A critical evaluation of the water reticulation system at Vlaklaagte Shaft, Goedehoop Colliery

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Synopsis

Water is a very important component in the production process at underground coal mines. Current unfavourable economic conditions have forced the coal mining industry to identify and address every possible bottleneck preventing optimal production. An increase in water-related downtime was identified as one of the bottlenecks at Goedehoop Colliery's Vlaklaagte Shaft. The purpose of this project was to identify the various causes that contributed to the high downtime (501 hours in 2013, which led to a potential profit loss of R12.9 million) and to suggest possible solutions.

After a thorough investigation the main causes of water-related downtime were identified as low water pressure and low water flow caused by pipe leakages and bursts. The main root cause for the low water flow and pressure was identified as being the low pressure resistance (1600 kPa) of the thin-walled galvanized steel pipes used in the underground inbye water reticulation system. The pipes were selected according to the previous 1000 kPa pressure requirement for the continuous miner. However, the pressure requirement changed to 1500 kPa, which resulted in the pipes being exposed to much higher pressures than designed for.

The water reticulation system was reviewed and current and future underground pipe layout and water requirements were determined for the shaft. The time frame in which the water consumption would be the highest was determined to be between 1 January 2014 and 7 September 2014. Machine and sprayer specifications were used to determine the water consumption at the shaft.

Three different solutions were considered to solve the water-related downtime problem and to ensure the efficient supply of water to the newly open sections. Permanent underground concrete dams, semi-mobile dams, or new pipe columns with a higher pressure resistance of 3200 kPa were considered. A trade-off study (taking into consideration cost, time to completion and ease of implementation, maintenance requirements, safety, and flexibility) was completed to determine which of these solutions would be most viable.

Keywords

water reticulation, down time, pipe bursts, leakages, cascade dam system, permanent dams, portable dams.

Mine background

Goedehoop Colliery is situated approximately 40 km east of Witbank in Mpumalanga Province. Currently Goedehoop has two underground shafts – Vlaklaagte Shaft, which is situated in the southern part, and Simunye Shaft, which is situated in the northern part – which consist of 11 sections. The bord and pillar mining method is employed for coal extraction and each section is equipped with one double-boom Fletcher roofbolter, one feeder breaker, three 20 t shuttle cars, and one continuous miner (CM).

Goedehoop produces 8.7 Mt of run-of-mine (ROM) yearly, of which 5 Mt are saleable. Ninety-nine per cent of the coal from Goedehoop is exported through Richards Bay (Becht, 2010).

Vlaklaagte Shaft is currently mining only the No. 4 Seam, as the No. 2 Seam has been mined out. The shaft produced approximately 320 634 t of coal per month in 2013 and made a profit of R120 per ton due to the high-quality coal (on average 27.5 MJ/kg) that is extracted at this shaft (Du Buisson, 2013). The shaft consists of six sections: Section 1 (Simunye), Section 2 (Magwape), Section 3 (Siyaya), Section 4 (Ngwenya), and Block 7 (Section 5/6 and Section 9/10).

The main water source for Vlaklaagte is the Komati Dam. Recycled water from surface is supplied from the return water dam (RWD) to underground sections 1 to 4 via a pipeline running alongside the conveyor belt. Sections 2 and 4 have been developed more than 8 km away from the RWD.

Water requirements

Water is utilized for many purposes, including dust suppression, cooling, and cleaning (Table I).

Current water reticulation system at Vlaklaagte Shaft

As indicated in Figure 1, clean water was supplied to the No. 4 Seam underground sections (via 200 mm galvanized steel pipes) from the surface water cleaning plant until 27 July 2013. The raw water dam received water from the Blesbok reservoir, and the water was then pumped to the water cleaning plant to process the water to drinking quality. However, the pipes that supplied clean water to underground workings from the raw water dam corroded. As a result, recycled water from the RWD (via 200 mm galvanized steel pipes) was used as a substitute. A filtration system consisting of 2 μm sieves was installed to remove solids (which cause blockages in the CM and belt sprayers) from the recycled water.

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Table I

Water users and requirements

Water users	Requirements
CM sprays	Requires water for the following purposes: dust suppression, cooling and cleaning. The CMs operate approximately 9 hours per day. According to Richard Lottering (2013), a Barloworld consultant, CMs requires a flow rate of between 120-135 liters/min and a pressure of 1500 kPa. Failing to adhere to the required flow rate and pressure will result in the CMs tripping which will cause downtime.
Feeder breaker and conveyor belt sprays	Three water sprays are fitted on every feeder breaker for dust suppression. A water spray is also required on every transfer point on the conveyor belt for dust suppression. All the sprays require a water flow rate of 15 liters/min at a recommended pressure of 1500 kPa (Pieterse, 2013)
Dust suppression for roads	Approximately 60 liters/min is required for road dust suppression (Louw, 2013).
Benicon (mini-pit)	Benicon is a mini-pit near Vlaklaagte that makes use of the water from the RWD and requires approximately 2.1 liters/min.
Cleaning	Cleaning requires approximately 120 liters/min (Horac, 2013)

Since 28 July 2013, water has been supplied to the No. 4 Seam from the RWD. The water cleaning plant therefore only supplies water to the change houses on surface, as recycled water is now being used to supply the underground workings.

Surface pump and pipe layout

The surface pump and pipe layout consists of a centrifugal pump (pump 2) which pumps water into a 23 000 litre tank. The water from the tank is pumped by a five-stage, 65 kW multi-stage pump (pump 1) to the underground sections. Figure 2 shows the surface pump and pipe layout. Standard 200 mm pipes are used on surface.

Figure 3 is a schematic illustration of the surface to underground pipe layout, including dimensions that are required to calculate the available head.

Underground pipe and pump layout

Figure 4 indicates the underground pipe layout and positions of different water users in the different underground sections at Vlaklaagte. Recently a 150 mm standard galvanized steel pipe size was selected and these pipes were tested to withstand a maximum pressure of 1600 kPa (Louw, 2013).

Summary of water requirements at Vlaklaagte Shaft

Table II is a summary of the water consumption at sections 1, 2, 3, and 4 of Vlaklaagte Shaft (31 December 2013).

Water problems experienced at Vlaklaagte

The water-related problems that led to downtime, may be attributed to the following facts.

