence the hydraulic capacity of pipelines
3	Assessment of pipe roughness based on field measurements
4	Development of a relationship to incorporate the influence of biofilm in the hydraulic assessment of pipelines
5	Regulatory framework and condition assessment of pipelines
6	Conclusion
7	Supporting material
8	References

2 Review of the factors which influence the hydraulic capacity of pipelines

2.1 Introduction

Traditionally, when energy losses in a pipeline are considered, a distinction is made between **secondary** (local) losses which relate to a secondary loss factor and the velocity squared and **friction** losses which are influenced by the roughness parameter λ (influences by the wall roughness and the viscosity of the fluid), the velocity squared, the length of the pipeline and the inverse of the diameter and the gravitational acceleration. Secondary losses related to **couplings and air pockets** and friction losses related to **biofilm growth** should also be considered in the hydraulic assessment of water conveyance systems. In the following paragraphs these aspects are briefly covered.

2.2 Secondary losses

Secondary losses occur at directional changes (bends), transitions, couplings, discontinuities or off takes, at stable air bubbles and at mechanical equipment (valves, etc.), which cause a "local" drop in the hydraulic grade line (available energy). The secondary loss, h_l, is determined by:

$$h_l = k\frac{V^2}{2g} \qquad \ldots(1)$$

Where:

h_l	=	Secondary loss, (m)
V	=	Average flow velocity, (m/s)
g	=	Gravitational acceleration (m/s²)
k	=	Secondary loss factor

The values of the secondary loss factor, k, are well documented for different components used in water systems (van Vuuren & van Dijk, 2012). **Table 2-1** and **Table 2-2** respectively reflect typical secondary loss coefficients at entrances, exits and bends as well as valves.

Table 2-1: Typical secondary (local) head loss coefficients for entrances and bends

<table>
<tr><td colspan="6">Entrances and exits (Stephenson, 1979)</td></tr>
<tr><td rowspan="2">Fitting</td><td colspan="5">Loss Coefficients</td></tr>
<tr><td colspan="2">Type</td><td colspan="3">k</td></tr>
<tr><td rowspan="4">Entrance</td><td colspan="2">Projecting</td><td colspan="3">0,8</td></tr>
<tr><td colspan="2">Sharp cornered</td><td colspan="3">0,5</td></tr>
<tr><td colspan="2">Slightly rounded</td><td colspan="3">0,25</td></tr>
<tr><td colspan="2">Bell mouth</td><td colspan="3">0,05</td></tr>
<tr><td rowspan="4">Exit</td><td colspan="2">Projecting</td><td colspan="3">1,0</td></tr>
<tr><td colspan="2">Sharp cornered</td><td colspan="3">1,0</td></tr>
<tr><td colspan="2">Slightly rounded</td><td colspan="3">0,5</td></tr>
<tr><td colspan="2">Bell mouth</td><td colspan="3">0,2</td></tr>
<tr><td colspan="6">Bends (USBR, 1987)</td></tr>
<tr><td rowspan="8">R_b = bend radius
d = pipe diameter</td><td colspan="5">k_b for Angles</td></tr>
<tr><td>$\mathbf{\frac{R_b}{D}}$</td><td>22,5°</td><td>45°</td><td>67,5°</td><td>90°</td></tr>
<tr><td>1</td><td>0,09</td><td>0,15</td><td>0,19</td><td>0,20</td></tr>
<tr><td>2</td><td>0,05</td><td>0,09</td><td>0,11</td><td>0,13</td></tr>
<tr><td>3</td><td>0,04</td><td>0,07</td><td>0,09</td><td>0,10</td></tr>
<tr><td>4</td><td>0,03</td><td>0,06</td><td>0,07</td><td>0,08</td></tr>
<tr><td>6</td><td>0,03</td><td>0,05</td><td>0,06</td><td>0,07</td></tr>
<tr><td>8</td><td>0,03</td><td>0,05</td><td>0,06</td><td>0,07</td></tr>
<tr><td>Contractions
(King, 1954)</td><td colspan="2">d_1/d_2</td><td colspan="3">k_a</td></tr>
<tr><td rowspan="9">Use the velocity in smaller pipe diameter</td><td colspan="2">1,1</td><td colspan="3">0,05</td></tr>
<tr><td colspan="2">1,2</td><td colspan="3">0,11</td></tr>
<tr><td colspan="2">1,4</td><td colspan="3">0,20</td></tr>
<tr><td colspan="2">1,6</td><td colspan="3">0,26</td></tr>
<tr><td colspan="2">1,8</td><td colspan="3">0,34</td></tr>
<tr><td colspan="2">2,0</td><td colspan="3">0,38</td></tr>
<tr><td colspan="2">2,5</td><td colspan="3">0,42</td></tr>
<tr><td colspan="2">3,0</td><td colspan="3">0,44</td></tr>
<tr><td colspan="2">4,0</td><td colspan="3">0,47</td></tr>
</table>

Table 2-2: Typical secondary (local) head loss coefficients for valves

Valves				
	k_v for openings			
Relative opening	**1/4**	**1/2**	**3/4**	**Full**
Gate	10	1,8	0,7	0,2
Butterfly	160	14	1,5	0,3
Y-pattern control (Globe)				
Disc	14	5,1	3,3	5,5
V-Port	7300	225	25	9
Sleeve	22	4,8	1,5	0,5
Needle	5	1,2	0,7	0,6
Ball	80	10	0,9	0
Check valves				
Valve type	**k_v**			
Swing depending on design	0,8 to 2,5			
Recoil (Globe)	12			
Swing	1,5 to 2,5			
Multi-disc	2,3 to 2,5			
Tilting disc	0,7 to 1,0			

2.3 Friction losses

Friction losses occur uniformly along the pipeline (assuming constant equivalent roughness and velocity), defining the friction slope or the energy grade line. The friction loss, h_f, is determined by:

$$h_f = \frac{\lambda L V^2}{2gD} \quad \text{... (2)}$$

Where:

h_f = Friction loss, (m)

λ = Pipe friction factor, defined from the Barr relationship derived from Colebrook-White relationship as: $\frac{1}{\sqrt{\lambda}} = -2\log(\frac{k_s}{3.7D} + \frac{2.51}{R_e\sqrt{\lambda}})$ for $R_e > 4000$

R_e = Reynolds number defined as: $R_e = \frac{VD}{\nu}$

ν = Kinematic viscosity of water, 1.101E-06 at 20°C, (m^2/s)

L = Length of pipe between points being considered, (m)

V	=	Average flow velocity, (m/s)
D	=	Internal diameter of the pipe, (mm)
g	=	Gravitational acceleration, (m/s²)
k_s	=	Absolute roughness of the pipe wall, (mm)

For any given situation where the discharge, internal diameter (D) and friction factor/parameter (λ) are known, the friction loss h_f can be calculated. <u>The shortcoming of this entrenched relationship used in the hydraulic assessment of pipelines, is the disregard for the influence of the biofilm and couplings on the hydraulic capacity. In **Sections 2.4** and **2.5** the influence of these parameters are discussed.</u>

Some of the references to the absolute roughness of the pipe wall are highlighted here. **Table 2-3** lists typical absolute roughness, k_s values for various pipe materials (Chadwick & Morfett, 1999).

Table 2-3: Typical k_s values for different pipe materials

Pipe material	k_s (mm)
Brass, copper, glass, Perspex	0,003
Asbestos cement	0,030
Wrought iron	0,060
Galvanised iron	0,150
Plastic	0,030
Bitumen-lined ductile iron	0,030
Spun concrete lined ductile iron	0,030
Slimed concrete sewer	6,000

Table 2-4 (Kamand, 1988) presents a summary of reported friction coefficients for PVC and cast iron, based on the work by other researchers.

Table 2-4: Values of pipe roughness (k_s), for PVC and cast iron (Kamand, 1988)

Reference	PVC	Cast iron
	k_s (mm)	k_s (mm)
Anderson (1967)	-	0,2591
Giles (1962)	-	0,2438
Hansen et al. (1979)	0,0015	0,26
Heermann and Khol (1983)	0,003-0,03	-
Jeppson (1976)	0,0021	0,26
King (1954)	0,00152	0,2591
Nelson (1976)	-	0,2591

Other references are also available as shown in **Table 2-5** **(Ojha, Lacouture, Gottschalk, & MacInnes, 2010)**.

Table 2-5: Suggested roughness values for different pipe materials (Ojha, Lacouture, Gottschalk, & MacInnes, 2010)

Pipe material	Suggested roughness parameter (mm)
Cast iron	0,26
Concrete	0,3 to 3
Precast concrete	9,0

Table 2-6 provides recommended absolute roughness values for concrete pipes (Wallingford & Barr, 2006).

Table 2-6: Typically recommended absolute roughness for concrete pipes (Wallingford & Barr, 2006)

Material	Suitable values for k_s (mm)		
	Good	Normal	Poor
Pre-stressed	0,03	0,06	0,15
Pre-cast concrete pipes with "O" ring joints	0,06	0,15	0,6
Spun pre-cast concrete pipes with "O" ring joints	0,06	0,15	0,3
Monolithic construction against steel forms	0,3	0,6	1,5
Monolithic construction against rough forms	0,6	1,5	-

In an unpublished research document obtainable in electronic format from the WRC (van Vuuren & van Dijk, 2006) (refer to **Chapter 7**) the following aspects were highlighted in more detail:

- Basic theory of pipe flow;
- Classical formulae for the calculation of the energy loss;
- Roughness parameters in pipelines; and
- An introduction to biofilm growth in pipelines.

As water infrastructure ages, the absolute roughness of the pipe will change and it is common that the roughness increases. Streeter (1971) proposed a linear relationship for the change in absolute roughness of the pipeline.

$$k_t = k_0 + \alpha t \qquad \ldots(3)$$

Where:

k_t = k-value at the end of period ‘t’ (mm)

k_o = k-value at start of period ‘t’(mm)

α = growth rate per period (mm/a)

t = time elapsed since the start of the operation of the pipeline, (years)

Colebrook and White (1937) reviewed data which was obtained from the New England Water Works and concluded that the yearly increase in the roughness could be between 0,0002 and 0,63 mm. It was also postulated that the change in hydraulic capacity was largely driven by the change in roughness and not the change in diameter, admitting that limited data was used and that large deviations were observed in individual cases.

Lamont (1981) used the Langelier Index (LI) (indicator of the saturation of the water with respect to calcium carbonate) as a water quality parameter to determine the change in roughness under corrosive conditions and proposed the following relationship for the annual increase in the roughness:

$$\alpha = 10^{-(4{,}08+0{,}38\ \mathrm{LI})} \text{ for LI} < 0 \qquad \ldots(4)$$

Suggested values for α are reflected in **Table 2-7**.

Table 2-7: Roughness growth rate for varying water quality (Langelier Index)

Langelier Index	Description of the attack	Yearly increase in roughness (mm/a)
0	Slightly	0,025
-1,3	Moderate	0,076
-2,6	Appreciable	0,250
-3,9	Severe	0,760

Lamot (1981) also indicated that, although it should be possible to determine the growth rate in roughness for conditions where the Langelier Index is positive (scale forming conditions), the limited data could not provide a sound relationship.

Costello (1982), Emery (1980) and Larson and Sollo (1967) also reported that reductions in the hydraulic capacity could be as a result of the aluminium concentration and pH.

AWWA (1962) reviewed 70 tests cases of steel pipes with cement mortar linings or protective coatings. The tests were conducted on pipes with diameters ranging from 100 to 400 mm and reported a change in the roughness up to 0,61 mm/a. **Table 2-8** reflects the calculated value of the change in the roughness obtained from the test cases.

Table 2-8: Calculated roughness growth rate data (AWWA, 1962)

City	Growth rate, α (mm/a)	Water quality description
Atlanta	0,610	Soft water
Fort Worth	0,550	Not documented
Denver	0,180	Mountain waters
New Orleans	0,160	River water (Raw)
Cincinnati	0,140	River water (Raw)
Chicago (south)	0,100	Lake water, alum treated
St. Paul	0,045	Unsoftened surface water
Chicago (north)	0,027	Lake water, alum treated
San Antonio	0,015	Wells in limestone

The major shortcoming of the AWWA (1962) review is that **no reference is made of the influence of biofilm growth** on the friction parameter.

2.4 Losses at couplings

The normal practice of the hydraulic assessment of pipelines excludes the secondary losses which occur at the couplings or at corroded field joints. **Figure 2-1** reflects the corrosion of the field joints on the Hendrina-Duva pipeline in South Africa (Sinotech CC, 2011).

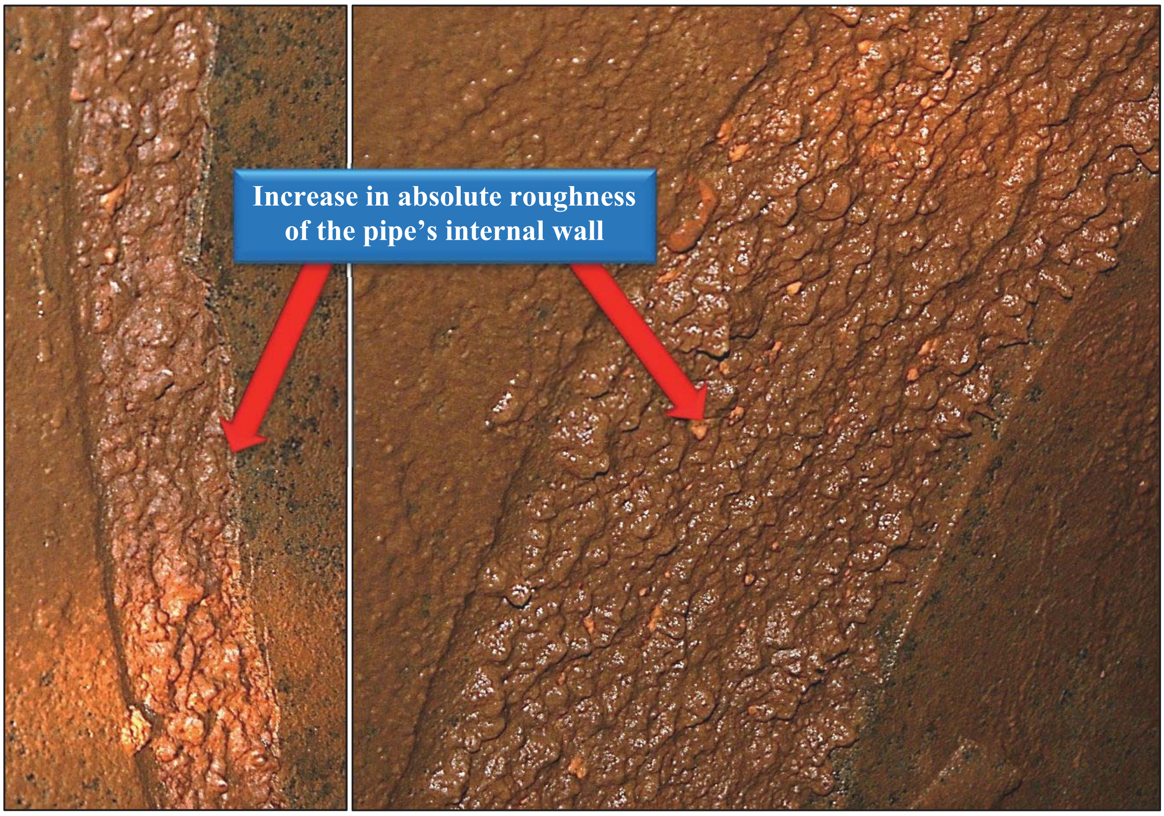

Figure 2-1: Corroded field joint of a bitumen lined steel pipeline

The lack of the known relationships to include the influence of couplings or corroded field joints, necessitated the adaption of existing relationships to cater for the influence on the hydraulic capacity.

The conceptual model proposed by van Vuuren and van Dijk (2012) to consider the **additional losses due to the coupling geometry**, suggested the inclusion of these secondary losses at the couplings, into the roughness parameter, lambda (λ) (refer to**Table 7-3, Section 7**).

This reasoning was based on the knowledge that the friction loss, h_f, in a pipeline can be calculated by the Darcy-Weisbach relationship and that by adding the influence of the losses generated at the couplings, some modification to the roughness parameter, λ, could be implemented to accommodate these (secondary) losses.

The additional loss at the couplings can be incorporated by increasing the value of lambda as follows:

$$\lambda_C = \lambda + \Delta\lambda \qquad \text{... (5)}$$

$$\lambda_C = (1 + \Delta)\lambda$$

or

$$\lambda_C = F_C \lambda \qquad \text{... (6)}$$

Where:

λ_C	=	Effective pipe friction factor (lambda) that includes the effect of the couplings, i.e. the design friction factor;
λ	=	Value of the calculated pipe friction factor (lambda) with the inclusion of the skin friction and the inherent resistance of the fluid;
$\Delta\lambda$	=	Change in the value of λ due to the influence of the couplings; and
F_C	=	Adjustment factor to be used to determine λ_c which can be obtained from **Figure 2-4**.

Figure 2-2 shows a cutaway of a Triplex coupling (Asbestos Cement Pipeline), illustrating the discontinuity in the outer annulus flow area between the pipe and the coupling.

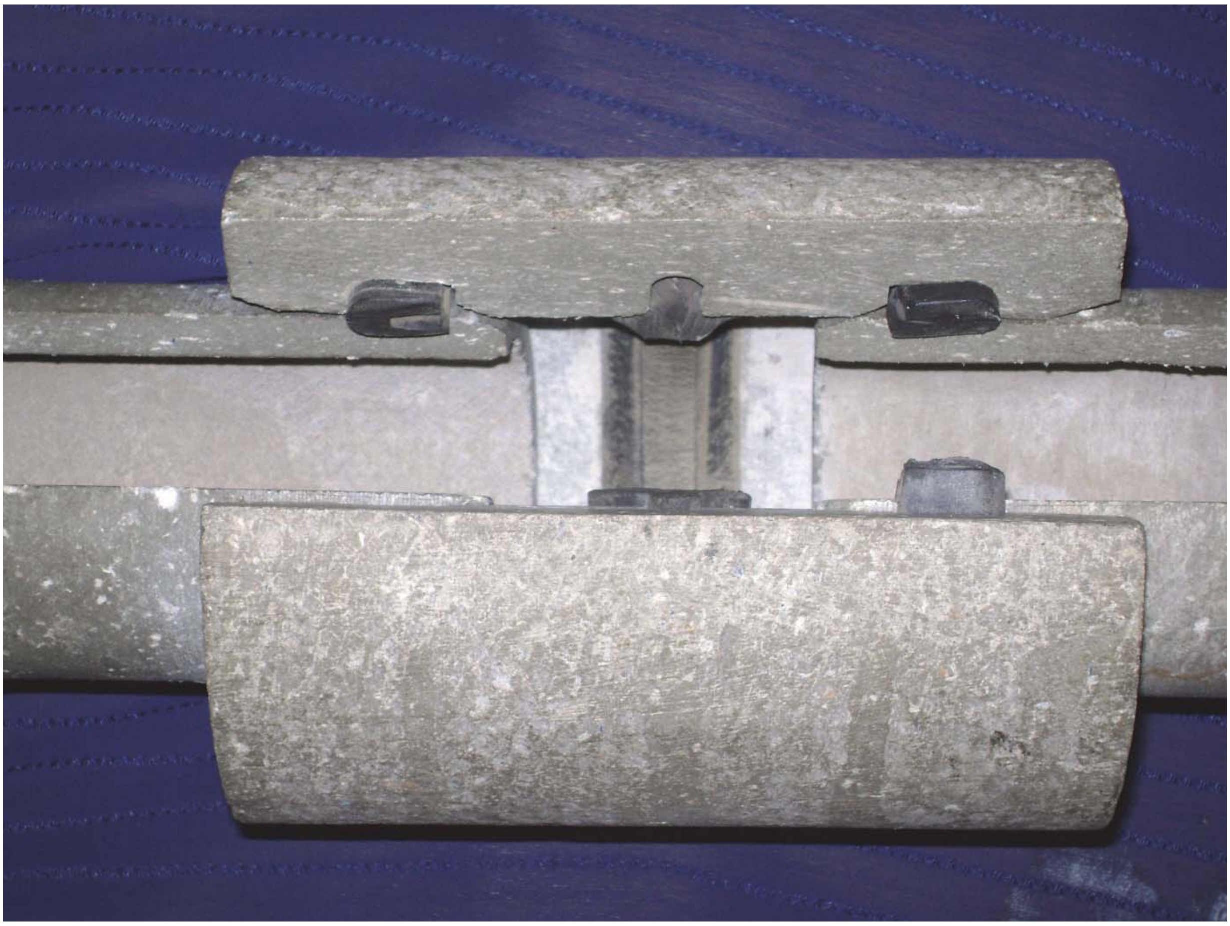

Figure 2-2: Triplex coupling showing the discontinuity of the outer boundary

Figure 2-3 shows a schematic layout of a typical coupling, reflecting the coupling's internal dimensional details which create a secondary loss. These losses may be taken into account by the proposed increase in the lambda value as a function of the Reynolds number (R_e) as shown in **Figure 2-4.** The variables indicated in **Figure 2-3** can be defined as follows:

Ls = Length of the discontinuity, (m);

Ds = Depth of the step, (m); and

D = Internal diameter of the pipeline (m).

