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Re-evaluation of gravity-fed backfill reticulation flushing using water and compressed-air-assisted system in deep underground mines: a case study

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Abstract

As underground mining operations extend to greater depths, cemented paste backfill (CPB) reticulation systems are increasingly subjected to operational conditions that diverge from their original design assumptions. One area significantly affected is the design of flushing systems, which are critical for maintaining flow reliability and preventing blockages. This paper presents a case study from the Gwalia gold mine in Western Australia where routine flushes failed to clear sections of the reticulation network below a certain mining level. This operation uses a gravity-fed CPB reticulation system with a nominal pipe diameter of 152mm and a plant flow rate of 140 m³/h. A detailed investigation combining field observations, hydraulic modelling, and air–water flow analysis revealed that the problem originated not from the air system performance, but from insufficient flushing water volume and flow velocity to sustain continuous flow through uphill sections. The study developed flow models using water as the base fluid to quantify minimum flushing volumes, pressure requirements, and air receiver capacities. Results indicated that approximately 21 m³ of water is required to initiate effective syphoning in the longest uphill section, while a 40 m³ air receiver, or 2 compressors, operating with a 14 m³ tank provide adequate air capacity for consistent flushing across the mine's life. Based on these findings, design modifications including increased water supply capacity, adjusted flushing sequences, and recalibrated pressure systems were recommended to improve flushing efficiency and reliability. The study highlights the need to periodically re-evaluate CPB reticulation flushing systems as mine geometry evolves, ensuring continued performance under deep mining conditions.

Keywords: *cemented paste backfill, design reticulation flushing, water and air flush*

1 Introduction

In the 1970s and 1980s, backfill material was often mixed using conventional concrete equipment and transferred pneumatically, as described by Patchet (1977). At that time, cemented hydraulic fill was the dominant backfilling method. The use of cemented paste backfill (CPB) as underground backfill began in 1979 at the Preussag's Bad Grund mine in Germany. However, CPB did not gain widespread adoption until the mid-1990s, when multiple plants were constructed in Canada, Africa, and Australia. The first United States CPB plant was installed at Lucky Friday mine in 1988. Notably, the first CPB stope was filled in 1989 at the Golden Giant Mine in Ontario, Canada. However, some sources suggest that Canada's first CPB plant was built in 1994 at Inco's Garson Mine (Stone 2014). In Australia, early developments included an initial attempt

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to build a CPB plant in 1984 (failed), following by Cannington commissioning a plant in 1997 and Mount Isa in 2001.

The CPB systems have since become essential components of modern underground mining operations (Safari et al. 2025). Unplanned downtime of a CPB system can cause substantial production losses as plants are typically required to deliver several thousand cubic metres of CPB underground each day. Modern underground CPB reticulation systems are designed to reliably deliver CPB through a network of vertical, interlevel boreholes, and horizontal piping to designated stopes. However, the installation, operation and breakdown management of these systems remain highly labour intensive, especially in CPB reticulation blockage scenarios. These events often necessitate manual identification and rectification of reticulation blockages or disconnections, compounding operational and maintenance costs. To mitigate these risks, several protection systems have been introduced, including inline dump valves, burst disks, and pressure relief spools. Morcombe (2019) reported that automated bypass valves can significantly improve response time and blockage recovery in deep underground mines.

As mines deepen and reticulation networks extend, the original design and operational philosophy of flushing systems may no longer suit current conditions, prompting the need for system re-evaluation. Flushing is critical to prevent CPB build-up and subsequent blockages, which can delay filling cycles and jeopardise production continuity. Proper flushing prevents build-up occurring in the system, which can lead to partial flow or complete blockages and delays during subsequent filling cycles. Effective flushing is required at the completion of routine operations, or during CPB delivery if a flow-loss event occurs due to blockage, stalling, or reticulation failure (pipe burst) (Griffiths 2019). System stalling where pressure falls below the level needed to drive CPB to the stope can lead to a full or partial retic blockage.

Most Australian CPB systems employ a combination of water and air flushing. When correctly designed, compressed air can significantly enhance the scouring effect of water flushing. After CPB-pouring shutdowns, multiple flushes are often required to clear lines, and confirm the correct route is open and clean. The use on start-up flushes might also include pre-wetting the pipework for smooth start-up. Common approaches include water flushing via the CPB hopper post-mixer or by pouring water directly into the mixer. More-advanced designs incorporate a dedicated water flush tank connected directly to the CPB borehole. The air flushing systems installed alongside the water systems include compressors and receivers sized according to reticulation volume and pressure requirements. The process typically involves introducing a sufficient volume of water to clear the line, followed by compressed air when the pressure inline is less than the air receiver pressure to accelerate flow and generate a two-phase (air–water) mixture. Using compressed air for scouring air flushing provides 2 key benefits when applied correctly. First, when sufficient water volume is used during the initial flush, most of the water is effectively pulled through the line. The subsequent introduction of compressed air at high velocities then helps entrain and remove residual water and CPB. Second, when an air flush (air burst) occurs immediately after a water flush, the air is expected to reach the water in the pipeline due to the air's increased velocity. This two-phase flow generates fluctuations in velocity and pressure, which enhances turbulence and aids in dislodging and transporting residual solids from the pipe wall. This turbulent two-phase flow creates alternating pressure and velocity fluctuations that dislodge and transport residual solids. However, insufficient water volume can result in stagnant zones or 'water locks', leading to surging, pulsation, and water hammer when air is introduced. These effects increase pipe wear, induce vibration, and compromise system reliability. To minimise these issues, flushing air velocities are typically designed between 10–15 m/s, consistent with wastewater standards (Water Corporation 2024).