- Water is pumped over very large distances, which means that major pipe friction losses need to be overcome. The pressure that is required at the CM has changed over the past years. Previously the CM required only 1000 kPa of pressure to operate. Pipes were selected according to this pressure requirement, and thin-wall galvanized pipes, which can withstand only 1600 kPa, were chosen.

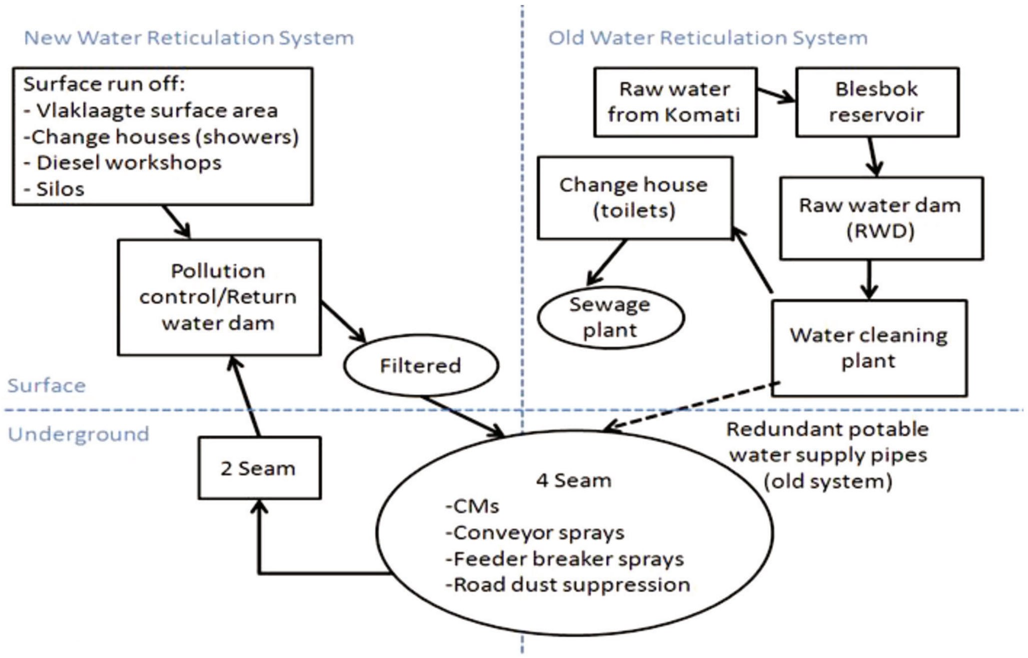

Figure 1—Overview of water reticulation system at Vlaklaagte

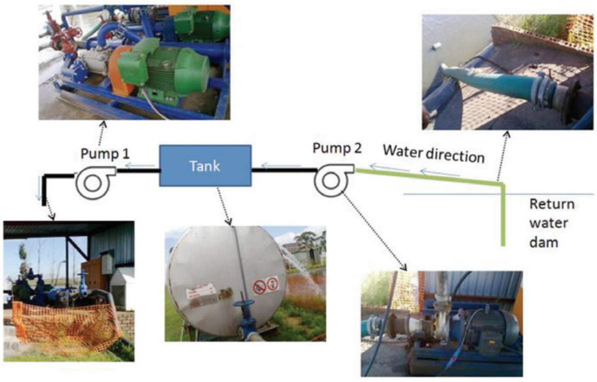

Figure 2—Partially flooded suction currently employed at Vlaklaagte

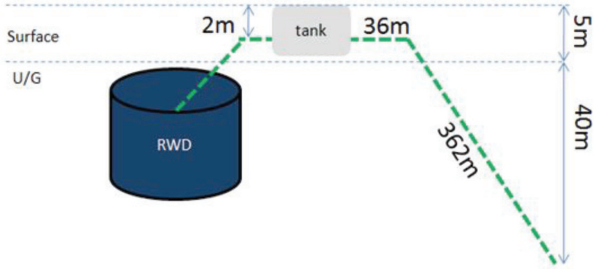

Figure 3—Surface pipe layout

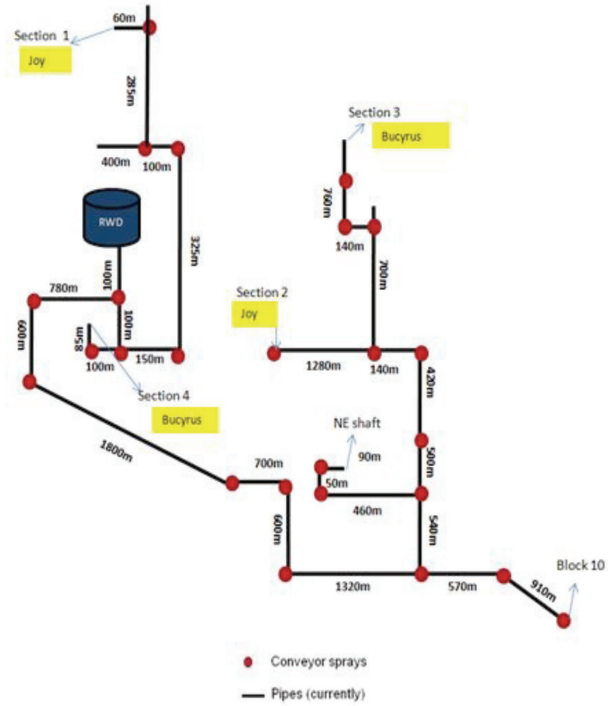

Figure 4—Underground pipe and pump layout at Vlaklaagte Shaft

However, the pressure requirement at the CM changed to 1500 kPa, which exposed the pipes to much higher pressures than they were designed for. No action has been taken so far to change the water reticulation system to adapt to this higher pressure requirement

➤ Vlaklaagte is an old shaft and therefore has an ageing infrastructure, including pipelines. The old infrastructure and increased pump pressures are the main causes of frequent pipe damage and leakages leading to low water flow and low pressure (or no water flow and no pressure) at the face

➤ Changes made to the water reticulation system over the past years (such as changes in the pipe sizes in underground sections, the change from clean water to recycled water, and changes to pump settings and the installation of new pumps) were not well documented