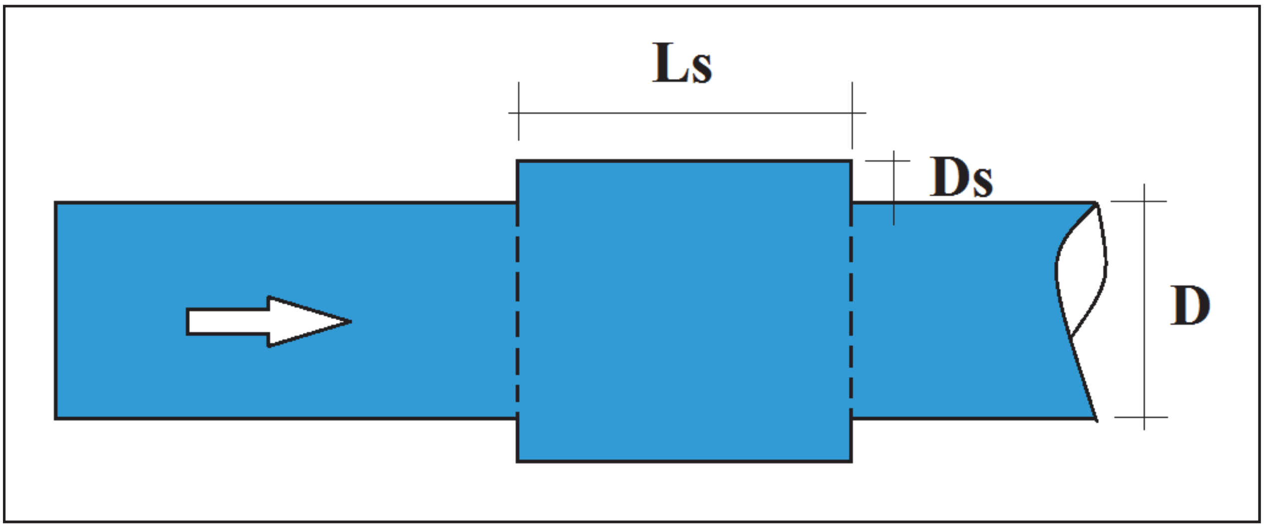

Figure 2-3: Internal dimensional details of the couplings which influence the secondary energy loss

This relationship reflected in **Figure 2-4** was based on experimental results obtained from the review of pipelines with the coupling spacing of 6 m apart (pipe length). If the spacing between the couplings is more than 6 m, the relationship will be conservative and the head loss will be overestimated (van Vuuren & van Dijk, 2006).

Another approach is to include the influence of couplings in the calculation of the losses in a pipeline by increasing the absolute roughness, k_s (Wallingford & Barr, 2006). This procedure is not reviewed in this report.

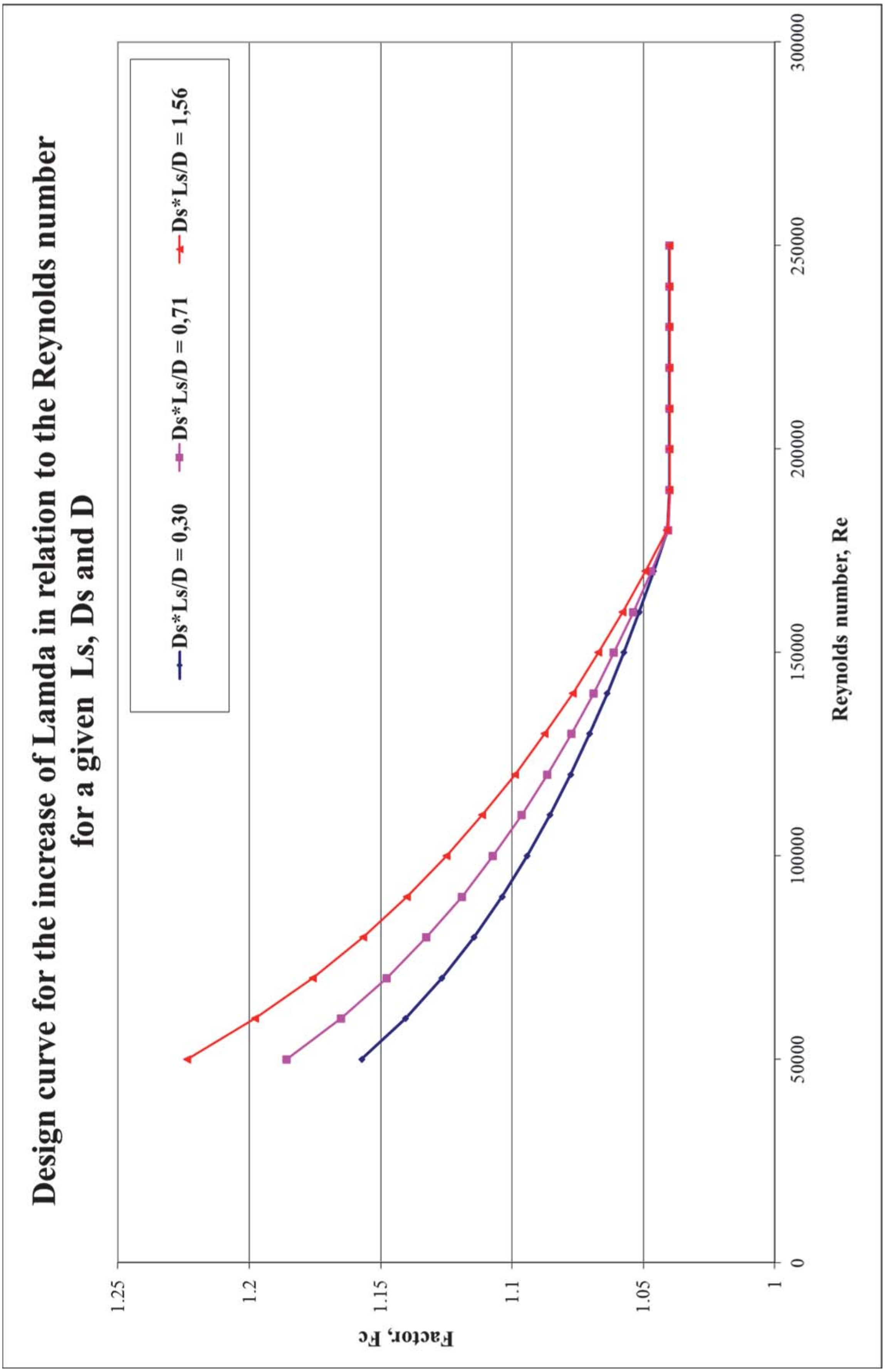

Figure 2-4: Relationship of Fc as a function of Reynolds number (Re)

The physical experimental results were also reviewed by undertaking CFD modelling. **Figure 2-5** shows a plot of the upper half of a pipeline in which the pressure variance is represented by contour lines along the vertical symmetric plane of a pipe with an internal diameter of 150 mm, Ls = 15 mm and Ds = 5 mm when it operates at 1,5 m/s.

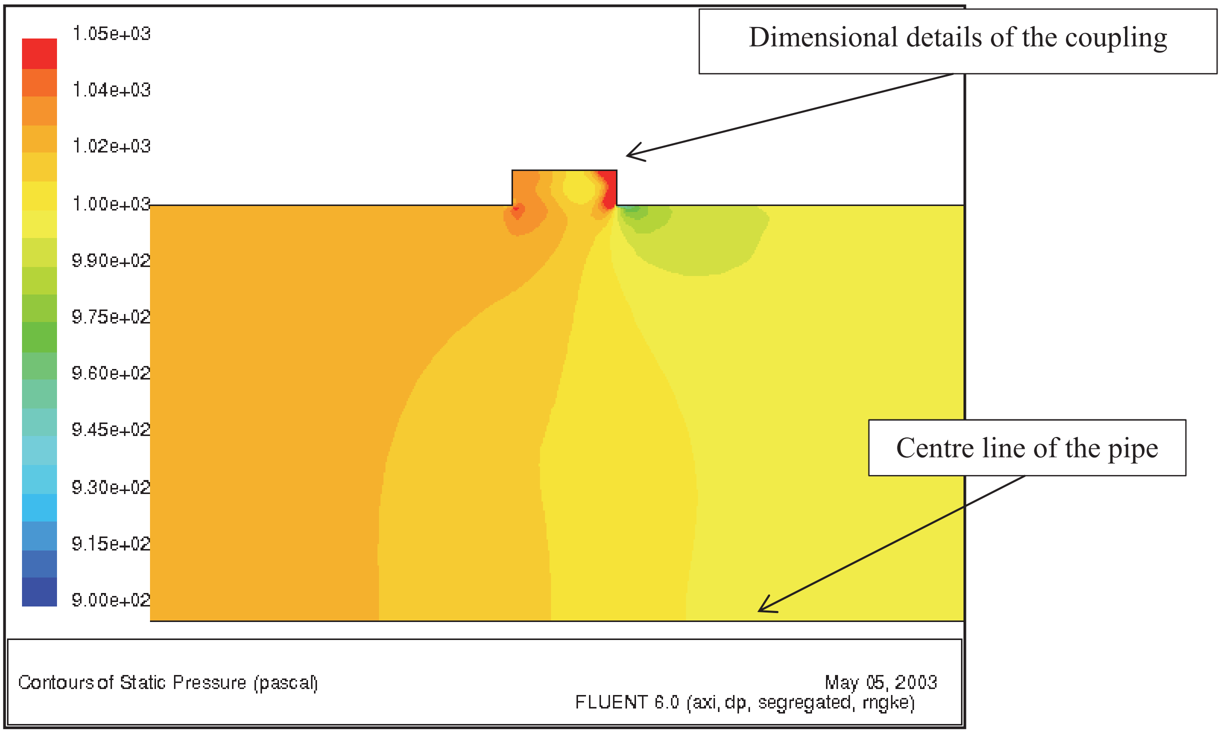

Figure 2-5: Pressure variation resulting from the discontinuity at a coupling

The results from the CFD modelling closely correspond to the physical experimental results.

2.5 Influence of air pockets on the hydraulic capacity of pipelines

2.5.1 Introduction

The optimization of the hydraulic capacity of water transfer systems has the underlying assumption that the pipeline is effectively de-aerated. Pipe failures, intermittent operation, and maintenance will result in sections of the pipeline to be partially or fully drained from time to time. During the filling and charging of the lines, air has to be released in such a manner to control the induced pressures associated with the slam of the air valve and the deceleration of the approaching water column towards a vent at the point in time when all the air has been released. The misconception related to the benefit of a high discharge capacity of air valves, has resulted in various pipe failures.

Effective de-aeration of a pipeline requires that:

- Free air should be transported hydraulically in the pipeline to positions where it can be released;
- A discontinuity in the crown of the pipeline should be provided, to allow the free air to enter into a holding space (the accumulator) below the air valve where the water can be displaced, providing storage capacity for the air, before being released through the air valve;
- A facility with sufficient volume (accumulator) should be provided for temporal storage of the air which has been intercepted through the discontinuity; and
- Correctly sized air valves or vents should be positioned along the pipeline at the required locations.

2.5.2 Discontinuity to trap the air

The complex nature of air movement and factors that influence the efficiency of the discontinuity, suggests that a conservative approach should be used when dimensioning a discontinuity to effectively intercept air bubbles in a pipeline. Applying this within the practical and financial constraints of water distribution systems design, the size of the discontinuity for effective de-aeration during pipeline operation should be based on the following recommendations (van Vuuren & van Dijk, The discontinuity required at an air valve or vent for effective pipeline de-aeration, 2012):

- The minimum discontinuity required for small pipes diameters (D < 300 mm) should be set equal to the diameter (an equal T). An equal T-piece is a standard pipe fitting for these diameters.
- For diameters between 300 mm and 1 500 mm the discontinuity should be greater than or equal to 60% of the pipe diameter but not smaller than 300 mm (**Figure 2-6 shows details for a 700 mm diameter pipeline**).
- Pipes with diameters in excess of 1 500 mm the discontinuity should at least be 35% of the pipe diameter, with a minimum of 900 mm, serving as an access point.

Figure 2-6: Provision made for an air valve on a 700 mm diameter water main

Based on the earlier comment that the air bubble will be transported at a higher velocity in pipelines with positive slopes, a conservative selection of the diameter of the discontinuity should be considered.

2.5.3 Pressure drop across an air bubble

Pipelines are constructed to follow the general profile of the ground for economical and hydraulic reasons. High and low points are therefore created and bends are used to accommodate the change in horizontal and vertical direction. In this report, the term "Apex" describes the highest point in a section of a pipeline, where air will accumulate due to buoyancy forces.

Energy loss in pipelines can be contributed to a number of physical factors of which friction at the pipe wall is the most important in long pipelines. Literature refers to energy loss at transitions, junctions, valves and apex points as secondary or minor losses.

Actual energy loss caused by localised air at apex points of pipelines, as well as the size of the localized air bubble have not been well documented (**Paragraph 2.2**).

The influence of trapped air at apex points on the energy loss is substantial and needs to be taken into consideration when designing pipelines. Based on the results, there are a number of factors that must be highlighted in the calculations of secondary pressure loss due to the presence of air (van Vuuren, van Dijk, & Steenkamp, 2004):

- Residual pressure in the pipe will determine the compression of the air bubble, and will hence influence the energy loss.
- The energy loss is proportional to the bubble size for a specific flow velocity and the secondary loss coefficient; k is inversely proportional to the flow velocity. **This finding suggests that the influence of the decrease in cross sectional flow area, contributes significantly more to the secondary loss than the length of a bubble (comparing similar air volumes) does**.
- The flow velocity is a crucial parameter for the stable size air bubble that will form at the apex.

2.5.4 Hydraulic transportation of air

A sound understanding of the factors affecting the hydraulic transportation of air in a pipeline is paramount for locating air valves. The movement of large air pockets in pipelines has been subject to the following investigations:

- Rising velocity of an air pocket, V_{g0}, in a closed conduit with a layout at different slopes under stationary or dynamic conditions, and;
- The required average water velocity, V to sweep the air pocket downstream with the flow, for various pipe inclinations and bubble sizes.

Although surface tension, inertia forces, viscosity and buoyancy forces influence the movement of air in water carrying conduits, it has been shown that in the context of pipeline engineering, only the inertia forces and buoyancy forces are significant**.** Wisner et al. (1975) have indicated that viscous effects were dictated up to Reynolds numbers, R_e, $\left(\frac{VD}{\upsilon}\right)$ of 10^5. For the case where buoyancy and inertia forces are dominant ($R_e > 10^5$), it follows from the balance of forces on the bubble that:

$$\frac{1}{2}\rho_L C_D A_g V^2 = (\rho_L - \rho_g) g \mathrm{Vol} \qquad \ldots(7)$$

With:

ρ_L	=	Density of the liquid (kg/m^3)
ρ_g	=	Density of the gas (kg/m^3)
V	=	Average velocity of the liquid (m/s)
Vol	=	Volume of the gas bubble (m^3)
A_g	=	Projected area of the air bubble in a plane normal to the direction of the Velocity (m^2)
C_D	=	Drag coefficient

By simplification and substitution it was shown that the rising velocity, V_{g0} of the air pocket can be determined by:

$$V_{g0} = K_1\sqrt{gD} \quad \text{where } K_1 \text{ is a constant} \qquad \ldots(8)$$

Kalinske and Bliss (1943) as well as Wisner, Mohsen and Kouwen (1975) suggest empirical formulae defining the critical velocity to hydraulically remove the air. The formulae were derived from the results obtained in tests performed on inclined pipes transporting a range of different sizes of air bubbles. The proposed formulae based on different air bubble sizes, yielded different values for the critical velocity to hydraulically transport air and are related to the slope and diameter of the pipeline:

$$\frac{Q_c}{gD^5} = 0{,}707\tan\theta \qquad \ldots(9)$$

During the hydraulic transport of the air bubbles, it can either be 'swept' (removed as a whole) or entrained into the solution. The water velocity required to transport the air is referred to as the clearing velocity, V_c.

The maximum bubble volume reviewed by Wisner, Mohsen and Kouwen (1975) was approximately 0.67 times the representative conduit volume $\frac{\pi D^3}{4}$ and the results were presented in a graphical format, with $\frac{V_c}{\sqrt{gD}}$ plotted on the vertical scale and $\sqrt{\sin\theta}$ plotted on the horizontal axis. In **Figure 2-7** the results obtained by Kent (1952) are also shown.

