Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_109

# Water management in interconnected underground mine voids during mine closure: lessons from the Witwatersrand Basin, South Africa

**Godfrey Madzivire [a,*], Selaelo Ramugondo [a], Ethel Munyadziwa Sinthumule [b], Rudzani Ramatsekisa [b], Viswanath Ravi Kumar Vadapalli [b, c]**

[a] *Minerals, Energy, Environment and Groundwater Unit, Council for Geoscience, South Africa*

[b] *Directorate of Mine Environmental Research and Sustainable Development, Department of Mineral and Petroleum Resources, South Africa*

[c] *Department of Geology, University of the Free State, South Africa*

## Abstract

*Underground mining in the Witwatersrand Basin, South Africa, resulted in the formation of extensive, interconnected mine voids. Following mine closure and the cessation of dewatering, these voids were filled with acidic mine water enriched in sulphates and potentially toxic elements, posing substantial risks to water resources. In response, a coordinated mine water management strategy was implemented. This involved 2 key interventions: (i) ingress control measures to reduce the inflow of surface water into abandoned mine workings, and (ii) active pumping and treating of mine water to maintain levels below defined environmental critical levels. These measures have been applied in the Western, Central and Eastern interconnected mining Basins. This paper presents lessons learnt from more than 2 decades of managing rising mine water within the Witwatersrand Basin.*

*Implementation of ingress control and managed pumping has been found to regulate the water entering the mine voids. This prevents flash flooding of the mine voids that produces highly polluted mine water. Analysis of water quality in the mine voids indicates that it gradually improves. This requires continued monitoring to adapt the water management plan according to the dynamic water quality. The experiences from the Witwatersrand Basin provide valuable science-based insights for sustainable mine water management strategies, such as nature-based technologies.*

**Keywords:** interconnected mine voids, sustainable mine water, ingress control, environmental critical level

## 1 Introduction

The closure of underground mines presents one of the most enduring environmental challenges. Deep underground mining forms extensive interconnected underground workings. Mine closure results in an abandoned interconnected mine void system. If not managed properly, these systems can fill with mine water, posing a threat to surface water and groundwater quality. The Witwatersrand Basin in South Africa represents the most prominent example of such a challenge (Matsumoto et al. 2016). It is a large, arcuate sedimentary basin hosting world-class gold deposits and associated uranium mineralisation. Mining has historically targeted auriferous conglomerates (reefs) at depths of up to several thousand metres underground, resulting in extensive, interconnected underground mine workings through shafts, haulages, crosscuts, ventilation workings and geological discontinuities.

* Corresponding author. Email address: gmadzivire@geoscience.org.za

Hydrologically, the Witwatersrand Basin comprises shallow, fractured and weathered aquifers overlying relatively low-permeability bedrock. The mine voids form a secondary drainage and storage network at depth. During the peak of gold mining in the goldfield, active dewatering of mine voids was undertaken to facilitate easy access to the mineral resources at depth. Following mine closure, the gradual refilling of mine voids occurred, posing a risk to surface water and groundwater. Based on hydrogeological and mining considerations, the Witwatersrand Basin is subdivided into 3 interconnected basins: the Western, Central and Eastern Basins (Figure 1). Each basin exhibits distinct geometries, connectivity, ingress characteristics and discharge pathways (Coetzee et al. 2011; Sheridan et al. 2015)