Recent studies support air-assisted, or two-phase, flushing as a more efficient method of pipeline cleaning. Bai et al. (2024) observed that introducing compressed air can reduce water consumption by 30%. Yuan et al. (2022) and Wang et al. (2025) further demonstrated that two-phase flushing in large-diameter and long-distance pipelines offers superior scouring through slug flow and high shear forces. Their study showed that adjusting the air-to-water ratio can reduce flush mixture density by up to 75% and increase flow velocity by 35%, resulting in a 17.2% reduction in single-phase water volume costs. Tang et al. (2020) further highlighted the beneficial turbulence and shear forces induced by slug flow, especially in sections with elbows or directional changes. The characterisation of air–water two-phase fluid flow was also investigated by

Catrawedarma et al. (2021). Wang et al. (2025) demonstrated that maintaining a bubbly flow at an air-to-water ratio not exceeding 4:1 optimises pipe flushing efficiency, significantly reducing water consumption for a copper mine in Africa.

Despite these findings, field experience shows that flushing efficiency can deteriorate as mine geometry changes or as operations extend deeper. At the Gwalia gold mine studied in this paper, inconsistent flushing performance was observed below the 1800 level, prompting a detailed investigation. The observed issues included incomplete delivery of flushing water and air, and unreliable compressor operation.

This paper presents a technical review and redesign study of the CPB reticulation flushing system for this deep underground mine. The objectives were to diagnose the root cause of flushing failure, quantify hydraulic and pneumatic requirements through flow modelling, and propose an optimised flushing system configuration capable of sustaining performance throughout the mine's remaining life.

2 Basis of design

For a typical air-flush system design, the CPB reticulation is assumed to be open ended and discharging at atmospheric pressure. This assumption simplifies calculations by allowing the compressor's free air delivery to be used directly for estimating flow requirements. However, at the mine under study, the system exhibited non-standard behaviour. Field observations showed that water flushes were not reaching the end of the reticulation below the 1800 level, indicating significant hydraulic resistance or backpressure within the pipeline. A detailed hydraulic model was therefore developed using water as the working fluid to quantify the required air-flushing pressure and identify the minimum water volume needed to initiate syphoning. Syphoning occurs when the water level at the start of an uphill section exceeds the elevation of its crest, allowing flow to continue through to the downstream section. Insufficient water volume or velocity results in a trapped water lock, preventing the flush from fully traversing the line. Figures 1 to 3 illustrate this behaviour, showing the transition from full syphon formation to partial flow and complete bypass under compressed air. Figure 1 shows a schematic of where water pools. The minimum amount of water to cause syphoning is when the water level at the start is equal to or higher than the peak of the uphill section, and the water leaving is equal to or lower than the lowest point of the dip.

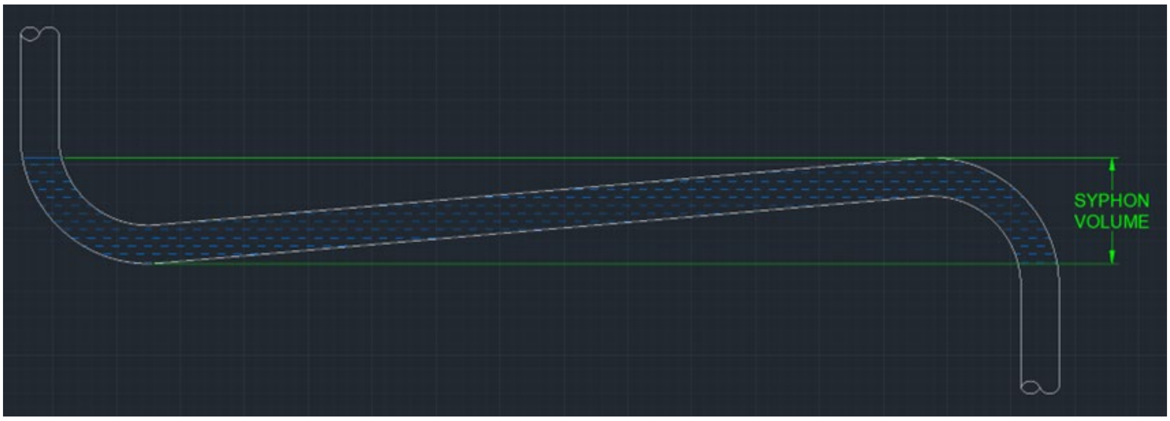

Figure 1 Minimum volume required to syphon

This water must be moving through the pipe rapidly to affect syphoning as well. When running slowly, it will trickle off and run away from the final crest without drawing the rest of the water with it, as per Figure 2.