The observed data were enclosed in an envelope line, which was then proposed as the design relationship (Wisner, Mohsen, & Kouwen, 1975) for the clearing velocity, V_c:

$$\frac{V_c}{\sqrt{gD}} = 0{,}25\sqrt{\sin\theta} + 0{,}825 \qquad \ldots(10)$$

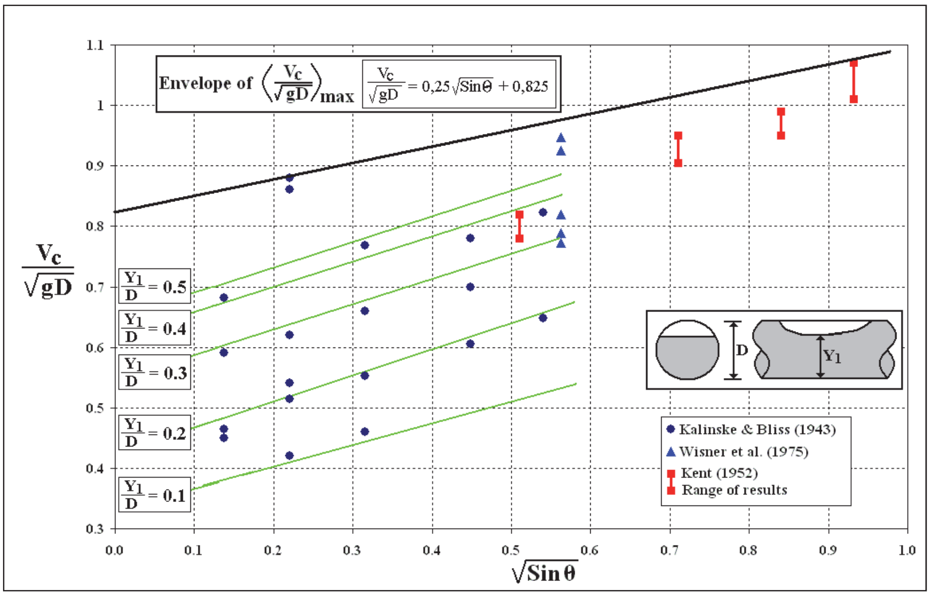

Figure 2-7: Comparison of Kent's formula with his experimental results

The clearing (sweeping) velocity to remove an air pocket has been investigated by several authors Mechler (1966), Kent (1952) and Ahmed et al. (1984). When their findings are plotted in a non-dimensional form of $V_c/\sqrt{gD}$ against the angle of the conduit (θ) it is noted that the clearing velocity to remove air pockets is generally larger than the rising velocity of air pockets in stationary water.

The clearing velocity increases with relatively larger air pockets, denoted in **Figure 2.7** by *n*, which represents the ratio of the air pocket volume to a representative conduit volume $\frac{\pi D^3}{4}$. Gandenberger's (1957) results indicate a maximum clearing velocity required at a conduit angle of about 50°. Kent's results do not indicate any such maximum value, probably due to the fact that the value of θ was not increased beyond 60° by Kent (1952) and hence he proposed the following relationship for clearing velocity:

$$V_c = 1,62\sqrt{\xi}\sqrt{gD\sin\theta} \qquad \ldots(11)$$

where the value of ξ is 0,58 when the air pocket reaches a certain size (L_b / D >1,5 – with L_b the length of the air bubble).

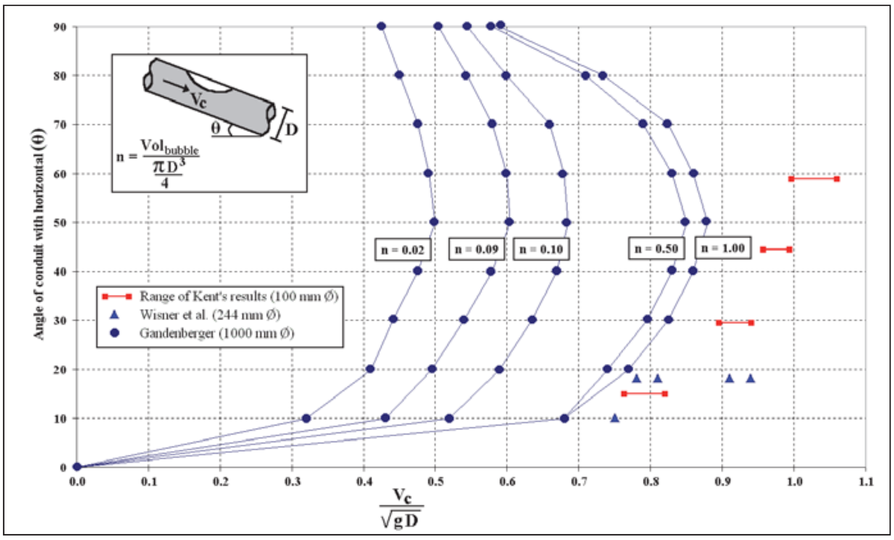

Figure 2-8: Clearing velocity for the removal of air from a pipeline

When the water velocity under the air pocket becomes supercritical, a weak hydraulic jump is formed on the downstream tail of the air pocket. If this is combined with an average velocity greater than 0,8 m/s in the pipe, entrainment of air bubbles occur and are transported downstream, thus reducing the air bubble. The reducing air bubble might at a point in time be swept along the pipeline. Ahmed et al. (The process of aeration in closed conduit hydraulic structures, 1984) investigated this for angles between 10° and 90° and found that the velocity upstream from the bubble must be at least 1,5 m/s to transport the air and suggested that to reduce the air pocket, the velocity should be more than 0,9 m/s.

Based on experimental work conducted on a 110 mm and 160 mm diameter transparent uPVC pipeline with the velocities varied between 0,5 and 2,0 m/s, the slope varied between 0 ° and 15 ° and the relative air bubble size $\left(\frac{Vol_{air}}{\frac{\pi D^3}{4}}\right)$ varied (0,024 < n < 0,540), it was found that the required velocity to hydraulically transport the air could be determined by the following relationship (van Vuuren, van Dijk, & Steenkamp, 2004):

$$V_{min} = a\sqrt{gD}\,\theta^b \qquad \ldots(12)$$

Where:

θ = Slope in degrees

a and b = Constants shown in **Table 2-9** for different size air bubbles (n)

Table 2-9: Values for the constants a and b in Eq. (12) for the different air bubbles sizes (n) reviewed

Bubble size	n	a	b	Goodness of the fit – R^2
Small	0,024	0,2068	0,3716	0,9254
Medium	0,072	0,2178	0,4007	0,9185
Large	0,540	0,2703	0,3686	0,8513

Escaramela et al. (2004) proposed the following relationship for the clearing velocity (V):

$$\frac{V}{\sqrt{gD}} = 0.5599\ (\text{Sin S})^{0,5} + a \qquad \dots (13)$$

Where:

S = Slope in degrees

a = Constant shown below for different size air bubbles

Table 2-10: Value of the constant a used in Eq. (13) for different air bubble sizes (n)

n	a
<0,06	0.4526
0,06≤ and < 0,12	0.5033
0,12 ≤ and < 0,30	0.5739
0,30 ≤ and < 2,00	0.6065

Figure 2-9 provides a comparison of the required clearing velocities suggested in Eq. (12) (van Vuuren, van Dijk, & Steenkamp, 2004)) and in Eq. (13) (Escarameia, Dabrowski, Gahan, & Lauchlan, 2004).

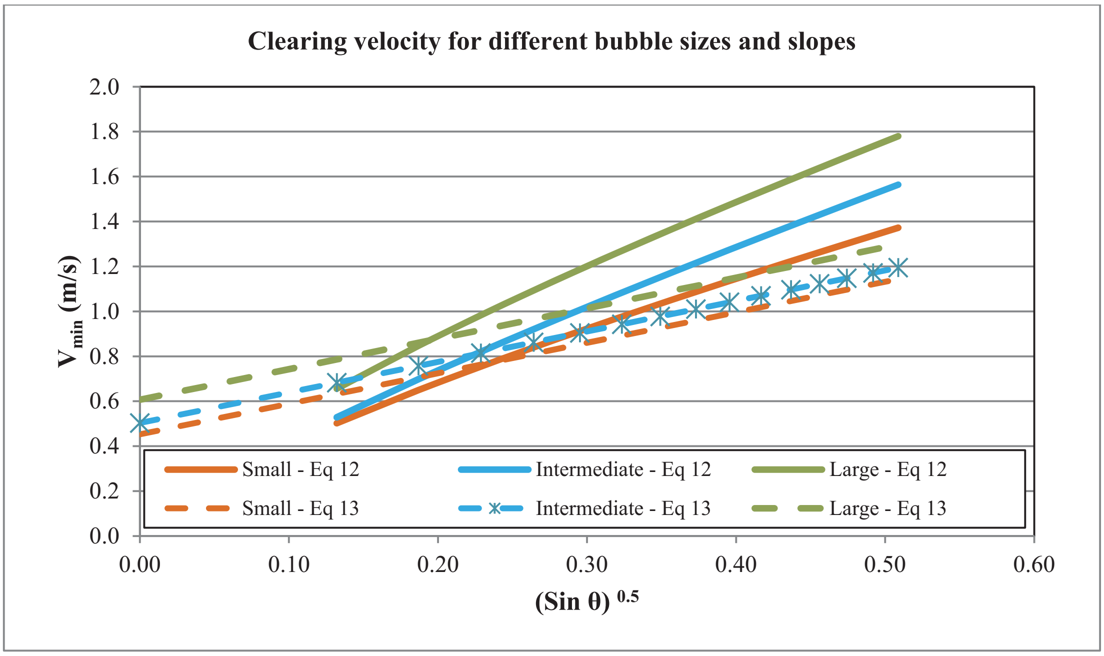

Figure 2-9: Required velocity to hydraulically transport air bubbles with different sizes

2.6 Influence of biofilm growth on the hydraulic capacity of pipelines

2.6.1 Introduction

The shortcomings in the relationships used for the hydraulic assessment of pipelines to incorporate the influence of biofilm growth are illustrated by including field measurements of the energy loss obtained from the following three schemes:

- Hydropower penstocks in Tasmania;
- Lower Blyde River Irrigation Scheme; and
- The raw water pumping main from Inyaka Dam to the Bushbuckridge Treatment Works

2.6.2 Hydropower Penstocks in Tasmania

The influence of biofouling in three hydropower penstock tunnels in Tasmania **(Barton, 2008)** was investigated and the change in the friction factor resulting from pigging was reported. In the case of the Poatina penstock which consisted of a surface and a tunnel section, it was found that the friction factor reduced significantly after the tunnel section was pigged, while the friction factor increased in the surface section of the penstock after pigging. The possible reason for the increase in the roughness in the surface section of the penstock was reported to be the bad state of the coal-tar enamel coating.

Figure 2-10 shows the change in the friction factor, λ resulting from pigging the biofouled Poatina penstocks.

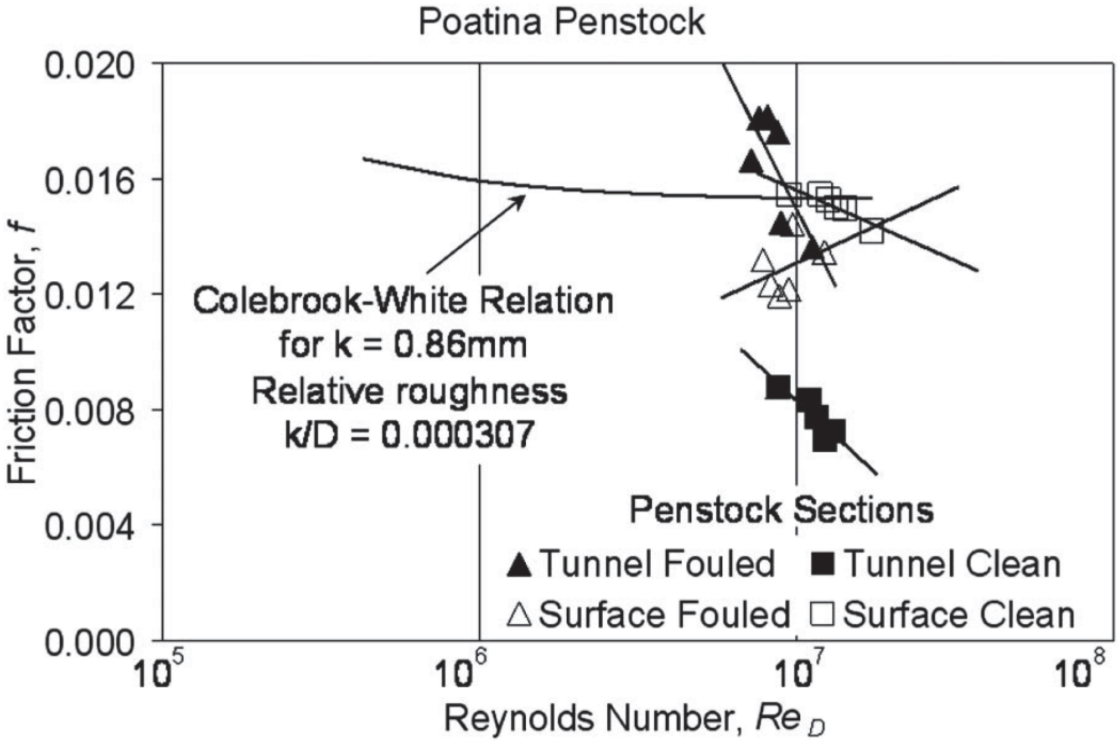

Figure 2-10: Graphical presentation of the change in the friction factor related to the pigging of the Poatina penstock, Tasmania (Barton, 2008)

2.6.3 Lower Blyde River Irrigation System (LBIS)

Due to a decrease in the system hydraulic capacity of the Lower Blyde River Irrigation System it was reviewed. The presence of biofilm was established (van Vuuren & van Dijk, Project K5/1820: Determination of the change in Hydraulic Capacity in Pipelines, 2012). The **influence of biofilm on the friction loss** depends on the growth rate and stable characteristics of the biofilm and whether it produces residual matter (such as Manganese Oxidizing Bacteria (MOB) or Ion Oxidizing Bacteria (IOB)) or whether it captures particles of sediment (produced elsewhere and transported by the flow).

Table 2-11 shows the recorded pressure heads just upstream of the strainers (at chainage 6 000 m) of the LBIS during the initial tests conducted in July 2010.

Table 2-11: **Field tests conducted on the LBIS (July 2010) to determine the change in the effective roughness**

Field test ID	Number of Strainers opened	Q (m^3/s)	Pressure at strainers (Upstream gauge) (m)
I	1	2,85	66,0
II	2	4,10	54,0
III	3	5,10	41,0
IV	3 + 4^{th} partially opened	5,45	35,5

Figure 2-11 shows the discharge through the scours at the strainers during the field tests.

Figure 2-11: Three scour valves opened during the field test on the LBIS (July 2010)

The recorded pressures were used to back calculate the equivalent current (2010) roughness values, k_s and were compared to the original roughness. A uniform growth rate (α) of the roughness is normally assumed, reflected by the following relationship:

$$k_t = k_0 + \alpha t \qquad \ldots(14)$$

Where:

k_t = k-value at the end of period 't' (mm)

k_o = k-value at start of period 't', (0,5 mm was used for k_s in the design of the LBIS to represent the conditions in an aged pipeline)

α = growth rate per period (mm/a)

t = 10 (years)

Table 2-12 shows the calculated current roughness in the upper 6 km section of the LBIS which was tested and it also indicates the rate of change in the roughness over a period of 10 years.

Table 2-12: Roughness (k_s) values and roughness growth factors (α) in the LBIS

Variable	Field test ID			
	I	II	III	IV
Average k_s (mm)	1,78	1,77	1,76	1,76
α (mm/a)	0,128	0,127	0,126	0,126

In cases where the back calculated roughness varies significantly at different flow rates, the following contributing aspects should be reviewed:

- Ensure that all the secondary loss elements are identified; and/or
- Review the secondary loss factors used in the calculation; and/or
- Assess the measurement accuracy of the recorded flow and pressure data.

In the case of the LBIS the biofilm (MOB) was the main contributor to the decay in the hydraulic capacity of the pipeline, resulting from an increase of the roughness of the pipeline from 0,046 mm (new pipeline) (White, 1999) to about 1,76 mm in 10 years (a 38 fold increase).

2.6.4 Bushbuck ridge water supply

The water supply system to the Bushbuckridge Water Treatment Plant consists of two 700 mm diameter steel pipelines with an internal epoxy coating. Field tests were conducted during February 2014 on the new 700 mm diameter pipeline which was installed in 2012/2013. The pipeline has a length of about 2 km, conveying the water from the raw water pump station at Inyaka Dam (**Figure 2-12)** to the raw water balancing dam (**Figure 2-13**) at the Bushbuckridge Water Treatment Plant (BRWTW).

Figure 2-12: Pump Station at Inyaka Dam

Figure 2-13: View of the balancing dam at the BRWTW

Based on the field tests, both the calculated roughness in 2015 and yearly increase in the roughness are reflected in **Table 2-13**.

Table 2-13: Calculated roughness of the Inyaka to Bushbuckridge pipeline

Pipeline	Diameter (mm)	Flow rate (l/s)#	Roughness of the pipeline		
			New (mm)	Current (mm)##	Yearly increase α (mm/a)
Inyaka	700	About 520	0.05	3.64	**1.44** ###

Notes:

Flow rate was captured on the SCADA system.

Colebrook-White relationship used to calculate k_s.

Excessive deterioration in the hydraulic capacity which might reduce when the biofilm growth has reached equilibrium.

3 Assessment of pipe roughness based on field measurements

3.1 Identification of the pipelines for review

The candidate pipelines suitable for the review of their roughness should have pressure tapping positions, flow recording sections, accurate as-built drawings with valve details and invert levels and the flow rate should be controllable. **Table 3-1** shows the pipelines which were selected for review during this study.

Table 3-1: Pipelines which were reviewed during this study

Location ID	Pipe ID	Water Transferred	Pipe diameter (mm)/Installation date	Pipe material/liner
1	Kloofsig	Sewage	250/1975	Steel/Bitumen
2	Erasmia		358/1978	Steel/Bitumen
3	De Rust	Raw water	110/1996	uPVC
4	Bergriver Dam to Wemmershoek River Release		1500/2008	Steel/CML
5	Blackheath Gravity Pipeline		1500/1980	PCP
6	Roodeplaat Dam to Roodeplaat WTW		800/2005	Steel/Epoxy
7	Roodeplaat WTW to Montana Reservoir	Treated water	750/2005	Steel/CML
8	Lower Blyde Irrigation System Pipeline (2010 Survey and Data Review 2012 to 2013)	Raw water	1500/2000	Steel/Copon
9	Inyaka		700/2012	Steel/Epoxy
10	Rietspruit to Davel		1300/1984	PCP

The locations of the pipelines, referenced numerically, which were reviewed during this study, are spatially reflected in **Figure 3-1**.