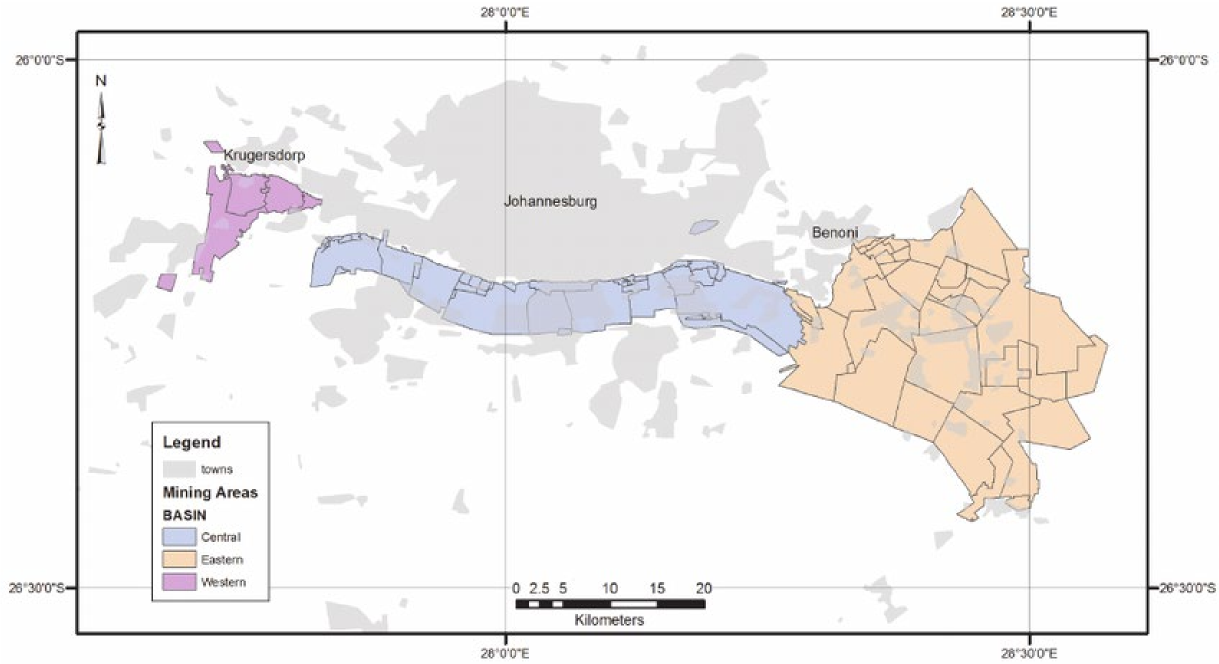



**Figure 1 The locality of the 3 basins of the Witwatersrand Basin**

After more than a century of intensive underground gold mining, widespread mine closures occurred around the late 1990s and early 2000s (Matsumoto et al. 2016). This resulted in the cessation of dewatering across the basin, and the mine water accumulated in interconnected voids. Acidic and highly polluted water was discharged to the surface in the Western Basin in 2002. This prompted the establishment of the Interministerial Committee (IMC) on acid mine drainage (AMD) in 2010 to develop a framework for managing mine water in the Witwatersrand Basin. The IMC appointed a team of experts (ToE) to develop an evidence-based approach to managing water. The ToE developed a mine water approach with 2 main recommendations (Coetzee et al. 2011):

1. pumping and treating mine water from the 3 basins to maintain water levels at least below the environmental critical levels (ECLs)
2. implementation of ingress control measures to prevent surface water from entering mine voids. This reduces the volume of water which needs to be pumped and treated, thereby reducing the operational costs of mine water management.

This paper consolidates lessons learnt over more than 2 decades of managing interconnected underground mine voids in the Witwatersrand Basin. It adopts a technical and policy perspective by looking at the regulatory framework and hydrogeological dynamics post closure of the mine in the basin. The objective is to identify and document lessons that can inform mine closure planning and post-closure water management in interconnected mine voids.

# 2 Methodology

Based on the ToE recommendation in 2011, the mine water management strategy was implemented in the Witwatersrand Basin through a coordinated approach between government departments and research institutions. The Department of Water and Sanitation and the Trans-Caledon Tunnel Authority implemented pumping and treatment of mine void water to prevent it from rising above the ECLs. The Department of Mineral and Petroleum Resources (DMPR) and Council for Geoscience identified ingress areas and implemented ingress control measures to prevent surface water from entering the mine voids. This research focused on data collected between 2012 and 2025 from the 3 treatment plants constructed to pump and treat water to prevent water levels from rising above the ECLs. In addition, a review was undertaken to understand how the legacy of mine water in the Witwatersrand Basin could have been prevented through policy and legislation.

According to the recommendations from the ToE to the IMC, the primary focus of the mine water management was the ECLs. These levels represent threshold water levels below which mine water must be maintained to prevent adverse environmental impacts. ECLs were determined based on mine void geometry and geology, surface topography, hydraulic connectivity, and risk to water resources and underground infrastructure. The ECLs that the ToE recommended for the 3 basins are shown in Table 1 (Coetzee et al. 2011).