Table III

Downtime hours summary (2013)

Section	Downtime hours	Related lost shifts*
Section 1	50	6.3
Section 2	82	10.3
Section 3	182	22.8
Section 4	187	23.4
Total	**501**	**62.6**

*Note: 8 hours represents 1 shift

Table II

Water requirements at Vlaklaagte Shaft (31 Dec 2013) for Section 1-4

Different activities requiring water	Number of	Flow of water required (l/min)	DOH (hours/day)	Quantity (l/day)	Quantity (l/s)	Quantity (m^3/month)	Optimal Pressure required (kPa)
CM (Joy)	2	120	9	129 600	4.0	3 888	1500 in pipe but 2000 at CM
Bucyrus (CAT)	2	135	9	145 800	4.5	4 374	
Conveyor sprays	25	15	21	472 500	6.3	14 175	1000-1800
Feeder Breaker sprays	12	15	9	97 200	3.0	2 916	1000-1800
Cars for dust suppression/ fire hydrants*				15 000	1.0	450	N/A
Cleaning (4 sections)	4		2	57 600	2.0	1 728	N/A
Benicon (Mini pit)				60 000	0.0	1 800	N/A
Total + 10%*				**107 5470**	**22.9**	**32 264**	

*10% was included to compensate for losses

- New underground mining blocks, such as the extension in Block 10, for which the current water reticulation was not designed, are being accessed further away from the shaft and the RWD.

Data from the water-related downtime logbook was sorted and analysed to determine the extent of the problem and to identify possible root causes leading to the high downtime. Block 7 (Section 5/6 and 9/10) was excluded from this investigation as Block 7 has a separate water reticulation system in place.

Table III indicates the total hours of production lost by each section from 1 January to 31 December 2013 due to water-related downtime. Sections 3 and 4 contributed the most to the total downtime of 501 hours. Solving the problems causing the high downtime in these two sections can eliminate 74% of the water-related downtime. Sections 3 and 4 were therefore selected for further investigations.

A summary of the combined impact of the different causes on both Section 3 and Section 4 is shown in the pie diagram (Figure 5). The chart clearly indicates that low water flow and low water pressure are the two main causes for downtime in these two sections.

Production losses due to downtime

Every time production stops the mine loses potential profit. The total potential profit lost in 2013 due to water-related downtime was calculated as indicated in Table IV and totalled R12.9 million (Du Buisson, 2013). An intervention was required to stop losses due to water-related problems and to ensure that the water requirements over the life of the shaft are met so that water problems do not occur in the future.

Objectives and methodology

The objectives and methodology are presented in Table V.

Results

The current water reticulation was reviewed to quantify the reasons for the pipe bursts. The future water reticulation system was also reviewed in order to determine the final pipe layout and underground dam placement.

Analysis of current water reticulation system

The pipe layout in Figure 5 can be analysed thoroughly by using the Bernoulli steady-state energy equation (White, 2011):

$$\left[\frac{P_1}{\rho g}+\frac{\alpha}{2g}V_1^2+z_1\right]=\left[\frac{P_2}{\rho g}+\frac{\alpha}{2g}V_2^2+z_2\right] \qquad [1]$$
$$+h_{turbine}+h_{pump}+h_{friction}$$

Table IV

Water-related downtime cost (1 January 31 December 2013)

Section	Hours on stop	Cutting rate (tons/hour)	Potential ROM tons	Yield	Sales tons	Potential Profit loss*
1	50	313	15625	0.59	9219	1.1
2	82	323	26486	0.61	16156	1.9
3	182	341	61971	0.71	43999	5.3
4	187	347	64796	0.59	38229	4.6
Total	501	1323	168878	2.50	107604	12.9

Potential profit loss = Hours on stop x Yield x Cutting rate x Profit

Table V

Objectives and methodology

Objective	Methodology
Quantify the problem	The downtime logbook was thoroughly investigated to: • Determine the total production hours lost due to water-related issues • Determine the potential profit that was lost due to water-related down time • Identify sections with the highest downtime; and • Determine the main causes of the high downtime The company, MCS, was consulted to determine the DOH of the CMs as well as the cutting rate of the CMs. Information on the yield and profit per ton was retrieved by consulting the financial department.
Review current water reticulation system	On-site investigations were conducted including: walking the pipelines, observing the different water consumers, manifolds, bends and pumps and where they were located.
Investigate and quantify water consumption for the current water reticulation system	The water consumption was calculated by investigating machine and sprayer specifications and also consulting with the Mine Overseer, Shift Boss and Pump Crew at Vlaklaagte Shaft.
Determine the life of mine (LOM) water requirements (to prepare for the future)	The LOM mining plan (obtained from the planning department) for the shaft was investigated and the Mine Planner and Mine Overseer were consulted in order to determine the LOM water requirements.
Investigate different methods for supplying water to newly opened sections and solving the water-related downtime problem	Information gathered from the mine was used. Various suppliers were also consulted including: • Lectropower • Eljireth • Incledon
Draw conclusions and make recommendations from the results of the investigation	Recommend the best method for supplying water to the current and newly opened sections.

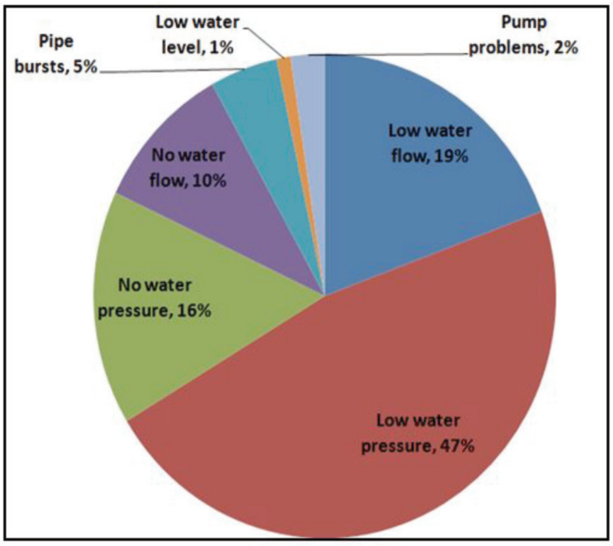

Figure 5—Main causes for water-related downtime in Section 3 and 4

Each term in the equation is a length or a head.