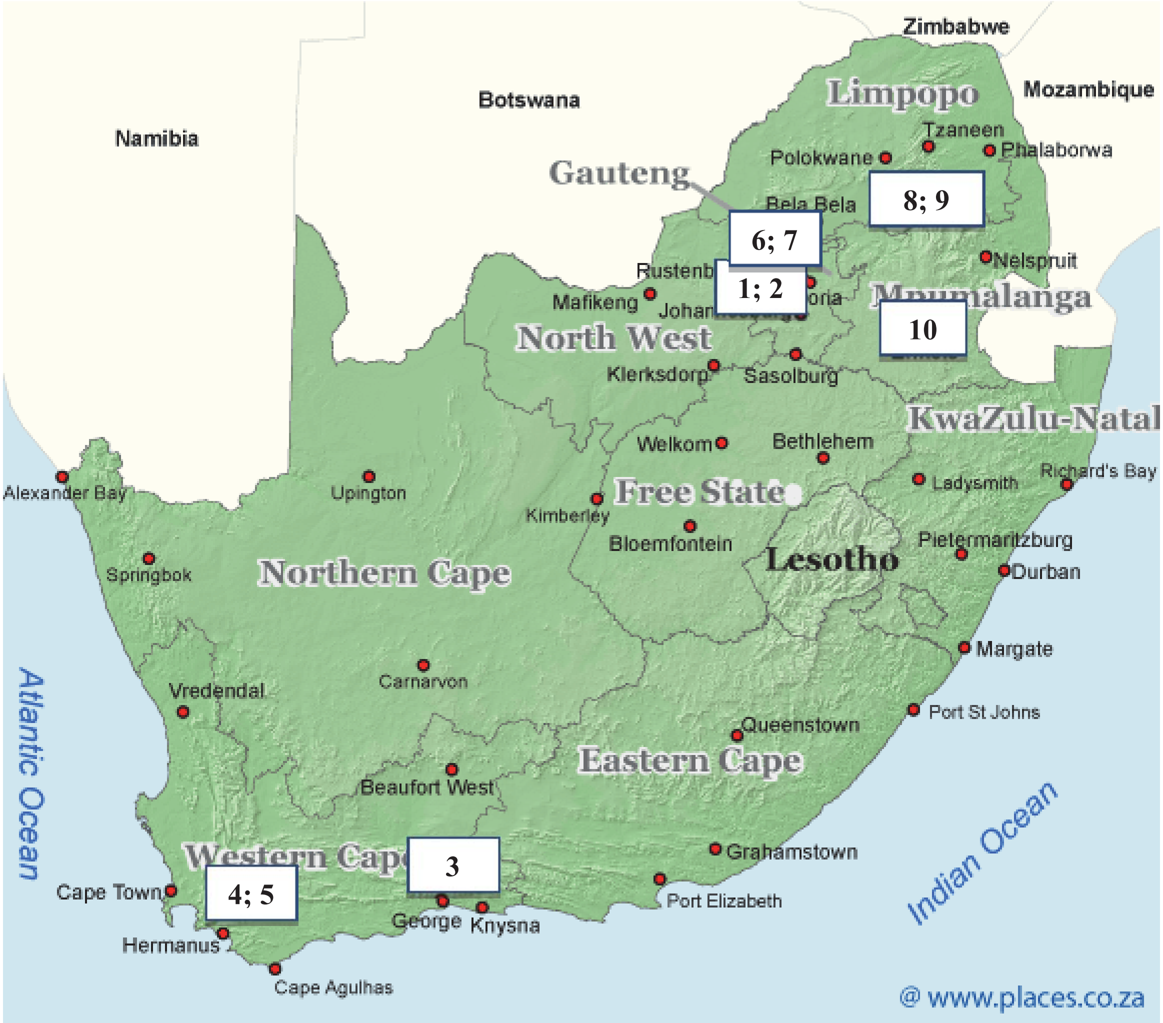

Figure 3-1: Location of the pipelines which were reviewed

Note: The pipeline details for the identification numbers are reflected in Table 3-1.

3.2 Pipeline details

The details of the various pipelines, grouped by the liquid transferred, are briefly referenced below.

3.2.1 Pipelines which were reviewed

The sewer, raw water and treated water pipelines which were reviewed are listed in **Table 3-2**, **Table 3-3** and **Table 3-4** respectively.

Table 3-2: Sewer pipelines reviewed

Location ID	Pipe ID	Pipe diameter (mm)/ Installation date	Pipe material/liner	Review date	Length of pipeline (km)	Operating flow rate (l/s)
1	Kloofsig	250/1975	Steel/Bitumen	July 2013	0,755	65-75
2	Erasmia	358/1978	Steel/Bitumen		1,935	60-90

Table 3-3: Raw water pipelines reviewed

Location ID	Pipe ID	Pipe diameter (mm)/ Installation date	Pipe material/liner	Review date	Length of pipeline (km)	Operating flow rate (l/s)
3	De Rust	110/1996	uPVC	April 2013	3,223	4,2 to 5,2
4	Bergriver Dam to Wemmershoek River Release	1500/2008	Steel/CML	June 2013	4,683	2 960 to 5 510
5	Blackheath Gravity Pipeline	1500/1980	PCP	June 2013	17,453	2 241 to 4 053
6	Roodeplaat Dam to Roodeplaat WTW	800/2005	Steel/Epoxy	February 2014	2,98	290 to 750
8	Lower Blyde Irrigation System Pipeline (2010 Survey and Data Review 2012 to 2013)	1500/2000	Steel/Copon	August 2010 September 2013	6,02	500 to 4300
9	Inyaka	700/2012	Steel/Epoxy	February 2014	2,418	260 to 530
10	Rietspruit to Davel	1300/1984	PCP	May 2014	36,8	565 to 1 915

Table 3-4: Treated water pipelines which were reviewed

Location ID	Pipe ID	Pipe diameter (mm)/ Installation date	Pipe material/ liner	Review date	Length of pipeline (km)	Operating flow rate (l/s)
7	Roodeplaat WTW to Montana Reservoir	750/2005	Steel/CML	February 2012	12,07	270 to 670

3.2.2 Reference to reports containing the description of the reviewed pipelines

The methodology used in the field investigations and the results which were calculated for the pipelines are documented in different reports reflected in **Table 3-5. Section 7** provides references to obtain a copy of the Reports.

Table 3-5: Reference to the different Reports which can be obtained (refer to Chapter 7)

Location ID	Pipe ID	Reference to the Reports in which the pipelines were described (refer to Chapter 7)
1	Kloofsig	K5 2140 DL3
2	Erasmia	
3	De Rust	
4	Bergriver Dam to Wemmershoek River Release	
5	Blackheath Gravity Pipeline	
6	Roodeplaat Dam to Roodeplaat WTW	K5 2140 DL5
7	Roodeplaat WTW to Montana Reservoir	
8	Lower Blyde Irrigation System Pipeline (2010 survey and Data Review 2012 to 2013)	
9	Inyaka	
10	Rietspruit to Davel	K5 2140 DL6

In the following sections the calculated roughness in the pipelines which were reviewed is shown.

3.3 Determination of the roughness of the pipelines which were investigated

3.3.1 Introduction

Included as supporting material (**Chapter 7**), the required preparations for conducting the field measurements to obtain reliable data for the assessment of the pipe roughness, are provided.

The pipelines which were identified in **Table 3-1,** were reviewed and the calculated current roughness as well as the yearly increases in roughness experienced in sewer-, raw- and clean water pipelines are provided below.

3.3.2 Review of the roughness of the pipelines

Table 3-6, **Table 3-7** and **Table 3-8** respectively show the calculated roughnesses for the pipelines conveying sewage-, raw- and treated water.

Table 3-6: Calculated roughness for the sewer pipelines

Pipe ID	Pipe diameter (mm)/ Installation date	Pipe material/liner	Roughness parameter		
			Reference roughness for a new pipe (mm) (Chadwick & Morfett, 1999)	Calculated roughness/aging	
				Colebrook-White (mm)	Yearly increase, α (mm/a)
Kloofsig	250/1975	Steel/Bitumen	0.06	0.541	0.0127
Erasmia	358/1982	Steel/Bitumen	0.06	0.636	0.0223

Table 3-7: Calculated roughness for pipelines conveying raw water

Pipe ID	Pipe diameter (mm)/ Installation date	Pipe material/liner	Roughness parameter			
			Reference roughness new pipe (mm) (Chadwick & Morfett, 1999)		Calculated roughness/aging	
			New	Aged	Colebrook-White (mm)	Yearly increase, α (mm/a)
De Rust	110/1996	uPVC	0.03	0.06	1.583#	0.0914
Bergriver	1500/2008	Steel/CML	0.06	0.3	1.7	0.214
Blackheath	1500/1980	PCP	0.2	0.5	0.85	0.019
Roodeplaat Dam	800/2005	Steel/Epoxy	0.008	0.046	0.95	0.25
Lower Blyde Irrigation System Pipeline	1500/2000	Steel/Copon			4.5 #	0.318
Inyaka	700/2012	Steel/Epoxy			3.64 #	1.198
Rietspruit to Davel (different sections)	1300/1984	PCP	0.06	0.15	0.257 to 2.232	0.006 to 0.069

Note:

The calculated roughness is ***much higher*** *than any documented "aged roughness". The high roughness in some of the pipelines can be attributed to the residual material deposited in the biofilm layer which reduces the internal diameter and significantly reduce the hydraulic capacity of the pipeline.*

Table 3-8: Calculated roughness for a pipeline conveying treated water

Pipe ID	Pipe diameter (mm)/ Installation date	Pipe material/liner	Roughness parameter			
			Reference roughness (mm) (Chadwick & Morfett, 1999)		Calculated roughness/aging	
			New	Aged	Colebrook-White (mm)	Yearly increase, α (mm/a)
Pipeline to Montana Reservoir	750/2005	Steel/CML	0.03	0.15	0.38	0.023

3.3.3 Graphical presentation of the calculated yearly increase in the roughness

Based on the recorded pressure drop over a known distance and the flow rate, the roughness at the time of the fieldwork was calculated and from that the yearly increase in the absolute roughness was derived. **Figure 3-2** shows the annual increase in the roughness for the different pipe diameters included in this study.

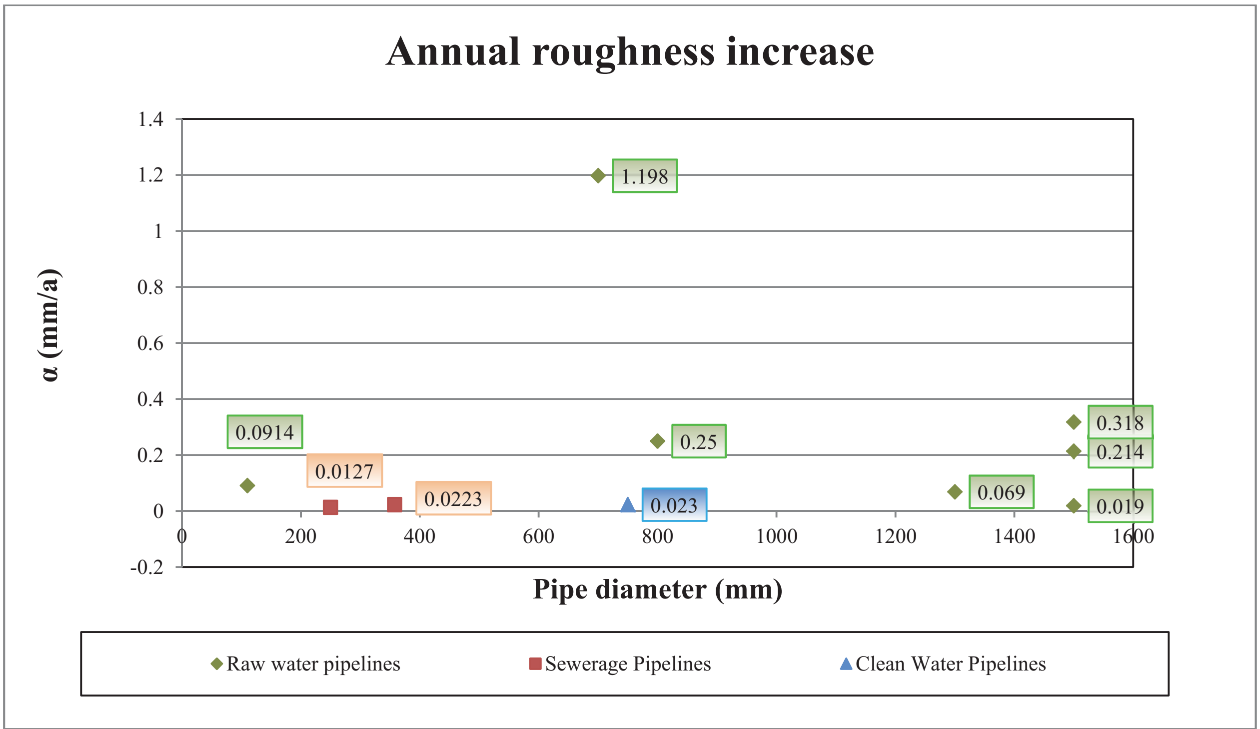

Figure 3-2: Graphical presentation of the annual increase in the absolute roughness for different pipe diameters

The high yearly increase in roughness of 1,198 mm/a for the Inyaka pipeline shown in **Figure 3-2,** relates to the type of biofouling which is experienced in the pipeline. The biofilm in the Inyaka pipeline precipitates residual material to a thickness of about 12 mm in one year.

4 Development of a relationship to incorporate the influence of biofilm in the hydraulic assessment of pipelines

4.1 Introduction

Contrasting to the notion which suggests that the wall roughness determines the hydraulic capacity of pipelines under rough turbulent conditions, this research indicates that biofilm is the dominating parameter affecting the hydraulic capacity in certain areas of South Africa. This suggests that the influence of biofilm should be incorporated in the formulation of the representative roughness for the pipeline. The adaptation of the relationship to determine the representative roughness in a biofouled pipeline should yield a roughness which can be used in one of the known relationships to calculate the energy loss in the pipeline. In the calculation of the energy loss the internal diameter should be equal to the original diameter minus two times the biofilm thickness ($D-2t_b$).

In the next paragraph an overview of the influence of biofouling in pipelines and how it can influence the hydrodynamic shear stress is given.

4.2 Overview to biofouling in water conveyance systems

Biofilm is defined as an accumulation of microscopic animals, plants and bacteria attached at an interface such as a liquid and a fixed boundary, also known as “slime”, “biological deposits”, “microbial mat”, and “organic glue” or by many other descriptive names. Biofilm formation results from a number of processes, which either increases (adhesion, attachment, growth) or decreases (detachment, death, grazing) the amount of accumulated biomass. Biofilm depends on ecosystems and nutrient cycles representing a unique form of life and plays a key role in production and degradation of organic matter in the cycle of phosphorus, nitrogen and sulphur. Biofilm could also present health risks if harmful bacteria is trapped in the biofilm layer.

In some cases, the entire water system can become covered by biofilm, consisting of very complex microbial populations. The occurrence of biofilm, in water conveyance systems, often has the **undesired consequence of increased friction, which causes higher energy consumption as was demonstrated in the Lower Blyde River Irrigation System and in the Bushbuckridge Water supply (Table 2-12 and Table 2-13).**

Figure 4-1 shows the residual layer of deposited material resulting from biofouling in the LBIS. In **Figure 4-2** the biofilm residual in the 700 mm diameter steel pipeline after 6 months in operation is shown.

Figure 4-1 : Example of biofilm growth (MOB) in large diameter pipelines (Blyde River Irrigation System)

Figure 4-2 : Example of biofilm growth (Inyaka Pumping Main) in the raw water pipeline supplying the Bushbuckridge Water Treatment Plant

Biofilm consists mainly of water, which is held by highly hydrated extracellular polymer substances (EPS). The EPS contributes 70-95% of the organic matter of the biofilm and the micro-organisms represent only a minor part of the mass and volume.

The physical properties (rheology) of biofilm determine the shape and mechanical stability of the biofilm structure and affect both the mass transfer and detachment processes. Knowledge of biofilm rheology is crucial to fully interpreting the behaviour of biofilm, particularly those growing in flowing fluids subjected to shear stresses (τ) that vary in magnitude and frequency.

The surface on which a biofilm develops is called a “substratum”. Biofilm accumulation is the net result of a number of physical, chemical and biological processes, each leading to either an increase or decrease in the amount of biomass accumulated at the substratum.

The yield point of biofilm growing in steady one-dimensional flow is a function of the magnitude of the hydrodynamic shear stress (τ_w) acting upon them during development. An increase in τ_w may result in thinning of the material and finally detachment of the biofilm structures.

The small dimensions and pliability of biofilm makes sample handling extremely difficult. The removal of biofilm from the substratum radically changes the integrity of the sample. Various methods have been developed to conduct simple stress-strain and creep experiments on cultured biofilm, for observing the structural deformations caused by changes in hydrodynamic shear stresses (τ_w) (Vieira, et al., 1993).

Biofilm behaves like elastic and visco-elastic solids below τ_w, but it behaves like visco-elastic fluids at shear stresses elevated above τ_w. Vieira, Melo and Punheiro (1993) found that the biofilms grown at elevated shear stresses were more cohesive than those grown at low shear stresses.

Reduction in thickness of the biofilm will effectively increase biofilm density and decrease porosity. Since it has been demonstrated that water could flow through biofilm channels (Stoodley, de Beer, & Lewandowski, 1994) and increase the supply of nutrients to the biofilm cells, a reduction of thickness can thus have a significant impact on the mass transfer processes.

Additional to reducing the porosity of the biofilm, the flattening of the individual structures squeezes water out of the EPS matrix, reducing the micro-porosity and solute diffusivity. Dehydration increases the stiffness and viscosity. The rate of diffusion of water back into the biofilm will determine the rate of recovery of the shape.

All the processes involved in biofilm development are influenced by hydrodynamic conditions in the bulk liquid. Micro-organisms are transported to the substratum by diffusion and gravitational settling. In the turbulent flow regime, a higher bulk flow rate will reduce the thickness of the liquid boundary layer and thereby decrease the distance that needs to be overcome to reach the substratum.

Although the higher flow enhances the transport of cells to the substratum, there is only a fraction that is able to establish irreversible adsorption to the surface. Rougher substrata offer protected areas, where the cells are shielded from flow, in a way that enables the cell to attach to the substrata.

4.3 Detrimental effects of biofilm fouling of pipelines

The detrimental effects of biofilm can be summarised as follows:

- Biofilm promotes the growth of pathogenic bacteria in drinking water pipes, may result in biocorrosion and may sustain the colonisation of undesirable organisms;
- Biofilm increases the friction resistance due to their visco-elastic nature, which leads to an increased energy demand (Characklis & Marshall, 1990); and
- Biofilm layers contribute to the formulation of corrosion tubercles, encrustation of organic and inorganic matter and extra-cellular polymers. These substances produce adverse impacts on the quality of distributed water and endanger public health and welfare.

A conceptual model to quantify the influence of biofilm on the hydraulic capacity is proposed in the next paragraph.

4.4 Influence of biofilm on the hydraulic capacity of water infrastructure

The **influence of biofilm on the friction loss or the roughness** parameter of pipelines has not been researched to any depth, hence a conceptual model to incorporate the influence of biofilm growth on the hydraulic roughness of pipelines is proposed.

The conceptual model (Biofilm Roughness Model, BRM) which defines the influence of biofilm on the absolute roughness, ignores the complex nature of the growth and detachment characteristics of the biofilm in water supply systems. It also assumes their presence in all systems but differentiates cases where the biofilm acts as a viscous layer and those cases where the biofilm produces residual matter or capture particles of sediment or transported debris.

The objective of the proposed conceptual biofilm roughness model (BRM) is to incorporate the influence of biofilm on the hydraulic capacity of water systems. In the BRM the following three biofouling options are considered:

1. **Option 1**: Not a significant layer of biofilm is present – the roughness of the pipe wall dominates the friction losses (**Figure 4-7**);

2. **Option 2**: Biofilm is present in the pipeline. The biofilm presents itself as a viscous substance without any residual by-products or captured foreign matter. The biofilm thickness could be minute (**Option 2A-Figure 4-8**) or it might extend to a thickness in excess of the roughness of the pipe (**Option 2B-Figure 4-9**); and

3. **Option 3**: The biofilm produces residual matter as in the case of MOB (Manganese Oxidising Bacteria) or Iron Oxidizing Bacteria (IOB) or captures material which has been transported. The matter builds up in the biofilm, decreasing the internal diameter and forms a hydraulic roughness and flow shear regime different to and independent of the surface roughness of the pipe (**Figure 4-10**).