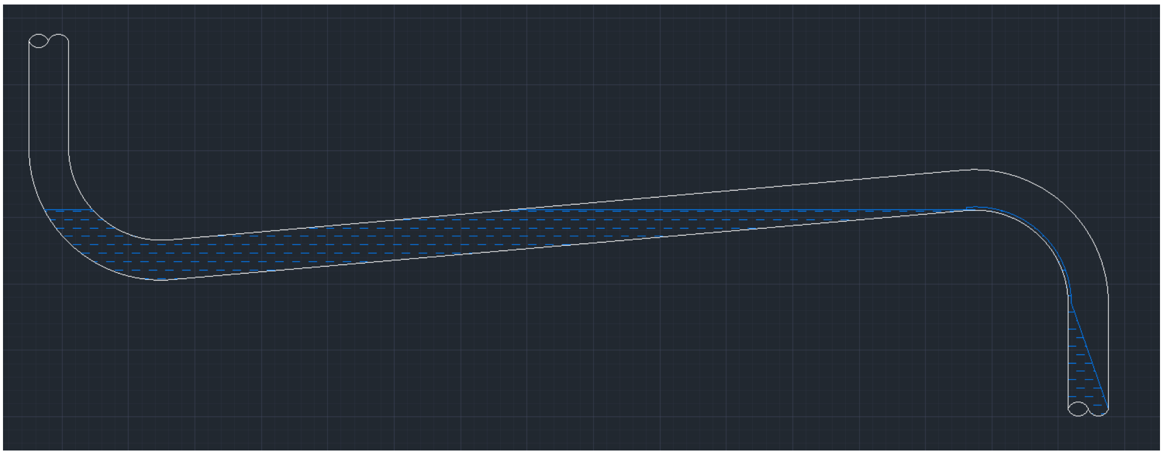

Figure 2 Insufficient water or velocity to syphon

This means that sufficient water must be fed to flush the system so that these water locks can be removed and allow for effective scouring by air. If these water locks are still present, then the compressed air will push the water to the side and find the easiest way through, as per Figure 3. This results in flushing water not exiting the system and a poor clean of the CPB line.

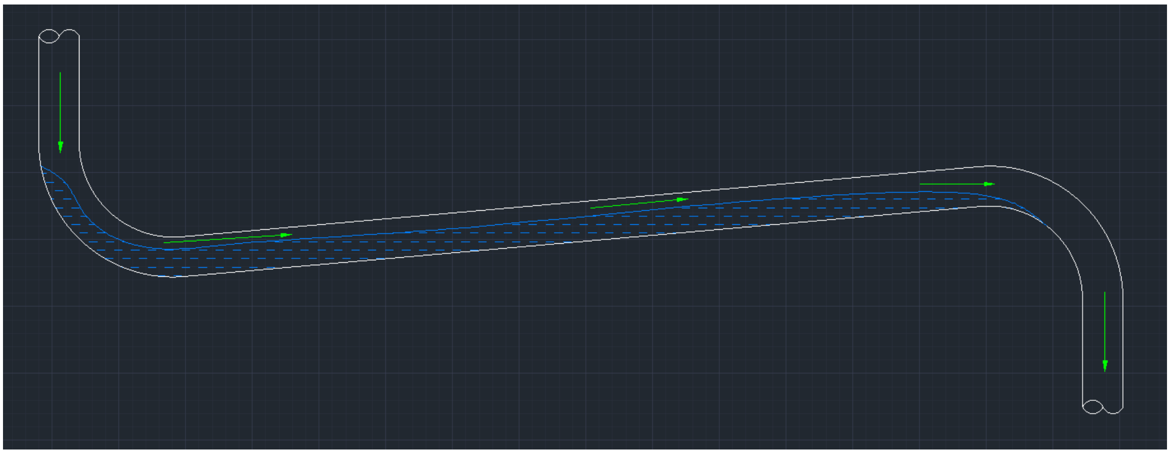

Figure 3 Compressed air bypassing water lock

To address this, the minimum water volume for each reticulation route was calculated based on pipe geometry and elevation changes. The flow model also assessed the influence of air pressure on displacing the water column through these sections. This modelling provided the foundation for sizing the air receiver and evaluating flushing efficiency under various configurations.

3 Design inputs

The following information was used as design inputs to the reticulation, as summarised in Table 1.

Table 1 Design inputs to reticulation design

Design input	Units	Value	Source
Mine plan		Deswik CAD file	Provided by the mine
CPB flow rate	m^3/h	140	Provided by the mine
CPB density	t/m^3	1.86–1.9	Provided by the mine
CPB friction loss range	kPa/m	4.5–5	Provided by the mine
Water friction loss	kPa/m	0.105–0.318	Assumption based on the pipe ID
CPB solid content	%	70–73	Provided by the mine
CPB reticulation size		DN150 Sch 80, DN200 S Sch 120, 152 mm SRCP*	Provided by the mine
Air-flush discharge time	min	1	Provided by the mine

* Steel wire reinforced composite pipe

4 Flow modelling

4.1 Overview

Four hydraulic models were developed for the existing reticulation network using water as the base fluid (Figure 4). The reticulation routing was developed with the following key considerations:

- Identifying 'worst-case' scenarios in terms of maximum required pressure, to assess the limitations of the current flushing system.
- Incorporating life-of-mine level plans to ensure long-term applicability and system compatibility.