α = Kinetic energy correction factor (in problems common to assume that $\alpha = 1$)

P_2 = Pressure required at the end of the pipe system (at the CM)

P_1 = Pressure at the inlet

V_1 = Velocity of the fluid entering the pipe (zero because static water is pumped out of the dam)

V_2 = Velocity of the fluid required at the end of the pipe system (at the CM)

Δz = Height difference/ elevation difference (m).

Equation [2] can be used to correlate the head loss to pipe flow problems (White, 2011).

$$h_{friction} = \frac{V^2}{2g}\left[f\frac{L}{D} + \sum K \right] \qquad [2]$$

where

f = Friction factor

D = Inner diameter (m)

K = Minor losses (read off from the table in Appendix H)

g = Gravitational acceleration (m/s^2)

V = Velocity of medium flowing through the pipe (m/s).

Every pipe section has a different flow rate because of the location of the different water users, which results in different frictional losses within each pipe section. A number was allocated to each pipe section in order to differentiate between them (as indicated in Figure 6).

Table VI

Friction factor calculation by using Bernoulli's equation

Section	Length (m)	Component	K factor	Total flow plus 10% wastage (l/s)	*u* (m/s)	Re	Friction factor*	H_{loss} (m)**
surface pipe	398	-	0	0.0	0.0	0	0.01964	0.0
1	100	Standard elbow	0.45	0.0	0.0	0	0.02157	0.0
2	780	Standard elbow	0.45	9.6	0.5	81 700	0.2263	17.8
3	600	Standard elbow	0.45	9.4	0.5	79 365	0.0227	1.3
4	1800	Standard elbow	0.45	9.1	0.5	77 031	0.02277	3.7
5	700	Standard elbow	0.45	8.8	0.5	74 697	0.02285	1.4
6	600	Standard elbow	0.45	8.5	0.5	72 362	0.02293	1.1
7	1320	T piece	0.9	8.3	0.5	70 028	0.02302	2.3
8	570	Standard elbow	0.45	0.6	0.0	4 669	0.03921	0.0
9	910	-	0	0.3	0.0	2 334	0.04787	0.0
10	540	T piece	0.9	7.4	0.4	63 025	0.02331	0.8
11	460	Standard elbow	0.45	0.6	0.0	4 669	0.03921	0.0
12	50	Standard elbow	0.45	0.3	0.0	2 334	0.04787	0.0
13	90	-	0	0.0	0.0	0		0.0
14	500	-		6.6	0.4	56 023	0.02366	0.6
15	420	Standard elbow	0.45	6.3	0.4	53 688	0.02379	0.4
16	140	T piece	0.9	6.1	0.3	51 354	0.02393	0.1
17	1280	Sharp exit	1	2.3	0.1	19 099	0.0282	0.2
18	700	Standard elbow	0.45	3.3	0.2	28 011	0.02628	0.2
19	140	Standard elbow	0.45	3.0	0.2	25 677	0.02668	0.0
20	760	Sharp exit	1	2.8	0.2	23 343	0.02714	0.2
21	100	T piece	0.9	6.3	0.4	53 688	0.02379	0.1
22	100	Standard elbow	0.45	2.5	0.1	21 221	0.02763	0.0
23	85	Sharp exit	1	2.3	0.1	19 099	0.0282	0.0
24	150	Standard elbow	0.45	3.3	0.2	28 011	0.02528	0.0
25	325	Standard elbow	0.45	3.0	0.2	25 677	0.02668	0.1
26	100	T piece	0.9	2.8	0.2	23 343	0.02714	0.0
27	400	-	0	2.5	0.1	21 008	0.02768	0.1
28	285	T piece	0.9	2.5	0.1	21 008	0.02768	0.1
29	60	Sharp exit	1	2.2	0.1	18 674	0.02832	0.0
Total								**30.5**

*The friction factor was calculated by using the Moody diagram. A friction factor calculator, which can be easily downloaded, was used to accurately determine the friction factor.

**The total head loss for each pipe section was calculated by using Equation [2].

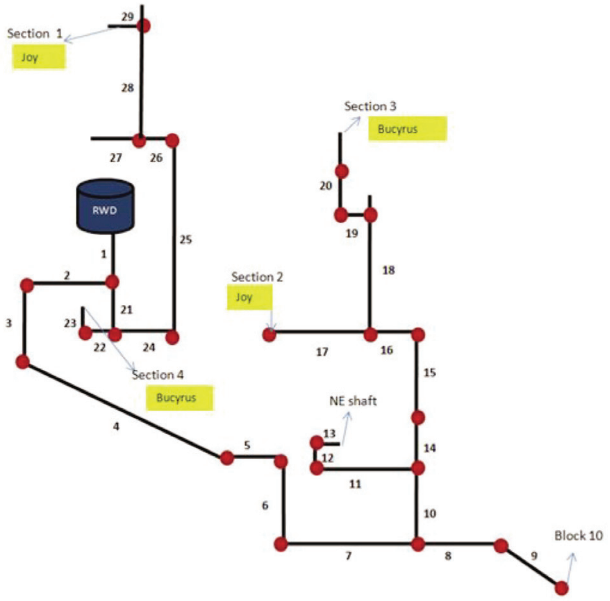

Figure 6—Pipe layout with the numbering of each pipe section (Dec2013)

Table VI details how the friction losses within each pipe section were calculated using Bernoulli's steady state energy equation. For all the calculations in Table VI it was assumed that e = 0.15 mm and μ = 0.001.