Figure 4-3 to **Figure 4-6** show examples of typical biofouling “options” in water mains, mimicking the three options catered for in the BRM (biofilm Options 1 to 3).

Figure 4-3: Typical view of the internal conditions of a pipeline with little or no biofouling (Option 1)

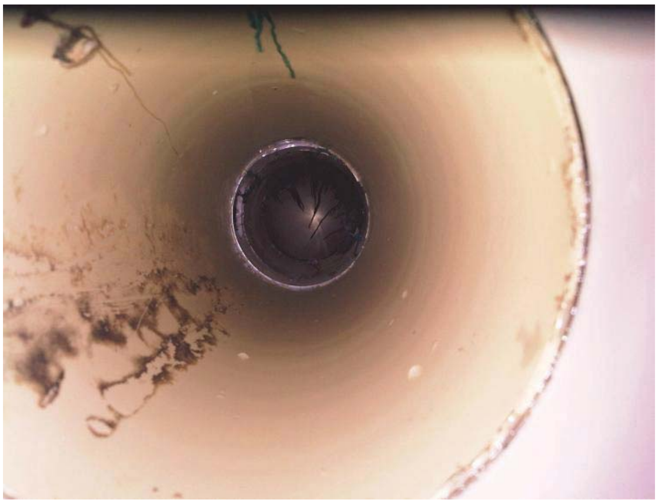

Figure 4-4: Typical view of the internal conditions of a pipeline with some biofilm growth but without residual material in the biofilm (Option 2A)

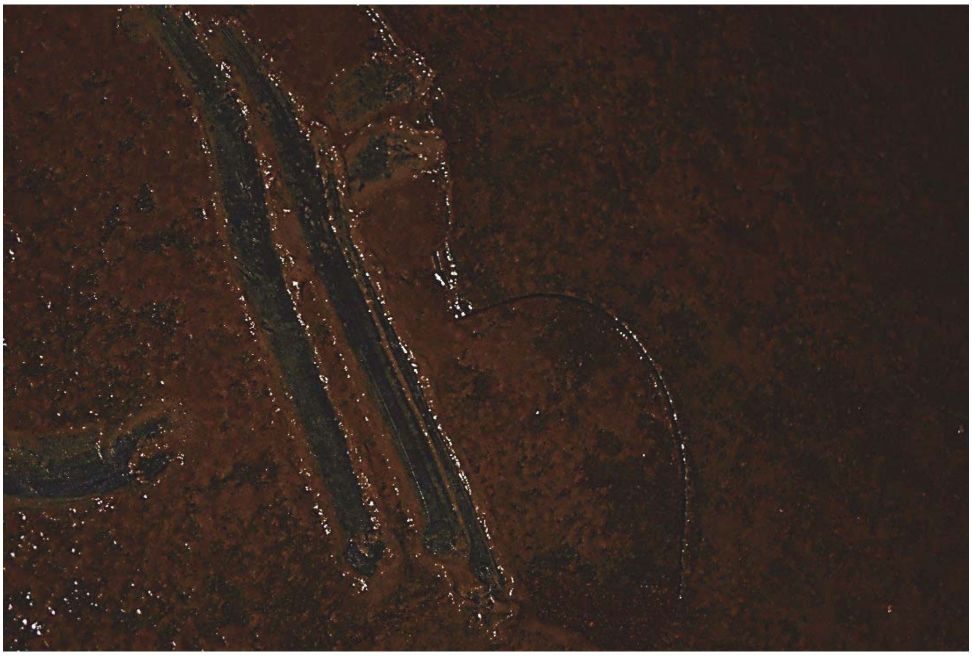

Figure 4-5: Biofilm growth on bitumen liner (Option 2B)

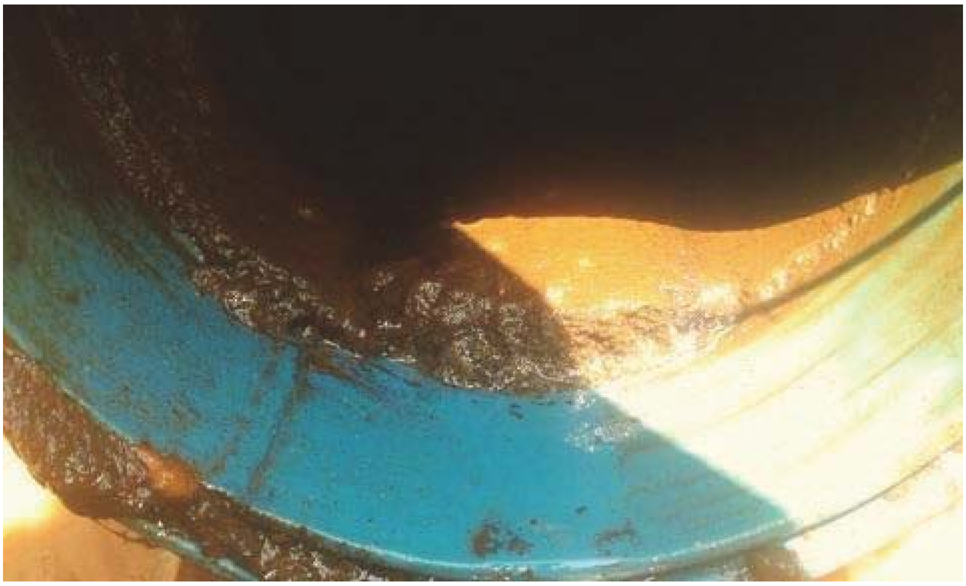

Figure 4-6: Typical view of the bio-fouling in a 200 mm thermoplastic pipeline where the biofilm produced residual material (MOB) (Option 3) (Courtesy Mr Org van Rensburg, LBIS, 2015)

A schematic presentation of the three biofouling options in water infrastructure, are shown in **Figure 4-7** to **Figure 4-10**.

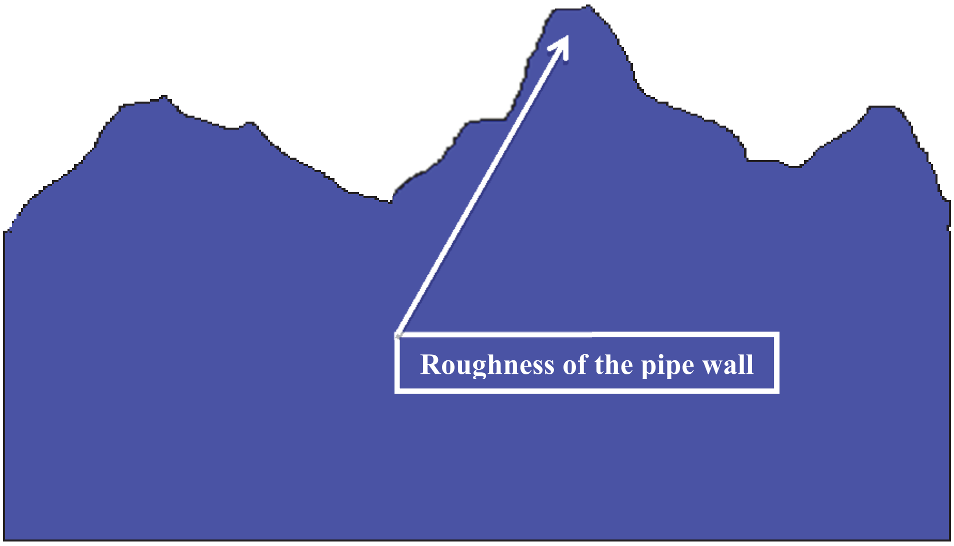

Figure 4-7: Option 1 – Virtually no biofilm growth is present in the pipeline

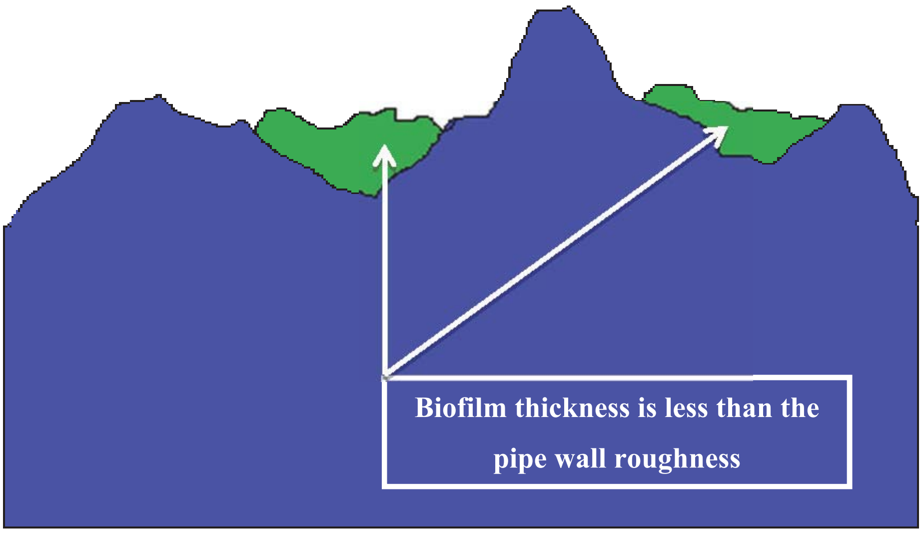

Figure 4-8: Option 2A – Biofilm has established on the pipe wall with the thickness less than the pipe wall roughness

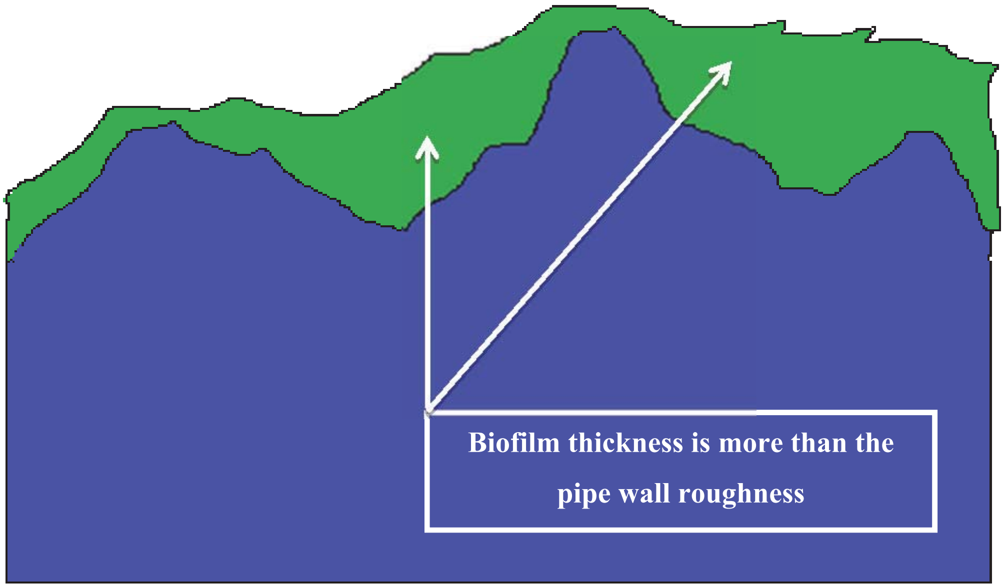

Figure 4-9: Option 2B – Biofilm is present and the thickness is more than the pipe wall roughness

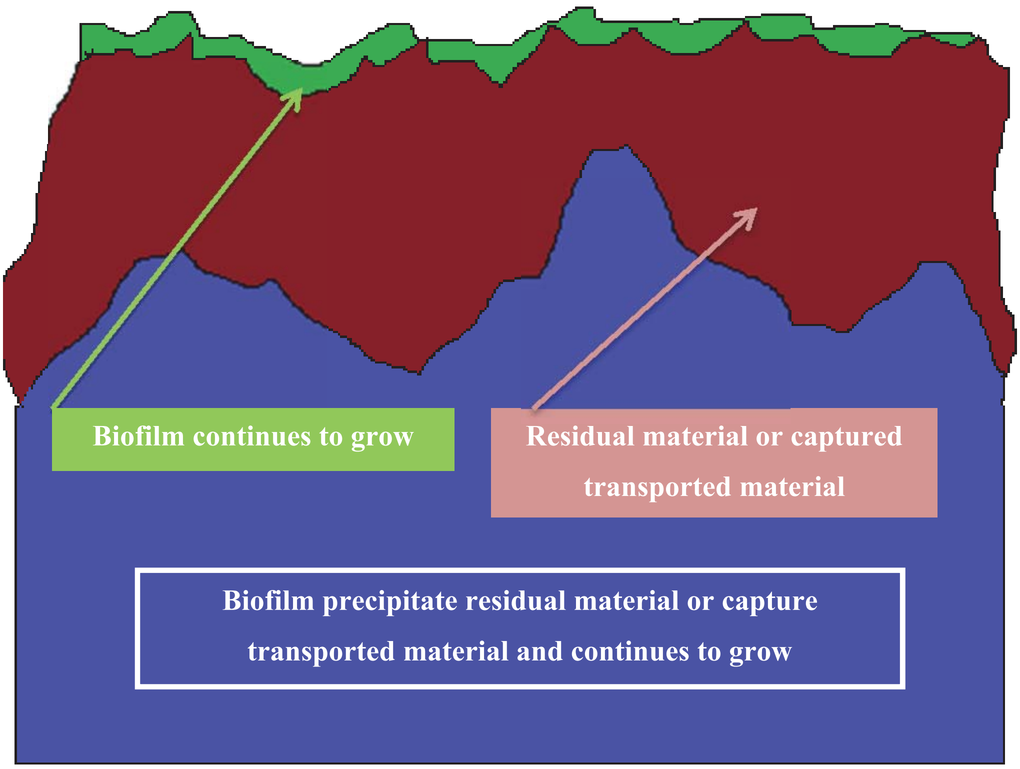

Figure 4-10: Option 3 – Biofilm growth has established in the pipeline, producing residual material or captures transported material in the biofilm

4.5 Adaptations in the absolute roughness to compensate for biofilm

Neither field data nor documented research provides sufficient information to derive relationships for the influence of biofilms on the absolute roughness of pipelines. Hence **conceptualization** of the influence of biofilm on the roughness is attempted and the relationship is then tested in **Section 4.6**. As an outset **Table 4-1** is used to provide the initial relationship between biofilm and absolute roughness, which will be modified and refined as more information and field data becomes available.

Table 4-1: Hypothetical (BRM) model to include the influence of biofilm on the absolute roughness of the pipeline

Biofilm description	Absolute internal roughness of a clean pipe, (mm)	Internal diameter (mm)	Expected biofilm thickness, t_b (mm)	Suggested parameters to be used in the calculation of the friction energy loss	
				Diameter (mm)	Absolute roughness (mm)
Option 1	k_s	D_0	none	D_0	k_s
Option 2A			<1		
Option 2B			1 to 6	$D_0 - 2\ t_b$	$k_s + t_b/X_2$ #
Option 3			2 to 18		$X_3\ t_b$ or alternatively $aX^n+bX^{n-1}+c$ ##

Notes:

\# *The viscous biofilm deforms and allows filament fingers to disturb the boundary layer. It is suggested that the value of X_2 equal to 200 is used, constituting 0,5% of t_b to be added to the absolute roughness (k_s).*

\## *The "surface form" of the biofilm which contains residual material has to be evaluated in more detail and the values of X, X_2 and the X_3 as well as the power n need to be evaluated in more detail.*

4.6 Verification of the BRM for biofilm option 3

In the case of the Lower Blyde River Irrigation System (LBIS) and the Bushbuckridge pipeline (Inyaka) it was indicated that **Option 3** biofilm growth has a major effect on the hydraulic capacity of the pipelines. A first assessment of the proposed BRM can be reviewed by applying the BRM for Option 3 (**Section 4.5**) on the recorded flow and pressure data for these pipelines. **Table 4-2** shows some of the characteristics of the pipelines as well as the recorded field data.

Table 4-2: Some pipeline characteristics and the field data to review the pipe roughness for Option 3 biofilm growth

Pipeline	Date	Internal diameter (mm)	Length of pipeline (m)	Flow rate (m^3/s)	Total head loss (m)	Secondary loss (m)	Friction loss (m)	Estimated biofilm thickness (mm)
Blyde (LBIS)	August 2015	1458	6 000	2.48	12.563	1.508	11.055	7 to 14
Inyaka	February 2014	699	2418	0.5338	10.698	0.148	10.55	14 to 18

By using the Barr relationship (**Section 2.3**) to back calculate the roughness for a given flow rate and recorded pressure drop, it was established that smaller diameter pipelines (Inyaka) are more sensitive than bigger diameters to the reduction in diameter due to biofouling (Option 3). This is mainly due to the significant influence of $\frac{k_s}{3.7D}$ in the following relationship.

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{k_s}{3.7D} + \frac{5.1286}{R_e^{0.89}}\right) \qquad \ldots(15)$$

The determination of the influence of bioufouling on the hydraulic capacity of pipelines requires an assumption (determination) of the biofilm thickness (t_b) to be able to determine the reduced internal diameter used in the back calculation of the surface roughness for Option 3 biofouling.

When the BRM is applied for Option 3 biofouling, the roughness is calculated for the recorded flow rate and energy loss for the reduced internal diameter of the pipe equal to the original internal diameter minus 2 times t_b. In **Figure 4-11** different field data sets are shown for which the roughness was initially calculated on the original internal diameter. For the same energy slope different roughnesses can be calculated for different assumed biofilm thicknesses. The range on the horizontal axis in **Figure 4-12** shown in the shaded boxes represents a biofilm thickness varying between 7 and 14 mm in the LBIS and 14 to 18 mm in the Inyaka pipeline.

The maximum recorded influence of the biofouling on the LBIS occurred in August 2015 (multiple data sets are available) and on the Inyaka pipeline during February 2014 (only one data set). These maximum recorded influences are shown in **Figure 4-12**. By fitting a curve through the upper values of these two data sets shown in **Figure 4-12**, for the Blyde and Inyaka pipelines, the relationships between k_s (vertical axis) and $t_b/(D-2t_b)$ (horizontal non dimensional axis) can be determined. The trend lines and the relationships are depicted in **Figure 4-12**. These relationships are repeated in **Table 4-3.**

Table 4-3: Relationship to calculate the roughness in the pipeline for Option 3 biofouling

Pipeline	Internal diameter (mm)	Relationship #	a	b	c ##
LBIS	**1458**	$\boldsymbol{k_s = aX^2}$**+bX + c**	**1580.0**	**-118.43**	**3.137**
Iyaka	**699**		**1046.3**	**-91.513**	**2.644**

Notes

\# *k_s was plotted against the non-dimensional value of $t_b/(D-2*t_b)$. In this case $X = t_b/(D-2*t_b)$*

\## *c represents the back calculated roughness if biofouling is ignored and the original internal diameter is used to calculate the flow area*

Based on the maximum recorded data sets and assumptions of the biofilm thicknesses, the "skin" roughness of the biofouled pipeline indicated by the dashed lines (minimum and maximum) in **Figure 4-13** for these two pipelines (LBIS and Inyaka) varies between 0.93 and 2.60 mm for the selected biofilm thicknesses.