**Table 1 The recommended environmental critical levels in metres above mean sea level (m.a.m.s.l.) by the team of experts in 2011**

| Basin | Environmental critical levels (m.a.m.s.l.) |
|---|---|
| Western | 1,530 |
| Central | 1,503 |
| Eastern | 1,150 |

## 2.1 Pumped and treated

To manage the water below the set ECLs in Table 1, high-density sludge (HDS) mine water treatment plants were constructed or refurbished at sites where the last operating mines had pumped and treated water before ceasing operations. Treated water is discharged to surface water resources. The recommended plant capacity of the HDS mine water treatment plant and the years the plants were commissioned are shown in Table 2.

**Table 2 Pumping rates recommended in 2011 by the team of experts (ToE) and years of commissioning**

| Basin | ToE recommended pumping rate (ML/d) | Commissioned |
|---|---|---|
| Western | 40 | 2012 |
| Central | 60 | 2014 |
| Eastern | 108 | 2016 |

## 2.2 Ingress control

The main source of water entering the mine void is rainfall. This was supported by observed high ingress volumes during the rainy season. Field investigations have identified water flowing from poorly maintained sewage treatment plants into ingress areas. There are 2 main pathways through which rainfall ends up in the mine void, as shown in Figure 2:

1. direct inflow of surface water into the mine void

2. rainfall infiltrates through soil and fractured rock and becomes groundwater. Shallow aquifers, perched aquifers and weathered zones above the mines transmit water downward through geological structures. Large karstic dolomite aquifers above mine voids can store groundwater and leak into abandoned mine workings.

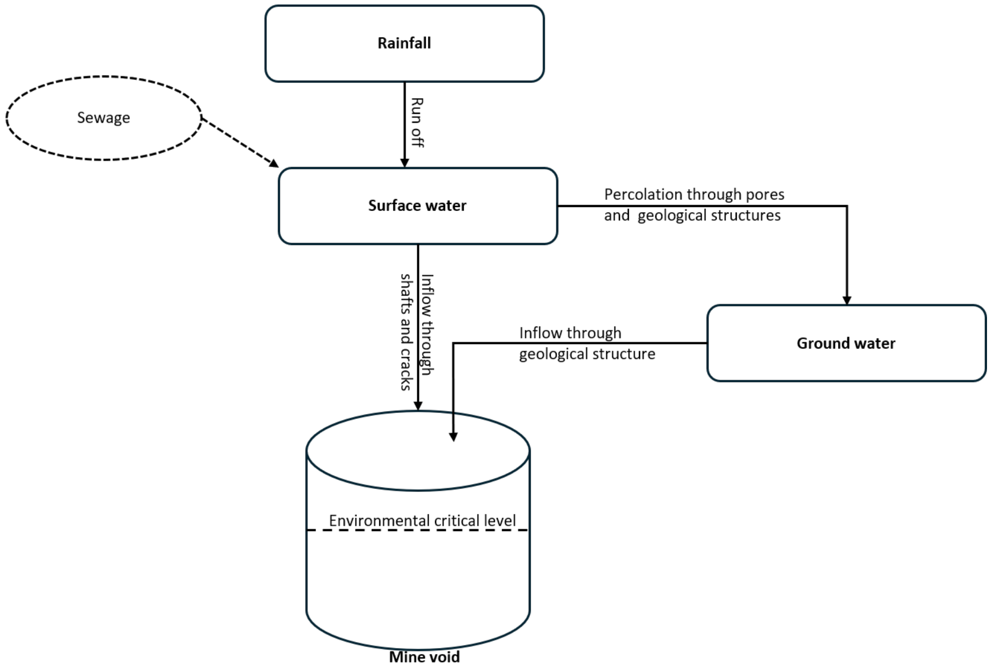



**Figure 2 Conceptual model for water ingress into the mine void**

Field investigations were conducted to understand the points and areas of water ingress into the mine voids, as shown in Figure 3 (Ramugondo et al. 2026). After implementation, the measure was monitored to assess its effectiveness.