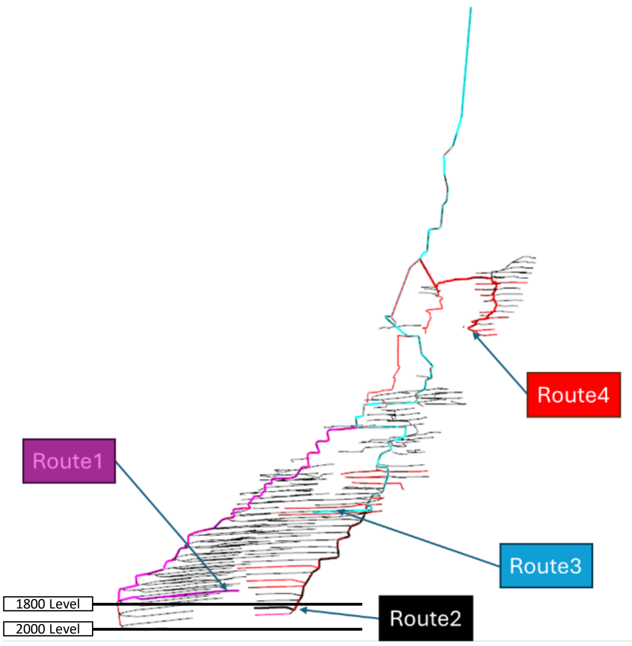

Figure 4 Overview of the reticulation routes for flow modelling

4.2 Analytical flow modelling

Analytical flow modelling was carried out using the following process:

1. Exporting the reticulation path for the stope in X, Y, Z coordinates.
2. Inputting the nominal reticulation piping specifications into the model tables, including internal diameter, pressure rating, and material types (e.g. borehole casing, steel backbone, and high-density polyethylene).
3. Entering the target flushing rate.
4. Applying water friction loss parameters.

These scenarios are illustrated in Figures 5 to 8, which present the detailed flow-modelling results. These dual-axis line graphs illustrate the relationship between operating pressure (kPa), hydraulic grade line (HGL), mine relative level (m) across a pipeline's total reticulation length, and expected freefall points.

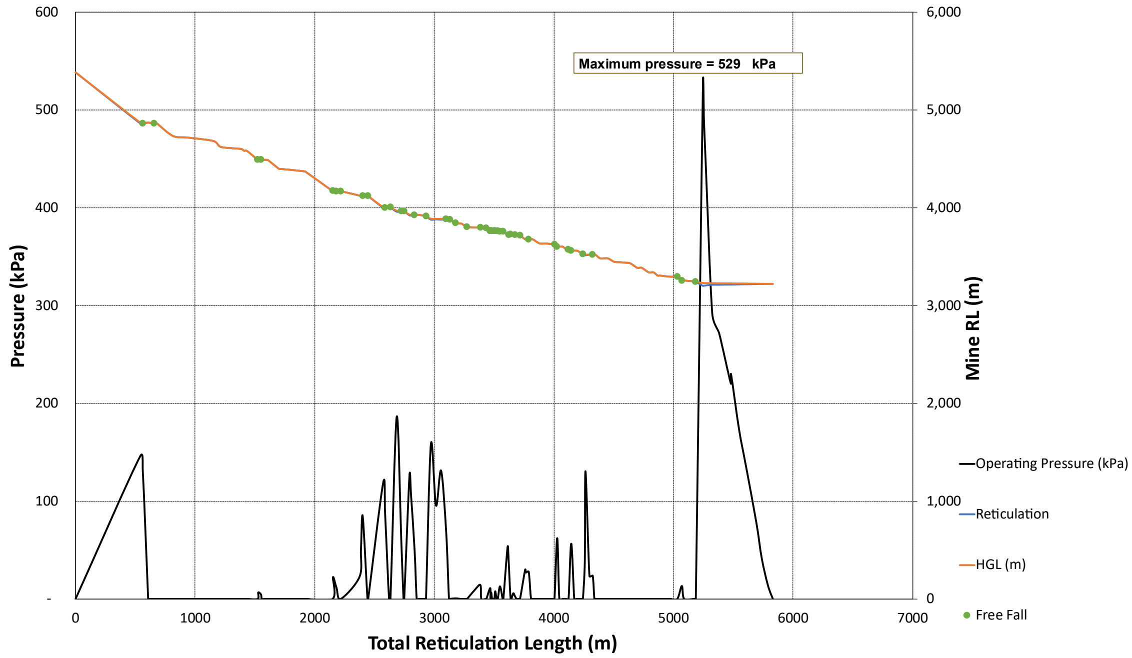

Figure 5 Reticulation route 1 flow modelling with water. HGP = hydraulic grade line, RL = relative level

Figure 5 presents the hydraulic profile for route 1, a total reticulation length of approximately 5,800 m. The orange HGL line descends from an elevation of 540 m down to roughly 320 m, with the majority of the pipeline categorised as being in 'freefall' (indicated by green dots). The black operating pressure line remains predominantly at zero for the first 2,000 m (except the first section after the surface borehole) before entering a highly volatile section characterised by frequent, sharp pressure spikes. These fluctuations culminate in a significant pressure surge at approximately 5,200 m, reaching a maximum pressure of 529 kPa, which corresponds to the final horizontal section of the reticulation.