It can therefore be argued (based on the limited data) that if Option 3 bioufouling occurs, the friction loss can be calculated on the reduced diameter with a roughness of the bioufouled pipeline of between 1 to 2.75 mm.

It is suggested that the relationships in Table 4-3 be used to calculate the expected long term roughness for pipelines in which biofouling Option 3 will occur.

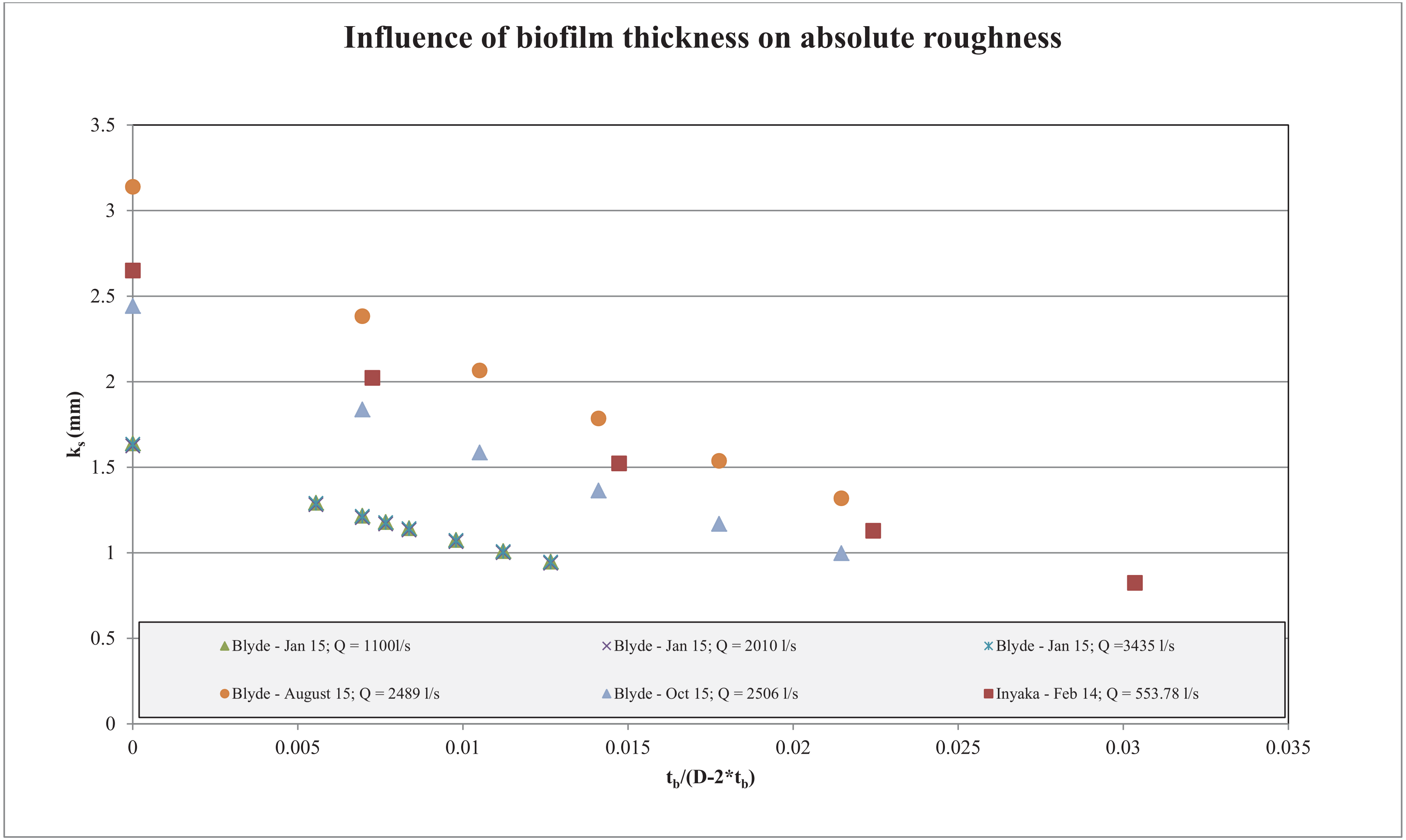

Figure 4-11: Proposed roughness/biofilm thickness relationships based on field data

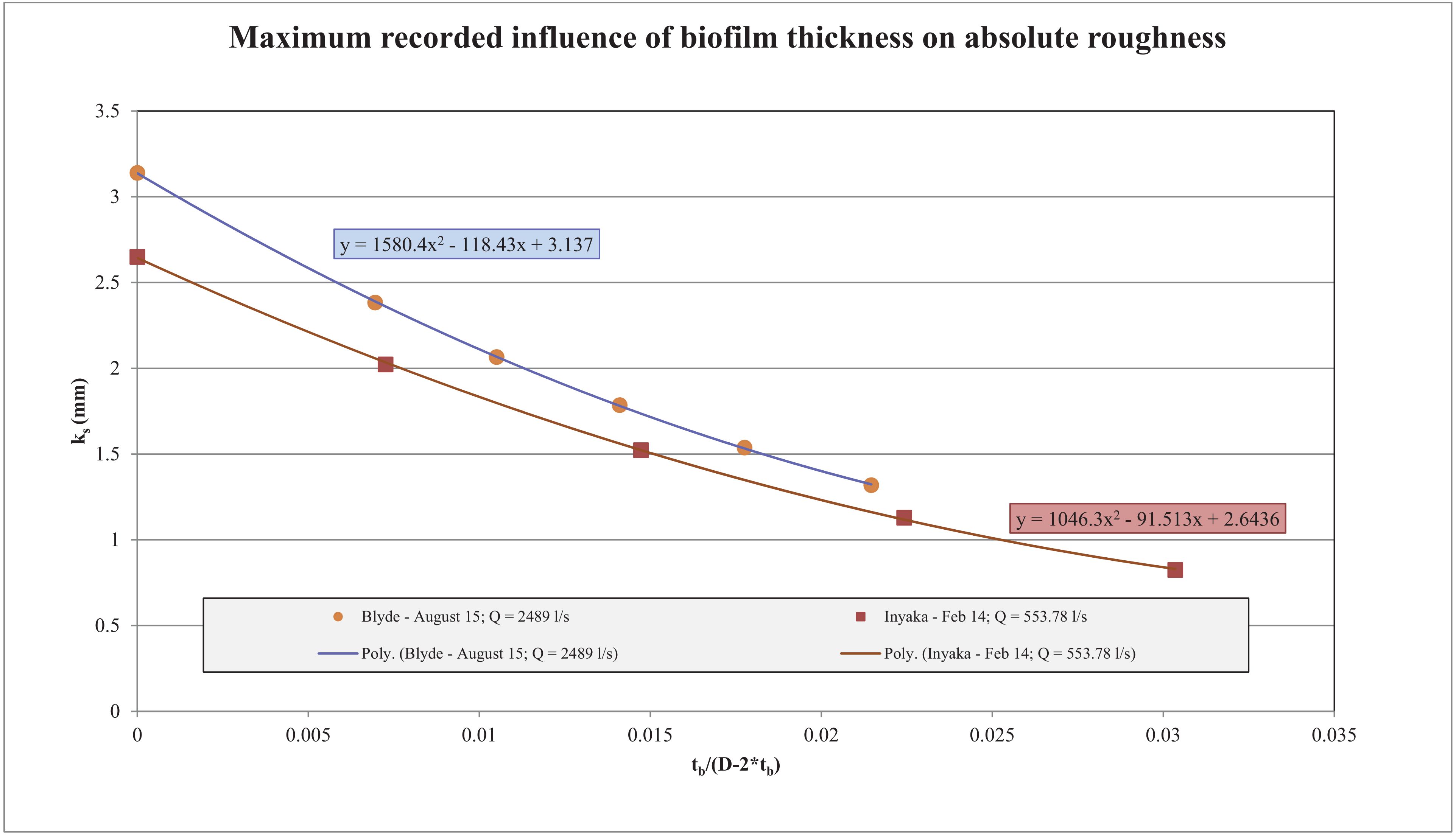

Figure 4-12: Data sets reflecting the largest recorded influence of biofouling on the hydraulic capacity

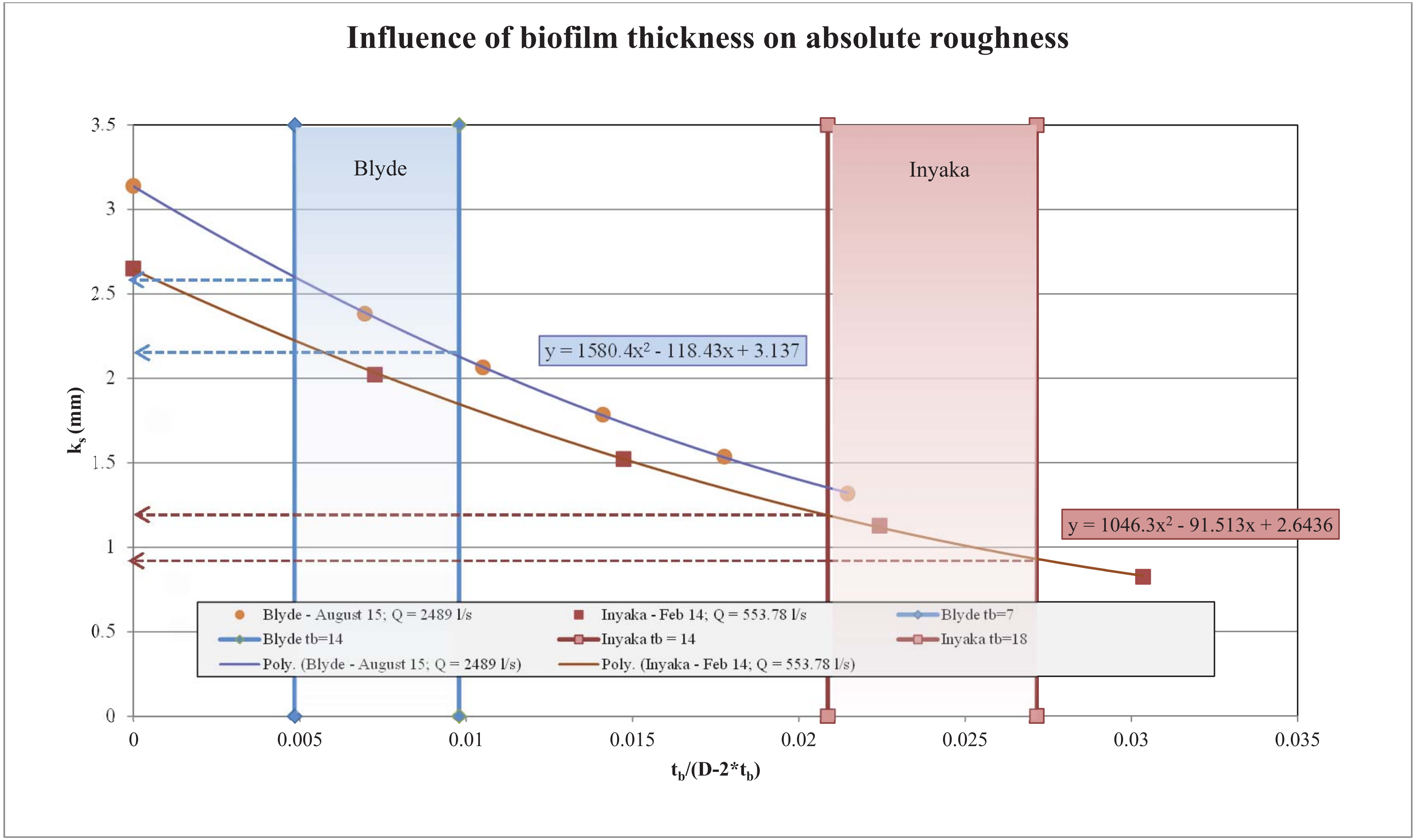

Figure 4-13: Maximum and minimum representative roughness calculated on the data sets with the largest influence on the hydraulic capacity

4.7 Some remarks on the influence of biofilm in pipelines and how to adapt the design considerations

The calculated roughness for the different pipelines which were reviewed during this research is well in excess of documented maximum values. In those cases where biofilm growth is experienced, the documented long term predicted roughness is frequently underestimated.

The recorded yearly increase in roughness which is much higher than published values, severely impacts the operating capacity of water conveyance systems and will increase the energy cost of pumping systems. It is therefore imperative that <u>periodic review of the hydraulic performance of conveyance systems **should be undertaken**</u>. This requires that during the design of water systems, provision should be made for sufficient access points to measure flow and pressure.

Based on the findings in this research, it is recommended that:

- Field verification tests of the hydraulic performance should be implemented as part of the infrastructure management of the water conveyance systems in South Africa;
- The monitoring of biofilm growth in pipelines should be expanded to be able to define the areas in South Africa where the hydraulic capacity could be detrimentally influenced by biofouling (especially Option 3 biofouling);
- The proposed model to calculate a representative roughness in biofouled pipelines (BRM) should be verified by further field measurements;
- A guide should be developed to establish the need for pigging installations on pipelines or the implementation of other anti-microbial growth options; and
- The database of pipeline performance should be compiled to provide design guidance for new installations by incorporating the long term expected pipe performance in the presence of biofilm growth (refer to **Section 5.6**).

5 Regulatory framework and condition assessment of pipelines

5.1 Introduction

It is common knowledge that the South African water infrastructure is aging, droughts occur occasionally, the water demand is increasing, maintenance is neglected and budget constrains confine the development and extension of the needed infrastructure to ensure a sustained water supply. This is a multi-facetted and complicated problem which the design engineer should consider by at least reviewing the regulatory framework under which the water infrastructure should be governed, be aware of ways in which the condition assessment of infrastructure should be performed, develop a thorough understanding of procedures which can be used for the assessment of the remaining useful life, and provide the required monitoring equipment to conduct the initial and subsequent assessment of the infrastructure's performance. These aspects are discussed in the following paragraphs. The discussion is supported by a summarized reference to the relevant regulations applicable to identify and define data requirements for condition assessment of water infrastructure. Although the focus is on South African Regulations relevant to water infrastructure, the review also includes references to international standards applicable to condition monitoring and technical risk assessment of engineered assets in the built environment.

5.2 Infrastructure Management

In a report, titled "Guidelines for Infrastructure Asset Management in Local Government, 2006-2009" published by the Department of Provincial and Local Government (DPLG), Republic of South Africa, it is indicated that an Infrastructure Asset Management Plan (IAMP) should be prepared for each of the sectors and that the IAMPs be used as input to the Comprehensive Municipal Infrastructure Plan (CMIP). The CMIP, which provides the capital for new, upgrading and replacement of infrastructure and for the operational and maintenance strategies, feeds into the Integrated Development Plan (IDP).

Table 5-1 reflects the proposed responsibilities of the Municipalities and provides a time frame for the implementation of the IAMPs.

Table 5-1: Responsibilities of Municipalities and a time frame for the implementation of asset management (DPLG, 2009)

Element of asset management	Requirement	Tips
IAM Policy	Council to adopt within 2 years	Commit to an implementation approach that is in line with the capacity of the Municipality
IAM Strategy	Optional as a separate document.	Do this once the IAM practices are mature.
IAMPs	IAMP for all sectors adapted by Council within a year (or IAMP scope covered in sector plan e.g. WSDP). Update each at least every 2 years.	Try one IAMP first, and then expand to other sectors.
CMIP	First CMIP adopted by Council within 2 years. CMIPs summarise key information and strategic issues across all sectors (consistent with information indicated in the sector IAMPs). Update annually.	All the IAMPs need to be completed first, even at a high level. CMIP needs to be brief and in a format that is understandable to non-technical people.

The document (DPLG, 2009) contains a pro-forma table of contents for the IAMP and defines the level of details to be included in the document. It also provides a schedule (tasks and time allocation) for the implementation of CMIPs. A key input for the development of CMIPs is sound data of the status of the infrastructure.

A "Tool Kit" was developed to assist in the implementation of IAM with a description of the standards and criteria (DPLG, 2009) as well as the level of service. It is uncertain what the level of "buy-in" and roll-out of the suggested implementation of the prescriptions of the Report (DPLG, 2009) is. The suggestion that **the implementation should be in line with the capacity within the municipality has delayed the implementation of Asset Management on a Local and National level and will potentially reduce commitment for the full implementation of asset management and reduce the urge for full responsibility**.

5.3 Some Regulations and Standards applicable on infrastructure management in South Africa

Some of the relevant legislation applicable to asset management which should be reviewed when an assets management plan has to be developed, are:

- National Water Act No. 36 of 1998;
- Water Services Act No. 108 of 1997;
- Municipal Structures Act No 117 of 1998;
- Public Finance Management Act Nos. 1 and 29 of 1999;
- Municipal Finance Management Act No. 56 of 2003; and
- Government Immovable Asset Management Act No.19 of 2007

Furthermore, the following applicable references and standards should be considered:

- RSA National Treasury Asset Management Practical Guide 2003 and Guideline 2004;
- RSA National Treasury Asset Management Framework 2004;
- British Standards Institution: Publicly Available Specification 55 (BSI PAS 55); and
- International Infrastructure Management Manual 2006, IMESA RSA edition.

5.4 Condition assessment of pipelines

5.4.1 Introduction

In a document compiled by EPA (USEPA, 2009) condition assessment technologies and investigative condition assessment approaches for waste water collection systems were published. The report highlighted the following aspects which are applicable to undertaking condition assessment in water mains:

- Identification of the condition assessment technologies;
- Evaluation of the relationship between performance and cost of innovative and advanced infrastructure monitoring technologies and their benefit to prevent catastrophic failures;
- Review of the application and transfer of assessment technologies for general application; and
- Preparation of protocols, methods and site selection criteria for field condition assessment and decision support systems.

5.4.2 A schematic of the condition assessment process

Condition assessment provides the critical information needed to assess the physical condition and functionality of waste water collection systems and to estimate the remaining service life and asset value.

Figure 5-1 reflects the steps of condition assessment.