As seen in Table VI the friction losses within the system amount to approximately 31 m. The required head of the pump can now be determined by using Bernoulli's equation (Equation [1]). Taking into consideration that:

- The static head available (as indicated in Figure 4) is 40 m
- Pressure in the pipes should not exceed 1600 kPa (or 163.2 m)
- The allowable head for the pump can be calculated as 123.2 m (163.2 m – 40 m)
- The frictional head loss in the total length (21 460 m) of pipe is 31 m
- P_1 = pgh (h = 2 m, as indicated in Figure 4 the water level in the tank is approximately 2 m above the pipeline exiting the tank)
- P_2 = 1500 kPa (the pressure required at the CM is 1500 kPa)
- $V_1 = 0$ m/s
- $V_2 = 0.13$ m/s (derived from the required flow rate of 135 l/min for the Bucyrus CM)

$$h_{pump} = \left[\frac{P_2}{\rho g} - \frac{P_1}{\rho g}\right] + \frac{V_2^2 - V_1^2}{2g} + h_{friction} - (z_2 - z_1)$$

$$= \left[\frac{1500\ 000}{1000 \times 9.79} - \frac{1000 \times 9.79 \times 2}{1000 \times 9.79}\right] + \frac{0.13^2 - 0}{2 \times 9.79} + 31 - 40$$

$$= 142.21 \text{ m}$$

It can therefore be concluded that the pump pressure required for supplying water at the required pressure and flow rate to the four underground sections will cause pipe breaks

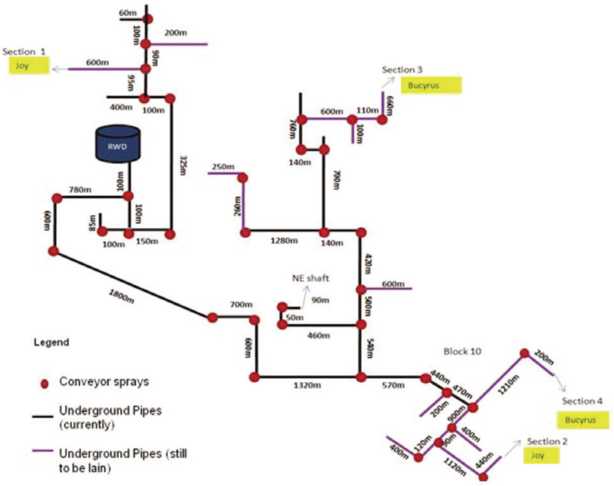

Figure 7—Future pipe layout

Table VII

Future water requirements (section 1, 2, 3, and 4) at Vlaklaagte Shaft (1 Jan 2014 – 7 Sept 2014)

Different activities requiring water	Number of	Flow of water required (l/min)	DOH (hours/day)	Quantity (l/day)	Quantity (l/s)	Quantity (m/month)	Optimal Pressure required (kPa)
CM (Joy)	2	120	9	129 600	4.0	3 888	1600 in pipe but 2000 at CM
Bucyrus (CAT)	2	135	9	145 800	4.5	4 374	
Conveyor sprays	33	15	21	623 700	8.3	18 711	1 600
Feeder Breaker sprays	12	15	9	97 200	3.0	2 916	1 600
Cars for dust suppression				15 000	1.0	450	N/A
Cleaning	4		2	57 600	2.0	1 728	N/A
Benicon (Mini pit)				60 000	0.0	1 800	N/A
Totals				112 8900	22.8	33 867	
Total + 10%						**37 254**	

*10% was included to compensate for losses and bursts. The required pump head (142.21 m) exceeds the allowable head of 123.2 m. No pump will therefore be suitable in this application. Three solutions to this problem were considered:

- To replace all the thin-walled pipes with thick-walled pipes with a higher pressure-holding capacity
- An underground cascade dam system using permanent underground dams
- An underground cascade dam system using semi-mobile underground dams.

The solutions needed to be implemented to satisfy the life-of-mine (LOM) water requirements. Therefore the LOM pipe layout and maximum future water requirements needed to be determined.

Summary of maximum future water consumption at Vlaklaagte Shaft

The maximum future water requirement for the shaft was determined to be during the period when sections 2 and 4 moved to block 10 and Section 1 had not been closed yet. A summary of the future water consumption for these four sections is given in Table VII.

Future underground pipe layout

The final pipe layout, including final pipe distances for the LOM of Vlaklaagte Shaft, is illustrated in Figure 7. In Figure 8, each pipe section was numbered to facilitate the analysis of the layout.

Table VIII

Pipe friction calculation using Bernoulli's equation

Section	Length (m)	Component	K factor	Total Flow plus 10% wastage (l/s)	*u* (m/s)	Re	Friction factor*	H_{loss} (m)**
surface pipe	398			19.75	0.69	103 729	0.0221	1.43
1	100	standard elbow	0.45	19.75	1.23	184 423	0.02114	1.12
2	780	standard elbow	0.45	19.5	1.21	182 088	0.02116	8.31
3	600	standard elbow	0.45	19.25	1.20	179 754	0.02117	6.24
4	1800	standard elbow	0.45	19	1.18	177 419	0.02119	18.20
5	700	standard elbow	0.45	18.75	1.17	175 085	0.02121	6.92
6	600	standard elbow	0.45	18.5	1.15	172 750	0.02123	5.78
7	1320	t piece	0.9	18.25	1.14	170 416	0.02125	12.39
8	570	standard elbow	0.45	7.5	0.47	70 034	0.02302	0.98
9	440	t piece	0.9	7.25	0.45	67 699	0.02311	0.71
10	200				-	-		-
11	470	t piece	0.9	7	0.44	65 365	0.02321	0.71
12	2320	standard elbow	0.45	3.25	0.20	30 348	0.02592	0.84
13	200	sharp exit	1	3	0.19	28 014	0.02628	0.06
14	900	t piece	0.9	3.5	0.22	32 683	0.0256	0.37
15	400				-	-		-
16	90	t piece	0.9	3.25	0.20	30 348	0.02592	0.03
17	1120	standard elbow	0.45	3	0.19	28 014	0.02628	0.35
18	440	Sharp exit	1	2.75	0.17	25 679	0.02668	0.12
19	120	standard elbow	0.45	0.25	0.02	2 334	0.04787	0.00
20	400				-	-		-
21	540	t piece	0.9	5.75	0.36	53 693	0.02379	0.57
22	460	standard elbow	0.45	0.5	0.03	4 669	0.03921	0.01
23	50	standard elbow	0.45	0.25	0.02	2 334	0.04787	0.00
24	90				-	-		-
25	500	t piece	0.9	5	0.31	46 689	0.02425	0.40
26	600				-	-		-
27	420	standard elbow	0.45	4.75	0.30	44 355	0.02443	0.31
28	140	standard elbow	0.45	4.5	0.28	42 020	0.02462	0.09
29	700	standard elbow	0.45	4.25	0.26	39 686	0.02483	0.42
30	140	standard elbow	0.45	4	0.25	37 351	0.02506	0.08
31	760	t piece	0.9	3.75	0.23	35 017	0.02532	0.36
32	600	t piece	0.9	3.5	0.22	32 683	0.0256	0.25
33	100				-	-		-
34	110	standard elbow	0.45	3.25	0.20	30 348	0.02592	0.04
35	660	Sharp exit	1	3	0.19	28 014	0.02628	0.21
36	200	t piece	0.9	4.5	0.28	42 020	0.02462	0.14
37	250	standard elbow	0.45	4.25	0.26	39 686	0.02483	0.15
38	325	standard elbow	0.45	4	0.25	37 351	0.02506	0.17
39	100	t piece	0.9	3.75	0.23	35 017	0.02532	0.05
40	95	t piece	0.9	3.5	0.22	32 683	0.0256	0.04
41	600	Sharp exit	1	2.75	0.17	25 679	0.02668	0.16
42	90	t piece	0.9	0.5	0.03	4 669	0.03921	0.00
43	200				-	-		-
44	100	t piece	0.9	0.25	0.02	2 334	0.04787	0.00
45	60				-	-		
Total								**68.03**