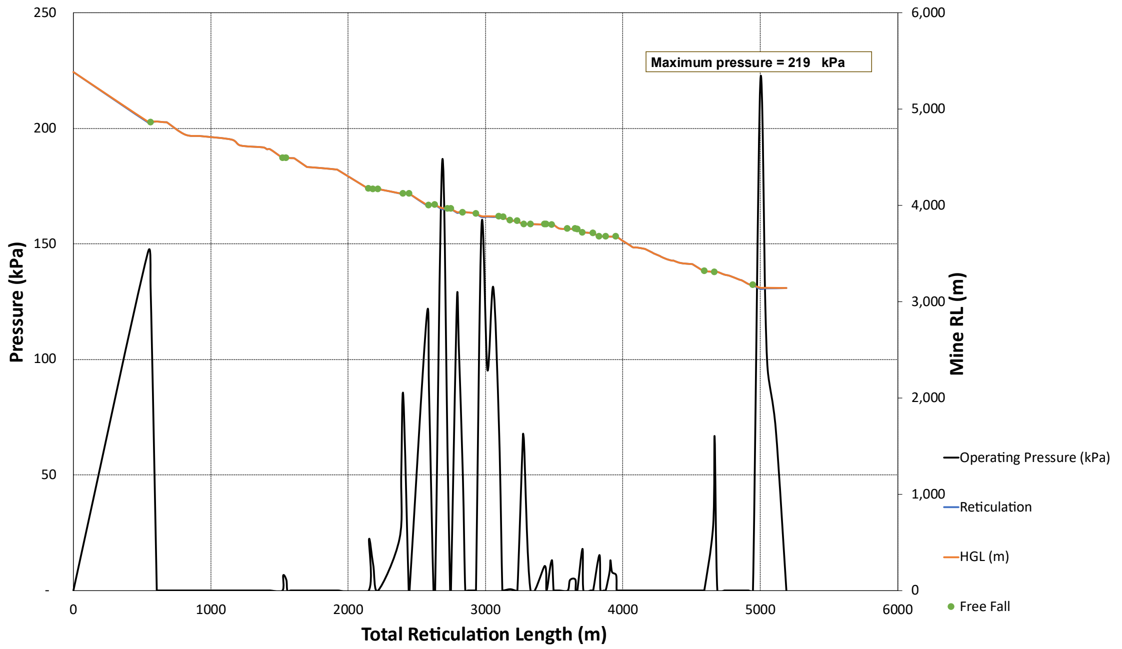

Figure 6 Reticulation route 2 flow modelling with water. HGP = hydraulic grade line, RL = relative level

Figure 6 shows the modelled route 2. The operating pressure remains low along most of the route, reflecting freefall conditions, but exhibits sharp spikes at specific points, particularly before long horizontal sections, where the flow transitions from vertical to horizontal. The maximum pressure of 219 kPa occurs near the 5,000 m mark.

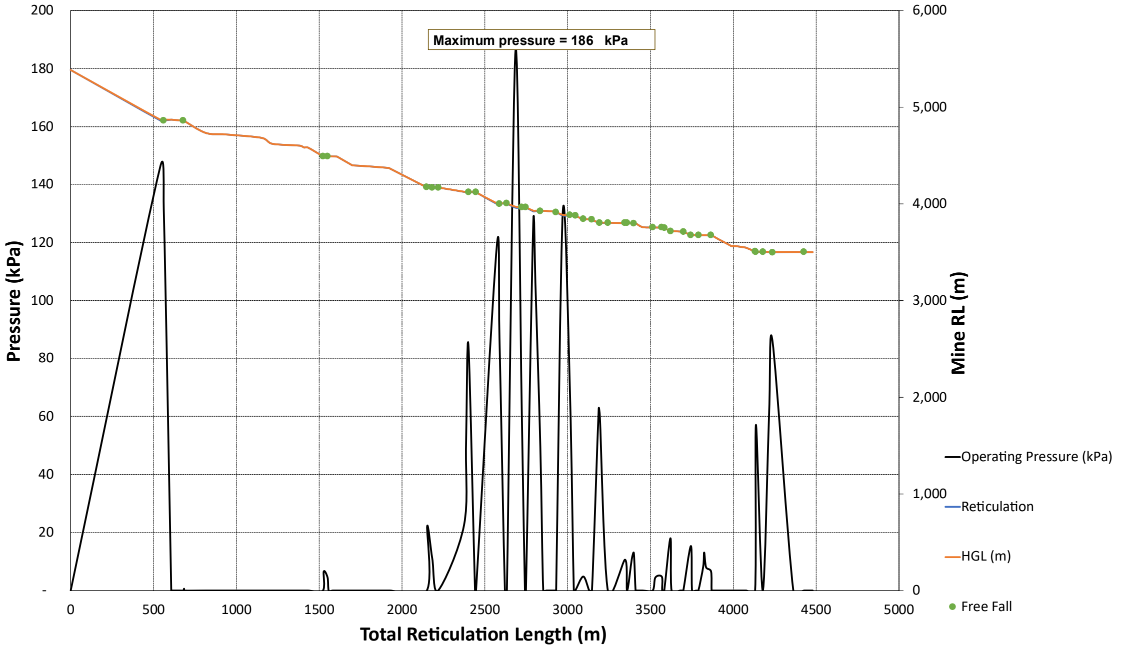

Figure 7 Reticulation route 3 flow modelling with water

Figure 7 shows the modelled route 3 similar to the previous models, where the operating pressure remains near zero along much of the route, indicating freefall conditions, but exhibits several sharp spikes where the flow transitions from vertical to horizontal sections. The maximum pressure of 186 kPa occurs around the 2,500 m mark.