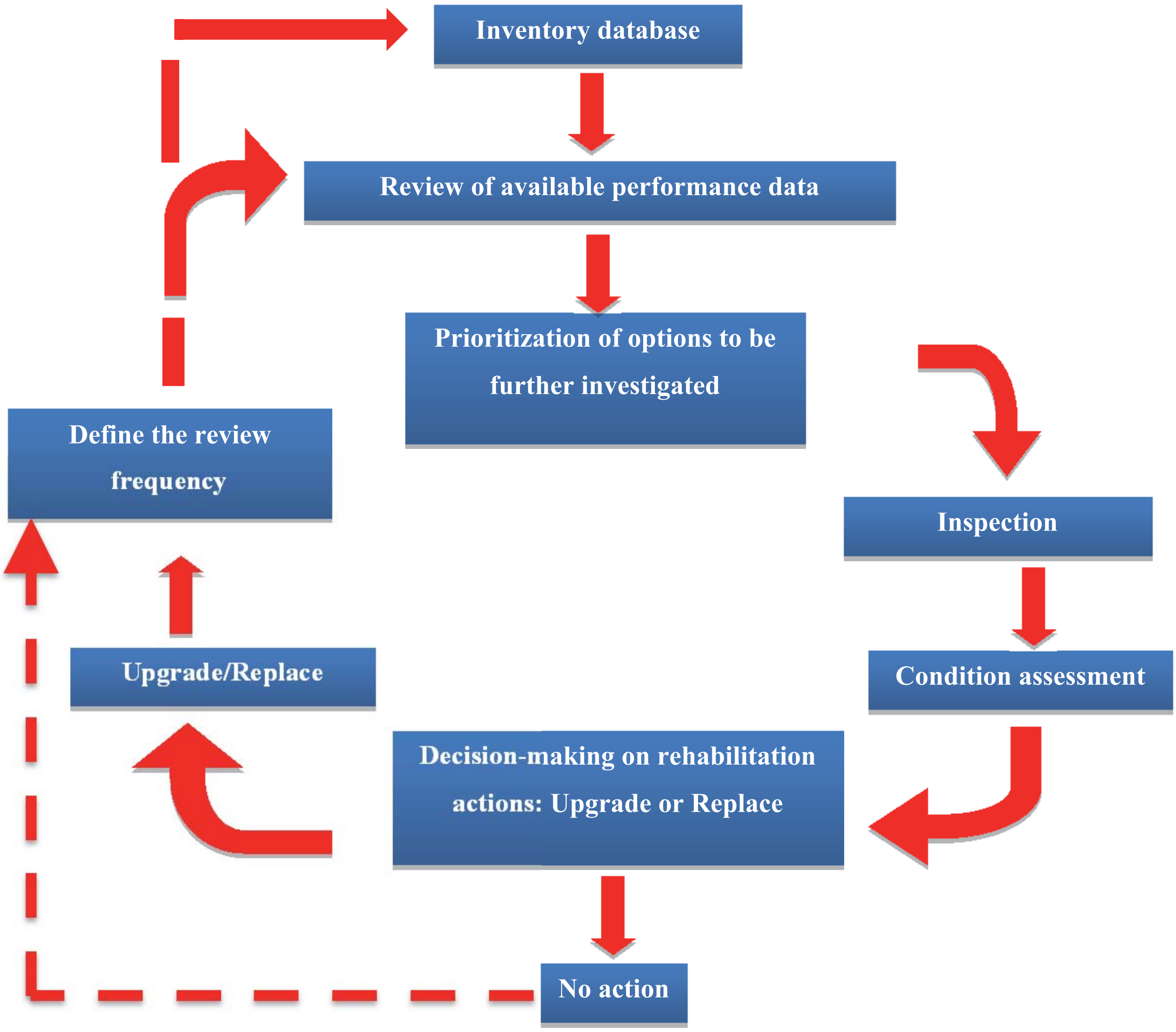

Figure 5-1: Steps of the condition assessment process

5.4.3 Rehabilitation or replacement

Based on the information obtained from the asset assessment inventory, a decision to rehabilitate or replace the infrastructure needs to be taken.

In general the decision for rehabilitation/replacement of infrastructure components is made based on one or more of the following actions:

- **Engineering calculations**: Interpretation of inspection data deterministically. The review of the wall thickness and assessment of the hydraulic capacity is typical engineering calculations.

- **Non-destructive testing (NDT)**: NDT could be employed (Misiunas, 2008) to verify the condition.
- **Probability of failure**: The objective is to provide a direct forecast of expected failures to occur. This is difficult to implement practically, because it will require extensive data and failures are normally site specific.
- **Remaining life estimation**: This procedure is commonly used to project the expected operational life of the asset. Standard coding systems were developed to define the condition and expected performance (NASSCO PACP standards).

Knowledge gaps and directives on the investigations to improve inspection technologies, trace the condition of assets over time and develop data management methods to compare historical data with the current condition by utilizing the current available technologies are referenced in the EPA guideline **(USEPA, 2009)**.

5.4.4 Performance criteria and critical parameters influencing the life expectancy of water infrastructure

The expected future behaviour of the infrastructure of our water services can be defined if a full understanding of the operational parameters, liquid characteristics, installation conditions and material characteristics (related to operational history, liquid characteristics and installation conditions) is known. Such relationships do not readily exist for the different components of water infrastructure and sanitation systems.

Reviewing the ability of water infrastructure components to "perform according to its purpose", requires a thorough understanding of the intended **purpose** and current **status** of the different components.

The key factors in water mains which could influence the expected remaining operational life are:

- Pipe material integrity;
- Manufacturing, transportation and installation;
- Actual pressure loading;
- Actual external loading and other stresses; and
- Actual deterioration rate (corrosion for ferrous pipes, or leakage rate and failures in other materials).

Asset management requires amongst others, a description of the physical extent of the project, technical details, operational capacity and constraints, current physical integrity, residual value and expected operational life. In the case of pumping mains the **operational efficiency** is a major concern, which might lead to a scenario where additional capital investments have to be compared with the **high energy cost** of the existing system. **This is currently a major focus due to the limited energy production capacity in South Africa and the high energy cost escalation**.

During the verification phase of infrastructure it is essential to establish the intrinsic value of the components, which can only be done if the efficiency and effectiveness can be quantified. This can be achieved by the assessment of available information or measurement of the performance of the system or system component.

5.4.5 Parameters to consider when determining the remaining useful life of a pipeline

The following are few of the parameters which should be considered in determining the useful life of a pipeline:

- Pipe material: How long can the pipeline withstand the internal and external environment?
- Installation conditions: Has the installation been done to acceptable standards?
- Installation procedure: The expected operating life will be influenced by the installation procedure and site supervision.
- Protective measures: Is the life expectancy of the pipeline dependent on the inclusion of protection equipment. Is the selected protection appropriate and has it been maintained?
- Hydraulic capacity: Can the demand be met using the system or should it be extended, refurbished or replaced?
- Water quality: Aggressive or scaling water could lead to corrosion or scaling of the pipeline.
- Operation of the system: How frequently is scheduled maintenance being conducted? Is the required production such that scheduled maintenance is disregarded?

These parameters can be weighed to provide infrastructure managers **a base for comparing the need for intervention to extend the useful life of infrastructure**.

Without operational performance data and a record of the failures which occurred, consideration might be given to performing non-destructive tests prior to the decision to refurbish, replace or upgrade the component.

5.4.6 Non-destructive techniques for condition assessment

5.4.6.1 Introduction

Numerous techniques have been developed for the assessment of water infrastructure (USEPA, 2010). The application of some of the available technologies is limited in South Africa by cost and probably the scale of the demand for these technologies. In the following paragraph the different non-destructive techniques are briefly referenced.

5.4.6.2 Non-destructive inspection technologies

A variety of technologies are available for the assessment of water infrastructure. **Table 5-2** reflects the typical application of the different technologies. **Table 5-3** reflects the typical failures of different pipe materials while **Table 5-4** indicates the type of the assessment procedures applicable for the different phases of the assessment of the infrastructure.

Table 5-2: Summary of the condition assessment technologies (USEPA, 2009)

	Camera				Acoustic			Electrical & Electro-magnetic			Laser	Innovative technologies						
	CCTV	Zoom camera	Digital scanning	Push-camera inspection	In-line leak detectors	Acoustic monitoring systems	Sonar	Electrical leak location	Remote field eddy current	Magnetic flux leakage	Laser profiling	Gamma-gamma logging	Ground penetrating radar	Infrared thermography	Micro-deflection	Impact echo/SASW	Ultrasonic pulse velocity	Guided Wave Ultrasonic
Application																		
Pipe type	G	G	G	S	G, F	F	G, F	G, F, S	G, F, S	G, F, S	G, F	G, F, S	G, F, S	G, F, S	G	G	G	F
Pipe material	Any	Any	Any	Any	Any	PCCP	Any	NF	F	F, PCCP	Any	C	Any	Any	B	B, C	C	F
Pipe diameter (in.)	>6	>6	6-60	1-12	≥4	≥18	≥12	3-36	≥2	2-56	>4	TBD	18-30	TBD	N/A	>6	TBD	>2
Defects Detected																		
Sediment, debris, roots	x	x	x	x			x				x							
Pipe sags & deflections	x	x	Partial	x			x				x							
External pits & voids												x			Partial	x		x
Corrosion & metal loss			Partial				x		x	x	x							x
Off-set joints	x	x	Partial	x														
Pipe cracks	x	x	x	x			x	x	x	x						x	x	x
Leaks	x	x	x	x	x			x	x				x	x				
Broken pre-stressed						x			x									
Wall thickness									x							x	x	x
Service connections	x	x		x								x						
Bedding conditions												x	x					
Bedding voids												x	x	x	Partial			
Deteriorated Insulation														x				
Overall conditions															x			

NOTE:

Pipe type: G - Gravity line F - Force main S - Service lateral

Pipe material: NF - Nonferrous F- Ferrous B - Brick C - Concrete PCCP - Pre-stressed concrete cylinder pipe

TBD - To be decided

N/A - not applicable

Adapted from USEPA 2009a

Table 5-3: Typical failures of different pipe materials used for waste water (USEPA, 2009) (adapted)

Defect	Concrete			Ferrous		Plastic	
	Concrete pipe	Asbestos cement	PCCP/CCP	Cast iron / Ductile iron	Steel	PVC	HDPE
Internal pipe surface							
Root intrusion	x	x	x	x	x		x
Grease build-up	x	x	x	x		x	x
Pipe wall condition							
Cracks / broken pipe	x	x					
Internal corrosion		x	x	x	x		
External corrosion			x	x	x		
Leakage							
General	x	x		x		x	
Joint leakage			x		x		
Leaking laterals				x			x
Alignment / grade							
Alignment				x		x	x
Joint Misalignment	x	x		x			
Excessive deflection					x	x	x
Grade						x	x
Other	1					2	3

Notes:

1 – Liner separation, weld failure
2 – Lateral connections
3 – Pressure capacity

Table 5-4: Typical non-destructive technologies applicable for the different stages of asset management

Program Objective	Flow data analysis	Camera			Acoustic			Electrical & Electro-magnetic			Laser	Innovative technologies						
		CCTV	Zoom camera	Digital scanning	In-line leak detectors	Acoustic monitoring systems	Sonar	Electrical leak location	Remote field eddy current	Magnetic flux leakage	Laser profiling	Gamma-gamma logging	Ground penetrating radar	Infrared thermography	Micro-deflection	Impact echo / SASW	Ultrasonic pulse velocity	Guided Wave Ultrasonic
Screening / Prioritization	x		x			x	x											x
Detailed inspection of internal surface conditions		x		x			x				x					x		
Detailed inspection of pipe wall integrity					x	x	x	x	x	x	x			x	x	x	x	x
Detailed inspection of pipe bedding and void conditions												x	x	x				

5.4.7 Non-destructive inspection technologies commonly used in South Africa

The common evaluation of the **visual status** of water conveyance systems is conducted by CCTV inspections. A number of companies offer this service.

The assessment of the initial **hydraulic capacity** and the change during operation provides a first indication of the combined interrelated aspects of pipe material deterioration, water quality, biofilm activity and operational impact.

The **structural integrity** of conveyance systems can be related to the extent of the deformation. A South African development of a "profilometer" has successfully been used to indirectly asses the structural integrity.

The use of sonic leak detection equipment, "smart-ball" technology or the "Pipe-diver" is rapidly developing and is the key for the review of the South African Water Infrastructure. The advantage of these technologies is that it is uninterrupted and that multiple data types could be gathered. **Leak detection and the structural integrity** of PCCP's are within the capacity of these techniques.

The information obtained during the assessment of the water infrastructure will ultimately be used to establish the need for rehabilitation (upgrade/renovation) or replacement. **Figure 5-2** provides a schematic flow diagram showing how the physical assessment of water infrastructure relates to the status review and financial process for the refurbishment or replacement of infrastructure.

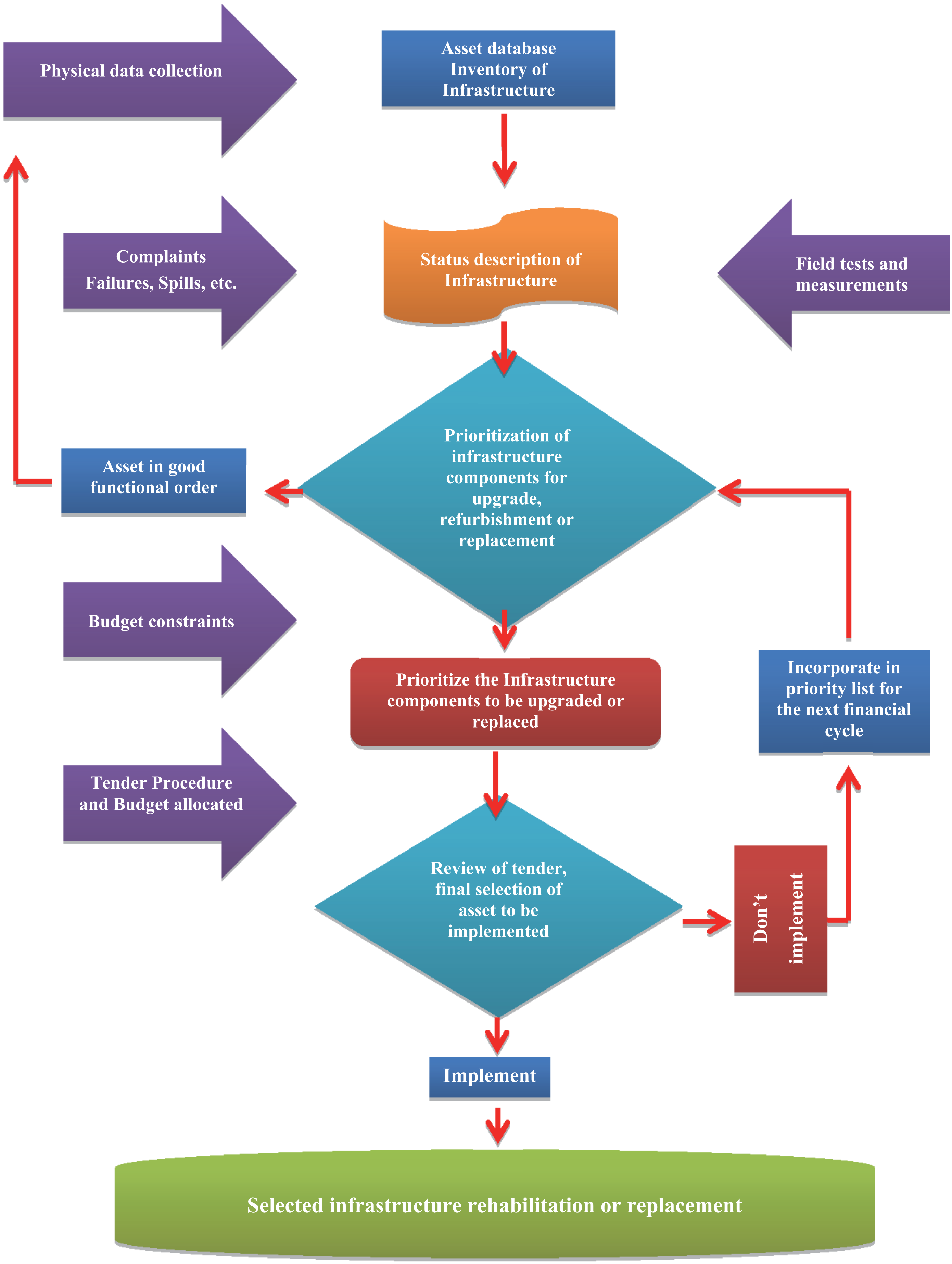

Figure 5-2: Flow diagram of the assessment to replace Infrastructure Components

5.5 Parameters included in the model to calculate the expected useful life of the water infrastructure components

A procedure was proposed (van Vuuren & van Dijk, 2012) to calculate the expected useful life of water infrastructure components. The useful remaining operational life of water infrastructure dependents on a number of critical parameters which could be interrelated, subjective, and hence a weighted value range for the parameter's influence on the remaining useful life is used in the weighted procedure.

By incorporating input from operational-, managerial- and design expertise and allocate a weight to the influence of the critical parameters on the remaining life, ranging from a "worst" to a "best" scenario the relative importance and influence of the different parameters can be prioritized.

It is assumed that a "parameter value" can be identified for the "worst" and "best" outcome for all the parameters which might influence the expected useful life. All possible outcomes will hence be flanked by these boundary parameter values. Based on these assumptions, the procedure to determine the influence of the critical parameter on the expected useful life can be determined by the identification of the critical parameters. In the case of pipelines the following parameters should be reviewed:

- Current capacity ($Q_{operating}/Q_{design}$);
- Sophistication of protection (internal liner, external coating, cathodic protection, etc.);
- Illegal (informal) connections;
- Installation condition (soil type, stray currents, high water table, infiltration into pipe);
- Construction standard (bedding, compaction, alignment, indentations, over-insertion of couplings, visible seals);
- Water quality (internal aggressiveness, pH, visible biofilm growth);
- Operational conditions (<55% of pressure rating, valve operation and maintenance, dynamic pressures, pump starts and stops, etc.);
- Temperature fluctuation & extremities;
- Operating time (24/7, day only, night only);
- Foreign matter inside pipe (sediment or debris); and
- Air valve operation and placement (position, size, connection to pipe).

The selected parameters which will influence the remaining useful life for pipelines are reflected in **Table 5.5**.

Table 5-5: Selected critical parameters to be reviewed for pipelines to determine the reduction in the useful life

Critical Parameters/criteria	Outcome or value	Weighted parameter value #
$Q_{operating}/Q_{design}$	0.5	0.8
	0.8	0.7
	>1	0.3
Is the protection maintained and in good condition	Good	0.8
	Moderate	0.6
	Poor	0.4
	Alarming	0.2
Number of illegal connections per Km	0	1
	2	0.8
	>3	0.2
Installation conditions	Good	0.95
	Moderate	0.85
	Aggressive	0.6
How well was the installation performed	Good	0.95
	Moderate	0.8
	Bad	0.3
Does the WQ influence the expected operational life	No	0.95
	Possible	0.75
	Yes	0.5
Is level of service acceptable to users	Yes	0.9
	Acceptable	0.7
	No	0.4
Do extreme operational conditions occur?	No	1
	Occasional	0.9
	Regularly	0.7
Operating time	24/7	0.7
	day only	0.85
	night only	0.95
Foreign matter inside pipe	Occasional	0.65
	After repairs	0.85
	Never	1
Air valve operation and placement	No de-aeration	0.8
	Normative location	0.9
	Effective with accumulator	1

Note:

\# *The values of the parameters must be obtained from applicable persons with experience in different sectors*

A spreadsheet was developed which can be used to determine the UEL for the following water infrastructure components:

- **Pipelines;**
- **Reservoirs; and**
- **Pump stations.**

Reference to the link for the download of the spread sheet is provided in Section 7.

5.6 Provision of monitoring positions

5.6.1 Introduction

The importance of obtaining operational data to verify the performance of water infrastructure components and to make an informed decision about the need to upgrade, refurbish or replace the component is paramount. Some details of the provision of locations where pressure recordings, flow measurements or biofilm monitoring can be conducted are briefly referenced below.

5.6.2 Provision of pressure tapping positions

Pressure recordings must be conducted at locations on pipelines where the following criteria are met:

- Pressure gauging positions must be accessible (close to roads);
- The location should free of groundwater or possible leak water;
- A tapping position with an isolating valve/cock to isolate the connection point should be available;
- It should be possible to secure access for the instrumentation;
- The flow between two consecutive pressure tapping locations should be controllable and hence there should be no large abstractions or inflow between the pressure tapping positions;
- The pipe material, cross sectional dimensions and age should preferably be the same for the section between the pressure gauging locations;
- All the secondary loss elements should be identifiable; and
- At least 3 pressure recording positions should be used to determine the hydraulic roughness in a specific section of the pipeline.