*The friction factor was calculated by using the Moody diagram. A friction factor calculator, which can be easily downloaded, was used to accurately determine the friction factor.

**The total head loss for each pipe section was calculated by using Equation [2].

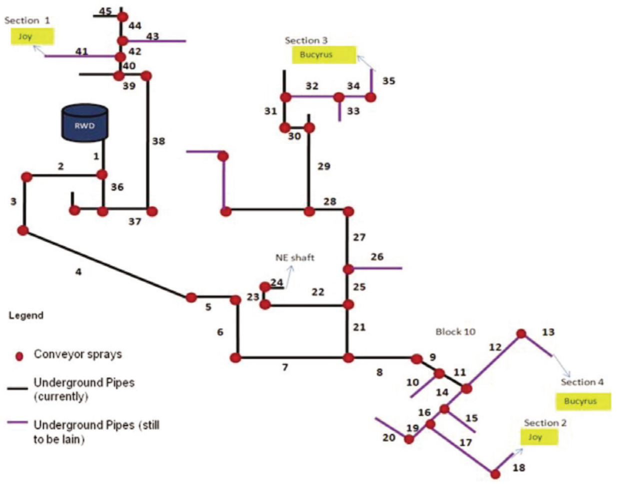

Figure 8—Future pipe layout with the numbering of each pipe section

Analysis of future pipe layout

Table VIII shows details of how the friction losses within each pipe section were calculated with the use of Bernoulli's steady-state energy equation. The total frictional losses were calculated to be approximately 68 m. Table VIII can be used to determine where the underground dams should be placed and how many dams would be required. The placement was determined by calculating the distances over which the pipe's maximum pressure rating will be exceeded.

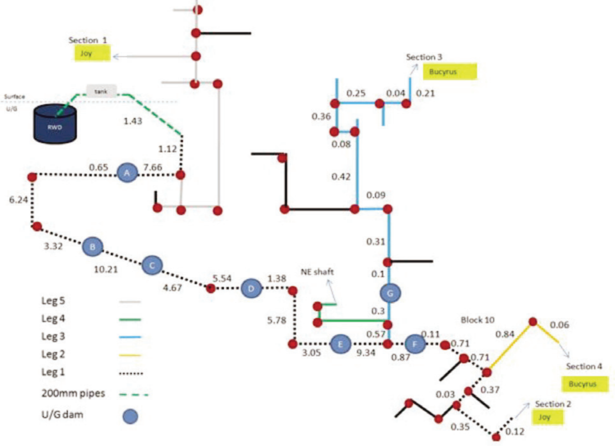

Figure 9—Dam placement for leg 1, 2, 3, 4 and 5

The pipe layout (Figure 7) is too complex to analyse as a single network. The network was therefore divided into five different legs in order to determine how many dams will be required and where the dams need to be placed. The logic behind determining when a dam will be required is simple: the pump needs to supply 153.22 m head at each outlet (spray), but the pipes can only withstand a maximum of 163.43 m, therefore whenever the pump needs to overcome frictional

Table IX

Calculation of how many dams will be required in leg 1 and where they are to be placed

Section	Friction loss (m)	Pressure required to overcome friction losses and still give the required 153.22 m head at the outlet	Comment
Surface pipes	1.43	154.65	
1	1.12	155.77	
2	8.31	164.08	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
2-damA	7.66	163.43	
damA-3	0.65	153.87	
3	6.24	160.11	
4	18.2	178.31	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
4-damB	3.32	163.43	
damB-5	14.88	168.1	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
damB-damC	10.21	163.43	
damC-5	4.67	157.89	
5	6.92	164.81	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
5-damD	5.54	163.43	
damD-6	1.38	154.6	
6	5.78	160.38	
7	12.39	172.77	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
7-damE	3.05	163.43	
damE-8	9.34	162.56	
8	0.98	163.54	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
8-damF	0.78	163.43	
damF-9	0.11	154.2	
9	0.71	154.91	
11	0.71	155.62	
14	0.37	155.99	
16	0.03	156.02	
17	0.35	156.37	
18	0.12	156.49	

Table X

Calculation of how many dams will be required in leg 2 and where they are to be placed

Section	Friction loss (m)	Pressure required to overcome friction losses and still give the required 153.22 m head at the outlet	Comment
Surface pipes	1.43	154.65	
1	1.12	155.77	
2	8.31	164.08	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
2-damA	7.66	163.43	
damA-3	0.65	153.87	
3	6.24	160.11	
4	18.2	178.31	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
4-damB	3.32	163.43	
damB-5	14.88	168.1	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
damB-damC	10.21	163.43	
damC-5	4.67	157.89	
5	6.92	164.81	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
5-damD	5.54	163.43	
damD-6	1.38	154.6	
6	5.78	160.38	
7	12.39	172.77	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
7-damE	3.05	163.43	
damE-8	9.34	162.56	
8	0.98	163.54	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
8-damF	0.78	163.43	
damF-9	0.11	154.2	
9	0.71	154.91	
11	0.71	155.62	
12	0.84	156.46	
13	0.06	156.52	