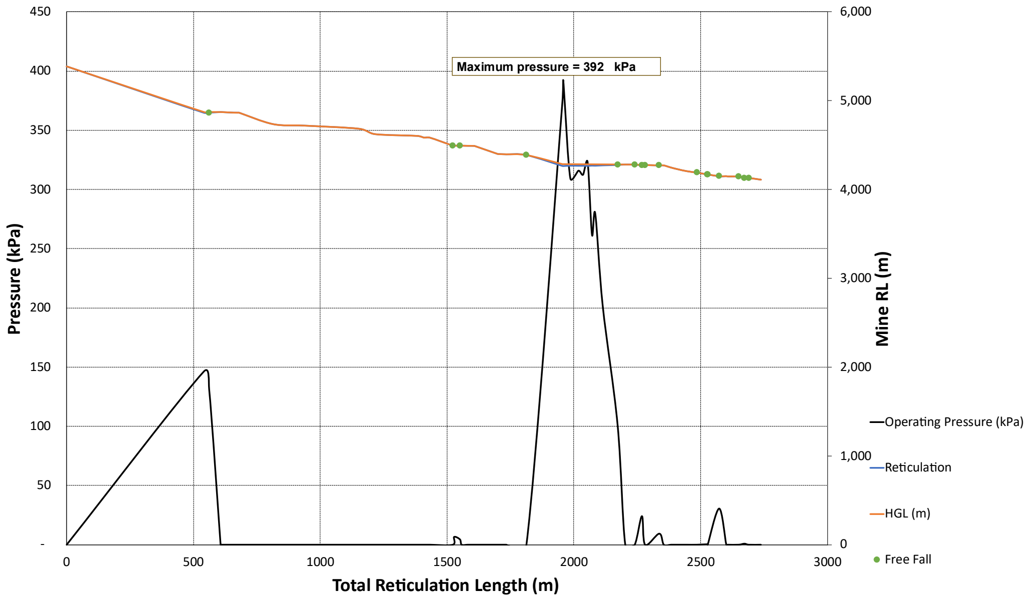

Figure 8 Reticulation route 4 flow modelling with water

The operating pressure for route 4 in Figure 8 shows two significant peaks: a minor one near the 500 m mark where the bottom of the surface borehole is, and a primary surge that reaches a maximum pressure of 392 kPa at approximately 1,950 m. Between these peaks and toward the end of the line, the operating pressure drops to or near zero, suggesting regions of low pressure or freefall within the reticulation system.

It should be noted that for the hydraulic modelling, it was assumed that the flushing rate is the same as the paste flow rate. The resulting pressure profiles and HGL outputs therefore represent pressurised flow conditions along an open-ended reticulation system.

Preliminary hydraulic flow modelling results revealed significant variation in pressure requirements between the different reticulation routes. These results confirm that effective flushing performance must be designed around the highest-pressure route to ensure adequate air and water delivery throughout the entire network. A summary of the flow modelling results is shown in Table 2.

Table 2 Flow modelling summary

Stope	Friction loss (kPa/m)	Max operating pressure (kPa)
R1	0.105–0.318	529
R2	0.105–0.318	219
R3	0.105–0.318	186
R4	0.105–0.318	392

Based on the modelling results and the maximum expected pressure of approximately 529 kPa (~5 bar assumption for this study), this value was used in the air compressor design to ensure that the supplied air pressure would exceed the required water pressure (for pushing water), thereby enabling effective flushing through the reticulation system.

4.3 Required water

The uphill sections of each route were analysed to identify the maximum syphon volume required for complete water displacement. Table 3 summarises these results.

Table 3 Uphill section volumes

	Longest (m)	Volume (m^3)	2^{nd} longest (m)	Volume (m^3)
Route 1	147	7.2	114	5.6
Route 2	147	7.2	114	5.6
Route 3	147	7.2	114	5.6
Route 4	427	20.9	147	7.2

Route 4 contained the most demanding section, requiring approximately 21 m^3 of water to achieve full syphoning, while the remaining routes required between 5 and 7 m^3. This section is highlighted in Figure 9.