Figure 5-3 provides photographic details of a typical pressure tapping position.

Figure 5-3: Pressure tapping position on an air valve body

Low frequency recordings (1 Hz) of the pressure can be used to establish the pressure drop between two measuring points along a pipeline for a constant flow rate. **Figure 5-4** reflects a HOBO U12 Outdoor 4 channel recorder which can be used to record the pressure. **Figure 5-5** shows a measuring "unit" or "box" (consisting of a HOBO data logger, two pressure transducers and a battery pac).

Figure 5-4: The Hobo U12 recording unit

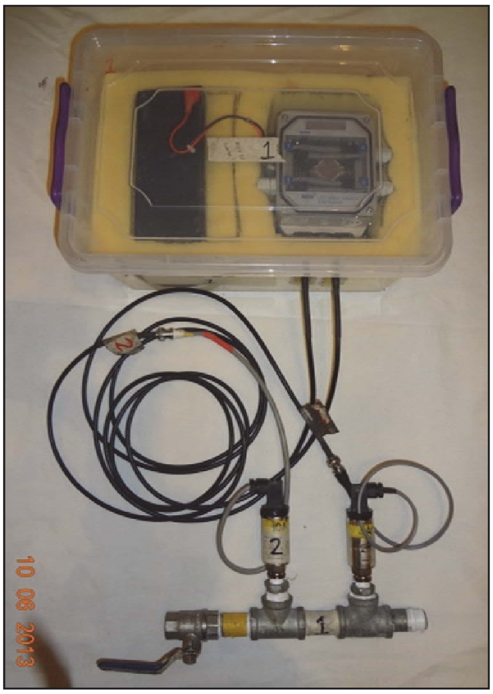

Figure 5-5: Data recording "box" linked to two pressure transducers installed on a manifold

5.6.3 Provision recording positions for flow measurements

Flow measurement must be conducted at locations along the pipeline where the following criteria are met:

- Flow gauging positions must be accessible (close to roads);
- The location should free of groundwater or possible leak water;
- It should be possible to secure the access to the instrumentation;

- A straight section of the pipeline with a length of at least 20 diameters should be accessible up to the shoulder of the pipeline;
- The flow rate at the flow recording position should represent the flow in the pipeline between the pressure recording positions, hence no large abstractions or inflows should be present;
- The pipe material, diameter, wall thickness, liner type and liner thickness should be known;
- The operational control should be able to regulate the flow for a sufficient time to ensure a constant flow condition; and
- The operational flow rate should be adjustable to provide at least 3 different constant flow rates (low, intermediate and high).

5.6.4 Provision of pigging stations to reinstate the hydraulic capacity

If biofilm growth occurs and is detrimental for the hydraulic capacity, the following biofilm mitigation options can be considered:

- Increase the pipe diameter during the design of the pipeline to account for additional friction losses (may be costly);
- Allow for mechanical cleaning of the system (pigging stations); and
- Provide facilities to conduct the dosing of biocides (expensive and difficult to achieve option).

If pigging of biofilm is viable, the suggested locations of the pigging stations should be determined. **Figure 5-6** reflects a typical pigging station on a 250 mm pipeline where the gooseneck is dismantled to function as receiving station from the upstream side as well as the launching station for the downstream (here diameter changes can be accommodated).

Figure 5-6: Examples of a pig station on a 250 mm pipeline

5.6.5 Biofilm monitoring stations

5.6.5.1 Introduction

During this project a sampling device to extract biofilm samples during normal operation was conceptualized. The device consists of the following elements (components):

- Extractable sampling disc (part of the pipe wall material) with guides to be able to place it back into the pipeline and ensure minimal local flow disturbances;
- A distant piece to accommodate the extracted disc;
- A lifting arrangement to be able to extract the disc from the pipeline;
- A valve that can isolate the disc from the pipeline;
- A valve to relieve the pressure after the isolating valve has been closed;
- A safety catch to restrain the disc and disc extracting components to drop during any steps of the biofilm sampling or disc extraction;
- An entry port through which the biofilm can be sampled while the disc is still under water (in cases where the disc is not extracted); and
- A bypass to be able to balance the pressure across the disc when it is reintroduced.

The detailed Solid Works drawings of the sampling device can be downloaded as referenced in **Section 7**.

5.6.5.2 Operation of the sampler

In **Section 5.6.5.3** some drawings to highlight the features of different components of the biofilm sampling device are included. Reference to these drawings will assist to understand the operation of the sampler.

The operation of the biofilm sampling device can be summarized for the different operation regimes as follows:

- **Normal operation of the pipeline**: During normal pipeline operating the disc will be positioned in such a way that the discontinuity of the pipe wall is minimised. The disc is of sufficient size to experience similar biofilm growth as the rest of the pipeline. During normal operation the isolation valve is open to accommodate the shaft of the lifting arrangement;
- **Removal and replacement of the disc**: While the pipeline is operational the lifting arrangement will be used to extract the disc into the distant piece on the outlet side (top) of the isolating valve. After the disc has been lifted the isolating valve and the bypass valve will be then closed. The pressure in the upper distant piece will be released by opening the drain valve to discharge the pressure. The disc can then be extracted. Replacing the disc will happen in the reverse order of the previous discussion.
- **Scraping of a biofilm sample**: The procedures discussed above for the lifting of the disc into the distant piece and depressurizing the distant piece will be followed. Then the biofilm sample will be collected by inserting a scraper or your hand through the sampling access point (a valve of sufficient diameter). The collected biofilm sample can be placed into the sampling probe under submerged conditions. The biofilm sample can then be prepared for analyses.

5.6.5.3 Photographic presentation of the biofilm sampling device

Figure 5-7 to **Figure 5-10** shows some features of the biofilm sampling device.

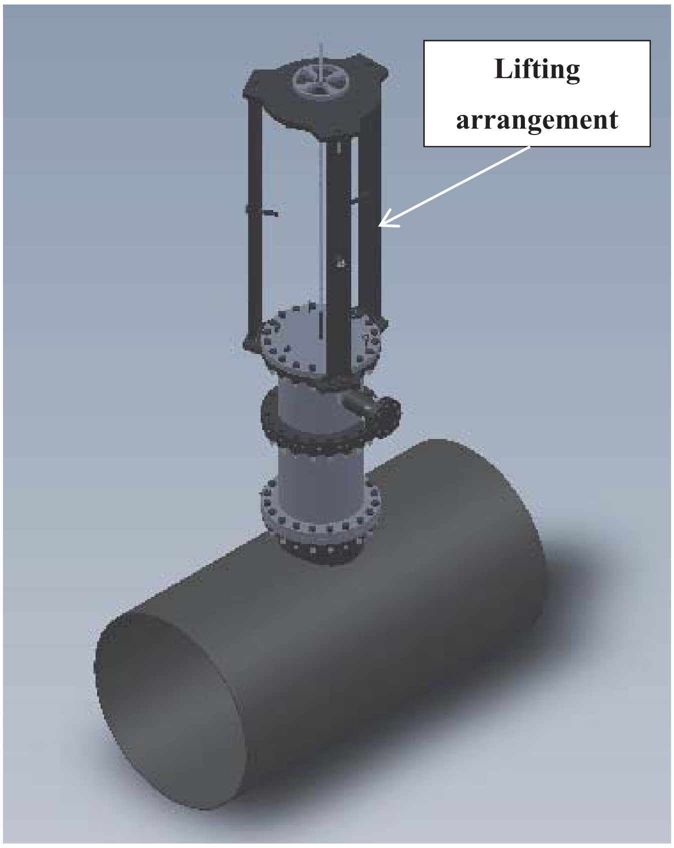

Figure 5-7: Isometric view of the biofilm sampler

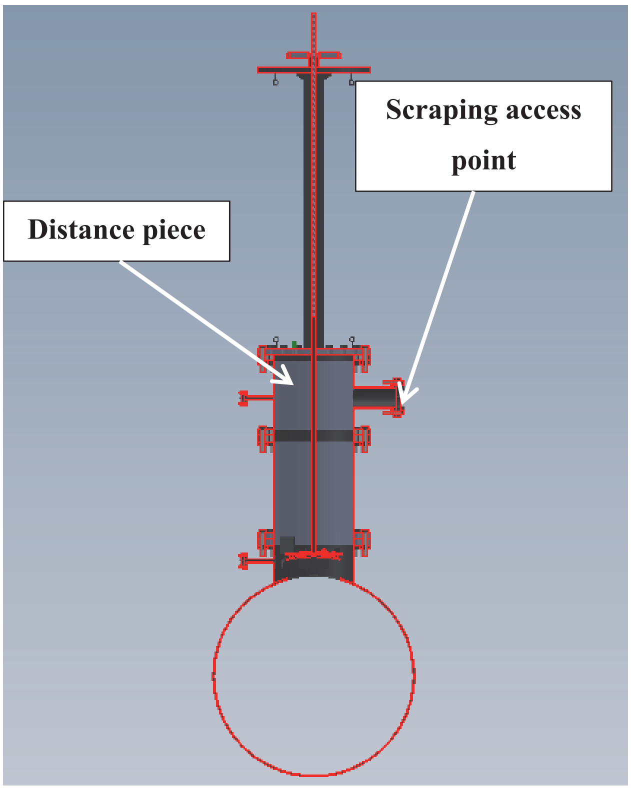

Figure 5-8: Section through the biofilm sampling device

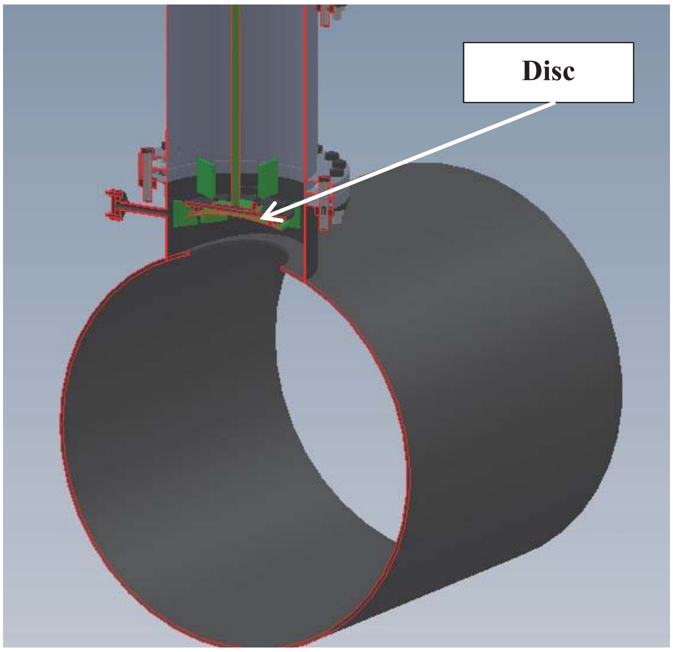

Figure 5-9: Section through the extractable sampling disc with the positioning vanes

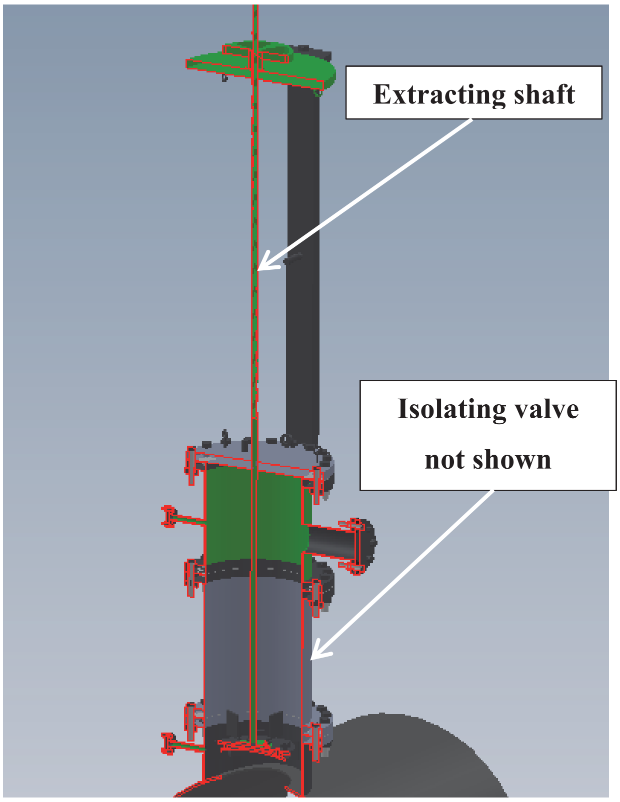

Figure 5-10: Section through the upper lifting arrangement showing the disc, extracting shaft and extracting wheel

6 Conclusion

During this research the hydraulic performance of a number of pipelines were reviewed by conducting field measurements of the flow rate and energy losses, from which the roughness of the pipelines was calculated. The calculated roughnesses were compared to the documented or referenced roughness for different pipe materials or liner types, which made it possible to calculate the yearly increase of the roughness.

The calculated roughness for the different pipelines which were reviewed during this research is well in excess of documented maximum values. In cases where biofilm growth was experienced, the documented long term expected roughness was significantly less than the calculated roughness. <u>This reflects that whenever biofilm growth occurs (Options 2 and 3 discussed in **Section 2.6**), the reference to and use of the surface roughness to determine the hydraulic capacity is misleading</u>.

The higher than published values of the yearly increase in roughness, negatively impact the operating capacity of gravity systems and will increase the energy cost of pumping systems. It is therefore imperative that periodic review of the hydraulic performance of conveyance systems **should be undertaken**. This requires access to flow and pressure gauging positions on the pipeline which will have to be considered during the design of water systems. In the design and tender detailing of pipelines, sufficient access points to measure flow and pressure must be provided. Whenever there is a probability that Option 3 biofilm growth might occur, biofilm mitigation options have to be considered during the design. These mitigation options might require the provision of pigging stations and biofilm sampling points (**Section 2.6**).

The management, operation and maintenance of the existing water infrastructure in South Africa are governed within a regulatory framework. The multi-facetted nature of infrastructure management was introduced by providing a summarized reference to the relevant regulations. It was proposed that the design engineer should have knowledge of the way in which the water infrastructure should be governed, be aware of ways in which the condition assessment of infrastructure should be performed, develop a thorough understanding of procedures which can be used for the assessment of the remaining useful life, and provide the required monitoring equipment to conduct the initial and subsequent assessment of the infrastructure’s performance. Although the focus is on South African Regulations, relevant to water infrastructure, the review also include references to international standards applicable to condition monitoring and technical risk assessment of engineered assets in the built environment.

6.1 Recommendation

Based on the findings in this report, it is recommended that:

- Field verification tests of the hydraulic performance of water conveyance systems should be implemented as part of the infrastructure management of the water infrastructure in South Africa;
- The monitoring of biofilm growth in pipelines should be expanded to enable the compilation of a "**national biofilm growth production map for pipelines**" for South Africa;
- Further research on the proposed model (BRM), to calculate a representative roughness in biofouled pipelines for Option 3 biofouling, is advised;
- A procedure should be developed to establish economic viability of pigging installations on pipelines and the implementation of other anti-microbial growth options; and
- The dataset of pipeline performance reviews should be extended to improve the design guidance for new installations by incorporating the long term expected pipe performance of biofouled pipelines and other capacity reduction factors in the design.

7 Supporting material

The supporting material as well as different reports which were compiled during the execution of this project is referenced below. The file structure of the supporting material is references in **Table 7-1**. The links to the different components (directories) of the supporting material is provided in **Table 7-3**.

Table 7-1: File structure for the supporting material

Directory	Description of the contents
Field tests	Preparing for fieldwork to be able to determine the hydraulic characteristics of the water infrastructure components
Biofouling	Articles related to biofouling and the influence of biofilm on the hydraulic capacity of the pipelines
Design	General pitfalls in pipeline design
Roughness	Related articles on roughness
Sample Report on the fieldwork	One of the reports compiled on the fieldwork conducted to determine the absolute roughness of existing pipelines.
Student contribution	Master's Thesis of a student who worked on this project
WRC Reports	Relevant reports which were previously completed by the project team.
Remaining operational life	Spread sheet to calculate the of the useful economic life (remaining operational life)
Biofilm Sampling device	Solid Works drawings of the sampling device.

Table 7-2: Overview of the supporting material

Directory	Article titles
Field tests	Preparing for fieldwork to be conducted to determine the change in hydraulic capacity in pipelines
Biofouling	1. Influence of hydrodynamics and nutrients on biofilm 2. The effect of turbulent flow and surface roughness on biofilm 3. The impact of biofilm development on pipe roughness and velocity 4. Understanding the impact of biofilm growth on pipe roughness
Design	1. Common pitfalls in hydraulic design of large diameter pipelines, Bennet and Glaser, 2001
Roughness	2. Absolute_Pipe_Roughness[1].pdf 3. Chlorine based biofilm control on the pipe roughness 4. Hydraulic roughness of biofouled pipes and improvements from cleaning 5. Influence of biofouling on friction and velocity distribution Perkins Henderson Walker L1 2012 6. Pipe roughness values
Sample Report on the fieldwork	1. DL 5: Pipelines reviewed Period 2
Student contribution	Rossnagel Master's Dissertation (5-Jan-2015)

WRC Reports	1. K5 1820 Report 02042012 V13 2. K5 1820 Executive Summary 09032012
Remaining operational life	Spread sheet titled: Asset Management Estimation of the Economic Useful Life.xlsm
Biofilm Sampling device	Different directories containing details of the Solid Works drawings: 1. Assembly 2. Individual parts 3. Joints

Table 7-3: Links to the directories which contains the contents of the supporting material

Directory	Description of the contents
Fieldwork	https://dl.dropboxusercontent.com/u/87808307/K5%202140-Preparation%20for%20fieldwork.pdf
Biofouling	https://www.dropbox.com/sh/droxn7ow9ewm7z4/AACdr4ZNrNm883eAkjp8veG_a?dl=0
Design	https://www.dropbox.com/sh/cwlbuasq5bfo9jl/AAByH27bQZox2XI4e4944l82a?dl=0
Roughness	https://www.dropbox.com/sh/bdvb7xadfly628g/AABhyORVEMtqKch79k1DG_qMa?dl=0
Sample Report on the fieldwork	**https://dl.dropboxusercontent.com/u/87808307/DL5%20K5%202140%20Report%20060314.pdf**
Student contribution	https://www.dropbox.com/sh/m0ns2t5xttvrrfa/AADLD9KhxGNmr6yEQct3ygbXa?dl=0
WRC Reports	https://www.dropbox.com/sh/was3go5772x8k3x/AAA2WAkRPJfgBWDV8RRL5r8-a?dl=0
Remaining operational life	**https://dl.dropboxusercontent.com/u/87808307/Asset%20Management%20Estimation%20of%20Economic%20Useful%20Life.xlsm**
Biofilm Sampling device	**https://dl.dropboxusercontent.com/u/87808307/Biofilm%20sampler%20assembly%20%28from%20joins%29.SLDASM** **https://dl.dropboxusercontent.com/u/87808307/Individual%20parts.zip** **https://dl.dropboxusercontent.com/u/87808307/Joins.zip**

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