Table XI

Calculation of how many dams will be required in leg 3 and where they are to be placed

Section	Friction loss (m)	Pressure required to overcome friction losses and still give the required 153.22 m head at the outlet	Comment
Surface pipes	1.43	154.65	
1	1.12	155.77	
2	8.31	164.08	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
2-damA	7.66	163.43	
damA-3	0.65	153.87	
3	6.24	160.11	
4	18.2	178.31	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
4-damB	3.32	163.43	
damB-5	14.88	168.1	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
damB-damC	10.21	163.43	
damC-5	4.67	157.89	
5	6.92	164.81	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
5-damD	5.54	163.43	
damD-6	1.38	154.6	
6	5.78	160.38	
7	12.39	172.77	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
7-damE	3.05	163.43	
damE-8	9.34	162.56	
21	0.57	163.13	
25	0.4	163.53	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
25-damG	0.3	163.43	
damG-27	0.1	153.32	
27	0.31	153.63	
28	0.09	153.72	
29	0.42	154.14	
30	0.08	154.22	
31	0.36	154.58	
32	0.25	154.83	
34	0.04	154.87	
35	0.21	155.08	

Table XII

Calculation of how many dams will be required in leg 4 and where they are to be placed

Section	Friction loss (m)	Pressure required to overcome friction losses and still give the required 153.22 m head at the outlet	Comment
Surface pipes	1.43	154.65	
1	1.12	155.77	
2	8.31	164.08	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
2-damA	7.66	163.43	
damA-3	0.65	153.87	
3	6.24	160.11	
4	18.2	178.31	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
4-damB	3.32	163.43	
damB-5	14.88	168.1	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
damB-damC	10.21	163.43	
damC-5	4.67	157.89	
5	6.92	164.81	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
5-damD	5.54	163.43	
damD-6	1.38	154.6	
6	5.78	160.38	
7	12.39	172.77	Exceeds the maximum 163.43 m that the pipes can withstand - a dam is required
7-damE	3.05	163.43	
damE-8	9.34	162.56	
21	0.57	163.13	
22	0.01	163.14	
23	0	163.14	
24	0	163.14	

Table XIII

Calculation of how many dams will be required in leg 5 and where they are to be placed

Section	Friction loss (m)	Pressure required to overcome friction losses and still give the required 153.22 m head at the outlet	Comment
Surface pipes	1.43	154.65	
1	1.12	155.77	
36	0.14	155.91	
37	0.15	156.06	
38	0.17	156.23	
39	0.05	156.28	
40	0.04	156.32	
41	0.16	156.48	
42	0	156.48	
44	0	156.48	
45	0	156.48	

Table XIV

Weighing of criteria for trade-off study

Criterion	Weighting (%)
Cost and payback period	40
Time to completion and ease of implementation	20
Maintenance	10
Safety	25
Flexibility	5
Total	100

losses exceeding the difference (163.43 m – 153.22 m = 10.21 m), the maximum head that the pipes can handle is reached and a dam is required. The calculation for legs 1–5 are presented in Tables IX – XIII. As seen in the tables, seven dams will be required in order to ensure that the maximum pressure of 1600 kPa is not exceeded. The locations of the dams on the underground pipe layout, for all five legs, are shown in Figure 9.

Trade-off study

The three possible solutions were traded off, using five criteria: cost, time to completion and ease of implementation, maintenance, safety, and flexibility.

Based on their importance and the preferences of Vlaklaagte Shaft, the criteria were weighted as set out inTable XIV. The solution that scores the highest in the criteria will be recommended for Vlaklaagte.

Table XV

Summary of how solutions performed against the criteria

	Solution 1	Solution 2a	Solution 2b
Cost	R 3 875 100	R 438 397	R 2 250 618
Time to completion and ease of implementation	Pipes are installed by Vlaklaagte's operational team. It takes approximately 1 week to install 1km of pipes, therefore to reinstall 14.5 km length of pipe will take approximately 14.5 weeks, which adds up to 102 days. This includes delivery and transport of the pipes and accessories. The implementation of this solution will be time consuming and more labour intensive that the other two solutions.	It will take a maximum of 1 week to build one U/G permanent dam. This includes transport of the material. Therefore it will take approximately 7 weeks to build the 7 permanent U/G dams. This amounts to 49 days. Eljireth Mining Services are building the U/G dams; therefore the implementation will be very easy for Vlaklaagte, because minimum labour will be required from Vlaklaagte's side.	It takes Lectropower approximately 3 weeks to build one underground portable dam and to deliver it to the mine. Therefore it will take approximately 21 weeks to build and deliver 7 dams. This amounts to 147 days. Lectropower are building the dams, therefore the implementation will be very easy for Vlaklaagte, because minimum labour will be required from Vlaklaagte's side.
Maintenance	Low maintenance requirements	Higher maintenance requirements than solution 1. Maintenance of permanent U/G dams is moderate. Vlaklaagte makes use of recycled water U/G and therefore silt will accumulate in the dams. If the silt accumulation becomes too high the dams will have to be cleaned.	Lower maintenance requirements than solution 2a. Maintenance of the semi-mobile U/G dams is less intensive than permanent U/G dams because it has a valve attached to drain the silt if it accumulates.
Safety	High safety	If well maintained, high safety. If the dams are well built and maintained there should be no safety hazard.	If well maintained, high safety
Flexibility	Flexible. Most of the pipes can be re-used for other projects after the Vlaklaagte closes.	Poor flexibility. The U/G semi-mobile dams will be not re-usable after Vlaklaagte closes.	Flexible. The semi-mobile U/G dams can be re-used for other projects after Vlaklaagte closes.