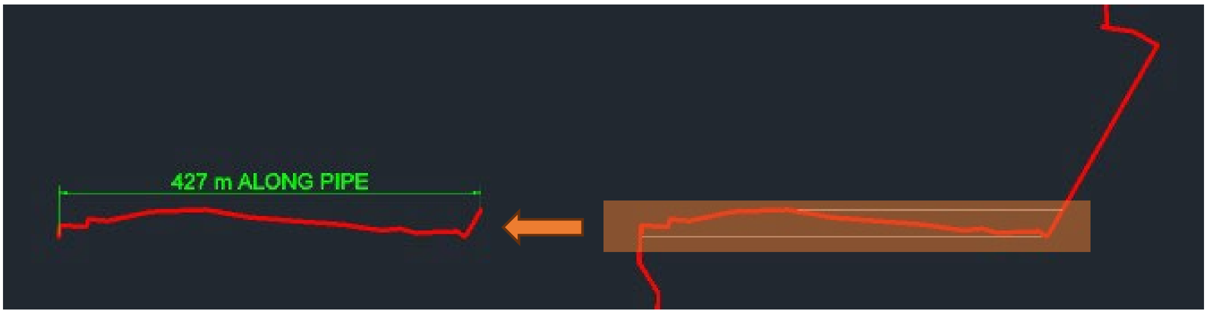

Figure 9 Route 4 longest uphill section

Field observations indicated that current operations used approximately 3 m^3 of water per flush, repeated 3 times. This intermittent approach was insufficient to generate the continuous flow and velocity necessary for effective scouring, allowing stagnant water to accumulate in low points and preventing complete discharge. To overcome this limitation, a continuous water-feed system was recommended. The proposed design includes a 50 m^3 water tank, high-flow low-head pump, and flow meter to deliver controlled water volume to the CPB hopper. The hopper's level sensor can be used for automatic pump speed control, preventing dry running and ensuring consistent flushing.

4.4 Required air

The total reticulation volume was estimated at 131 m^3, based on updated field measurements of installed piping and borehole diameters. This volume was used to determine the required air receiver capacity using Boyle's law, with an initial pressure of 10 bar absolute and a target of 3 bar absolute. Four operational configurations were modelled:

- one compressor + 14 m^3 receiver tank
- two compressors + 14 m^3 receiver tank
- one compressor + 40 m^3 receiver tank
- two compressors + 40 m^3 receiver tank.

Flushing durations were then calculated for both standard shutdown/start-up and deep-level (below 1800L) operations.

4.5 Air supply scenarios

Based on the data provided by the mine site, a discharge time from 964 kPa down to 518 kPa in 11 seconds, and a total pressure drop from 964 to 347 kPa over 51 seconds, were used in the calculations. To calculate the required air receiver size, the contribution of the air compressor during discharge has been ignored. Using Boyle's law:

$$P_1 \times V_1 = P_2 \times V_2 \tag{1}$$

where:

P_1 = the initial pressure in the receiver (in absolute pressure)

V_1 = the volume of the receiver

P_2 = the target pressure in the reticulation system (assumed to be 3 times atmospheric pressure for flushing)

V_2 = the total volume of the reticulation system and the receiver.

given:

P_1 = 10 bar absolute

P_2 = 3 bar absolute

V_2 = 131 m³ (retic volume).

Using Boyle's law:

$$10 \times V_1 = 3 \times 131 \tag{2}$$

$$V_1 = \frac{3\times131}{10} \approx 39.3\ m^3 \tag{3}$$

Therefore, a total receiver volume of approximately 40 m³ is required.

The following 4 scenarios were considered based on the current 14 m³ air receiver capacity, estimated flush and refill times, and the potential addition of a second compressor.

Note: for simplicity, the air discharge rate was assumed to be constant, and the flushing time was taken as one minute per cycle.

4.5.1 Scenario 1: one compressor + 14 m³ tank

A. Normal flush (shutdown and start-up)

- Air receiver contribution:

$$\frac{40}{14} = 3\ times \tag{4}$$

- Time to fill 14 m³ tank from 3 bar to 10 bar:

$$\frac{14 \times (10-3)}{10} \approx 10\ min \tag{5}$$

- Total flush cycle:

$$(Flush\ time + refill\ time) \times 3 = (1 + 10) \times 3 = 33\ min \tag{6}$$

B. Air flush to the levels below 1800L

- Total air needed to pressurise the reticulation system:
  - To raise 131 m³ from one to 5 bar

$$10 \times V_1 = 5 \times 131 \tag{7}$$

$$V_1 = \frac{5 \times 131}{10} \approx 66 \ \ m^3 \quad (8)$$

- Air receiver contribution:

$$\frac{66}{14} = 5 \ times \quad (9)$$

- Time to fill 14 m³ tank from 5 to 10 bar:

$$\frac{14 \times (10-5)}{10} \approx 7 \ min \quad (10)$$

- Total flush cycle:

$$(Flush \ time + refill \ time) \times 5 = (1 + 7) \times 5 = 40 \ min \quad (11)$$

4.5.2 *Scenario 2: 2 compressors + 14 m³ tank*

A. Normal flush (shutdown and start-up)

- Air receiver contribution:

$$\frac{40}{14} = 3 \ times \quad (12)$$

- Time to fill 14 m³ tank from 3 to 10 bar:

$$\frac{10}{2} = 5 \ min \quad (13)$$

- Total flush cycle:

$$(Flush \ time + refill \ time) \times 3 = (1 + 5) \times 3 = 18 \ min \quad (14)$$

B. Air flush to the levels below 1800L

- Total air needed to pressurise the reticulation system:
  - To raise 131 m³ from 1 to 5 bar:

$$10 \times V_1 = 5 \times 131 \quad (15)$$

$$V_1 = \frac{5 \times 131}{10} \approx 66 \ \ m^3 \quad (16)$$

- Air receiver contribution:

$$\frac{66}{14} = 5 \ times \quad (17)$$

- Time to fill 14 m³ tank from 5 to 10 bar

$$\frac{7}{2} = 3.5 \ min \quad (18)$$

- Total flush cycle:

$$(Flush \ time + refill \ time) \times 5 = (1 + 3.5) \times 5 = 22.5 \ min \quad (19)$$

4.5.3 *Scenario 3: one compressor + 40 m³ tank*

A. Normal flush (shutdown and start-up)

- Air receiver contribution:

$$\frac{40}{40} = 1 \ time \quad (20)$$

- Time to fill 40 m³ tank from 3 to 10 bar:

$$\frac{40 \times (10-3)}{10} \approx 28 \ min \quad (21)$$

- Total flush cycle:

$$(Flush\ time + refill\ time) \times 1 = (1 + 28) \times 1 = 29\ min \tag{22}$$

B. Air flush to the levels below 1800L

- Total air needed to pressurise the reticulation system:
  - To raise 131 m³ from 1 to 5 bar

$$10 \times V_1 = 5 \times 131 \tag{23}$$

$$V_1 = \frac{5 \times 131}{10} \approx 66\ m^3 \tag{24}$$

- Air receiver contribution:

$$\frac{66}{40} \approx 2\ times \tag{25}$$

- Time to fill 40 m³ tank from 5 to 10 bar

$$\frac{40 \times (10-5)}{10} \approx 20\ min \tag{26}$$

- Total flush cycle:

$$(Flush\ time + refill\ time) \times 2 = (1 + 20) \times 2 = 42\ min \tag{27}$$

4.5.4 Scenario 4: 2 compressors + 40 m³ tank

A. Normal flush (shutdown and start-up)

- Air receiver contribution:

$$\frac{40}{40} = 1\ time \tag{28}$$

- Time to fill 40 m³ tank from 3 to 10 bar:

$$(\frac{40 \times (10-3)}{10})/2 \approx 14\ min \tag{29}$$

- Total flush cycle:

$$(Flush\ time + refill\ time) \times 1 = (1 + 15) \times 1 = 15\ min \tag{30}$$

B. Air flush to the levels below 1800L

- Total air needed to pressurise the reticulation system:
  - To raise 131 m³ from 1 to 5 bar:

$$10 \times V_1 = 5 \times 131 \tag{31}$$

$$V_1 = \frac{5 \times 131}{10} \approx 66\ m^3 \tag{32}$$

- Air receiver contribution:

$$\frac{66}{40} \approx 2\ times \tag{33}$$

- Time to fill 40 m³ tank from 5 to 10 bar:

$$(\frac{40 \times (10-5)}{10})/2 \approx 10\ min \tag{34}$$

- Total flush cycle:

$$(Flush\ time + refill\ time) \times 2 = (1 + 10) \times 2 = 22\ min \tag{35}$$

The summary in Table 4 shows that using 2 compressors with the existing 14 m³ receiver provides optimal efficiency, achieving a complete flush cycle in approximately 18 minutes, compared to 29–30 minutes with a single compressor setup.

Table 4 Air-flush scenarios summary

Configuration	Flush time (min)	Flush time below 1800L (min)
1 compressor + 14 m³ tank	33	40
2 compressor + 14 m³ tank	18	22.5
1 compressor + 40 m³ tank	29	42
2 compressor + 40 m³ tank	15	22

Note: times include total system fill and preparation as interpreted from client input

The results presented are based on idealised operating conditions for the longest currently configured pipeline route. Flushing performance in the field is expected to be highly variable and influenced by factors such as discharge location, pipeline layout, and the operational state of the system. Under non-routine or upset conditions, blockages may not be removed with a single flush, and repeated flushing events may be necessary to restore full flow.

5 Recommendations

The investigation confirmed that the observed flushing inefficiency was primarily due to inadequate water volume rather than a failure of the air flushing system. To improve system performance and reliability, the following actions are recommended:

1. Install a continuous water-flushing system comprising a 50 m³ tank, flow meter, and pump to provide sufficient and consistent water volume. This configuration will ensure effective syphoning through uphill sections and eliminate stagnant water pockets.
2. Operate dual compressors with the existing 14 m³ receiver tank. This setup delivers sufficient air volume and pressure to maintain an average flushing duration of 18 minutes across all routes and throughout the mine's life of operation. Please note that this calculation does not account for any potential air leakage in the system.
3. Verify and calibrate pressure instrumentation to correct discrepancies between air receiver pressure gauges and Citect control system readings.
4. Review and modify the flushing sequence from the current alternating air–water cycles (3 × water + 3 × air) to 3 consecutive water flushes followed by 3 consecutive air flushes. This sequence will improve flow continuity and reduce overall flushing time. Any changes must follow site risk assessment and management of change processes.
5. Plan for future system optimisation. Pressure levels below 5 bar may not be sufficient to flush deeper levels (e.g. below 2000L). A staged upgrade to increase air capacity or receiver volume should be considered as mining progresses.

6 Conclusion

This study demonstrated that the combination of improving the flushing water quantity to allow for syphoning through the uphill sections and improving the air scouring supply and sustainable pressure represents the most reliable way to reduce or eliminate flushing issues. The proposed upgrades are expected to reduce flushing time by approximately 45%, improve system cleaning efficiency, and ensure robust operation as mining advances to greater depths.

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