Table XVI

Evaluation Solution 1

Criterion	Weighting factor	100	75	50	25	0	Total
Cost	40%	<R1mil	R1mil-R3mil	R3mil-R7mil	R7mil-R12.9mil	>R12.9mil	20
Time to completion and ease of implementation	20%	0-1 month to completion. Very easy to implement	2-3 months to completion. Easy to implement.	3-4 months to completion. Fairly easy to implement.	4-5 months to completion. Difficult to implement.	>5 months to completion. Very difficult to implement.	10
Maintenance	10%	No maintenance required	Low maintenance	A fair amount of maintenance required	High maintenance-intensive	High maintenance-intensive	7.5
Safety	25%	Completely safe	Very safe	Fairly safe	Low safety	Unsafe	18.8
Flexibility	5%	Completely flexible. Equipment can be moved around underground with ease and all equipment can be fully re-used after closure of Vlaklaagte	Flexible. Equipment can be moved around underground with relative ease and some of the equipment can be re-used after closure of Vlaklaagte	Relatively flexible. Equipment can be moved around underground but with difficulty and very little of the equipment can be re-used after closure of Vlaklaagte	Low flexibility. Equipment might be moveable underground but with extreme difficulty and very little or none of the equipment can be re-used after closure of Vlaklaagte	Inflexible. Equipment cannot be moved around underground and none of the equipment can be re-used after closure of Vlaklaagte	3.8
Total	100%						60

Summary of how solutions performed against the criteria

A summary of how the three solutions performed against the criteria is given in Table XV. This table forms the basis for rating the solutions.

After taking Table XV into consideration, the solutions were rated according to the evaluation rubric that was drawn up as indicated in Tables XVI–XVIII. According to the evaluation rubric, building permanent underground dams scored the highest with a value of 73.8.

Table XVII

Evaluation Solution 2a

Criterion	Weighting factor	100	75	50	25	0	Total
Cost	40%	<R1mil	R1mil-R3mil	R3mil-R7mil	R7mil-R12.9mil	>R12.9mil	40
Time to completion and ease of implementation	20%	0-1 month to completion. Very easy to implement	2-3 months to completion. Easy to implement.	3-4 months to completion. Fairly easy to implement.	4-5 months to completion. Difficult to implement.	>5 months to completion. Very difficult to implement.	15
Maintenance	10%	No maintenance required	Low maintenance	A fair amount of maintenance required	High maintenance-intensive	High maintenance-intensive	5
Safety	25%	Completely safe	Very safe	Fairly safe	Low safety	Unsafe	12.5
Flexibility	5%	Completely flexible. Equipment can be moved around underground with ease and all equipment can be fully re-used after closure of Vlaklaagte	Flexible. Equipment can be moved around underground with relative ease and some of the equipment can be re-used after closure of Vlaklaagte	Relatively flexible. Equipment can be moved around underground but with difficulty and very little of the equipment can be re-used after closure of Vlaklaagte	Low flexibility. Equipment might be moveable underground but with extreme difficulty and very little or none of the equipment can be re-used after closure of Vlaklaagte	Inflexible. Equipment cannot be moved around underground and none of the equipment can be re-used after closure of Vlaklaagte	1.3
Total	100%						73.8

Table XVIII

Evaluation Solution 2b

Criterion	Weighting factor	100	75	50	25	0	Total
Cost	40%	<R1mil	R1mil-R3mil	R3mil-R7mil	R7mil-R12.9mil	>R12.9mil	30
Time to completion and ease of implementation	20%	0-1 month to completion. Very easy to implement	2-3 months to completion. Easy to implement.	3-4 months to completion. Fairly easy to implement.	4-5 months to completion. Difficult to implement.	>5 months to completion. Very difficult to implement.	5
Maintenance	10%	No maintenance required	Low maintenance	A fair amount of maintenance required	High maintenance-intensive	High maintenance-intensive	7.5
Safety	25%	Completely safe	Very safe	Fairly safe	Low safety	Unsafe	12.5
Flexibility	5%	Completely flexible. Equipment can be moved around underground with ease and all equipment can be fully re-used after closure of Vlaklaagte	Flexible. Equipment can be moved around underground with relative ease and some of the equipment can be re-used after closure of Vlaklaagte	Relatively flexible. Equipment can be moved around underground but with difficulty and very little of the equipment can be re-used after closure of Vlaklaagte	Low flexibility. Equipment might be moveable underground but with extreme difficulty and very little or none of the equipment can be re-used after closure of Vlaklaagte	Inflexible. Equipment cannot be moved around underground and none of the equipment can be re-used after closure of Vlaklaagte	1.5
Total	100%						56.5

Conclusions

The water-related downtime problem at Vlaklaagte Shaft was quantified through a thorough investigation of the downtime logbook. The main causes of water-related downtime were identified as low water pressure, and low water flow caused by pipe leakages and bursts, the main root cause being the low pressure resistance of the thin-walled galvanized steel pipes used in the underground inbye water reticulation system, which cannot withstand the increased pressure now required by the CM. The ageing infrastructure and increased pump pressures are also contributory factors.

The current water reticulation system was reviewed and an underground pipe layout was drawn up for the shaft after on-site investigations. The water consumption of the current water reticulation system was determined from machine and sprayer specifications. The LOM plan was used to determine the maximum LOM water requirements, and the time frame in which the water consumption would be the highest was determined.

Three different solutions were considered to solve the water-related downtime problem and to ensure the efficient supply of water to the newly opened sections. Permanent underground concrete dams, semi-mobile dams, and new pipe columns with a higher pressure resistance of 3200 kPa were considered. The dam placement was determined by calculating the friction loss within each pipe section using Bernoulli's energy equation. The conclusion was that seven underground dams should be placed to ensure that the maximum pressure of the pipes (1600 kPa) is not exceeded.

The solutions were compared using an evaluation rubric. Building permanent underground dams was determined to be the cheapest solution (R438 397) and can be implemented in the shortest time (49 days). Cost and time to completion were critical for the solution to be a viable option. The payback period for the cost associated with building underground permanent dams was determined to be 0.035 years, and the solution will save the mine R12.9 million. Building permanent underground dams was therefore identified as the best solution for implementation.

Recommendations

It is recommended that seven permanent underground dams should be built at Vlaklaagte Shaft to solve the water-related downtime problem and ensure the efficient supply of water to the newly opened sections.

Suggestions for further work

- A sensitivity analysis should be done on the weighting factors of the different criteria used to trade off the three possible solutions. This will give an indication of how changes in the weighting of each criterion would affect the outcome of the trade-off study
- Studies can be done on a more effective recording system for water-related downtime and for recording changes made to the water reticulation system.

Acknowledgement

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