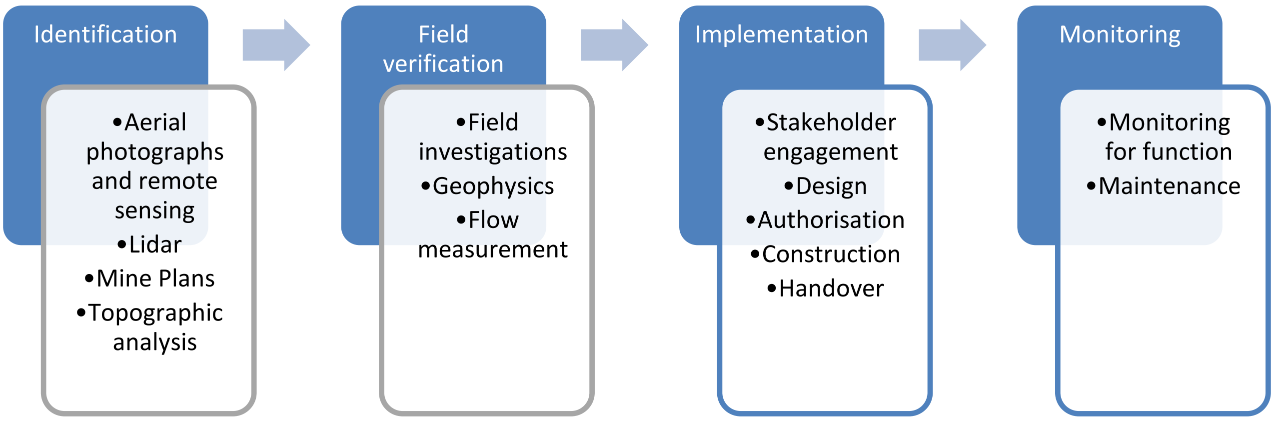



**Figure 3 Ingress control implementation**

Ingress control measures were implemented in the Central and Eastern Basins (Ramugondo et al. 2026). The major challenge encountered was vandalism by illegal miners. Currently, the only functional ingress control measures are in the Eastern Basin. The ingress control measure that was implemented in the Central Basin was vandalised.

## 2.3 Data gathering through continuous monitoring and research

For the past 20 years various research and continuous monitoring have been undertaken (Madzivire et al. 2023, 2026). Monitoring was essential to evaluate the effectiveness of the recommended interventions. Monitoring included measurements of pumping volumes, mine water levels relative to ECLs, and water quality parameters including pH, sulphate concentrations and dissolved metals. Based on the monitoring data, estimated ingress volumes were calculated by conceptualising the mine void as a simple open space with no variation in surface area, with elevation that fills with water from the surface (water ingress) and is drained by pumping, as shown in Figure 4.

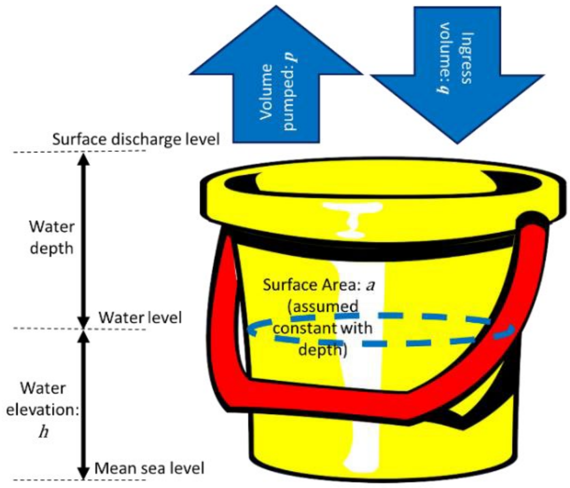



**Figure 4 Conceptual model to estimate ingress volumes into the mine void**

This allows the following parameters to be calculated as follows:

- For each measurement, $i$, the water level ($h_i$) is calculated by subtracting the reported water depth from the collar elevation of the measurement shaft.
- The daily change in water level (Δh) for day $i$ is then calculated by subtracting the water elevation of the previous day from the $i$-th measurement.

$$\Delta h_i = h_i - h_{i-1} \quad (1)$$

This is related to net ingress volume ($q_i$ -$p_i$) by the relationship:

$$\Delta h_i = \frac{q_i - p_i}{a} \quad (2)$$

Estimated ingress was calculated by identifying 2 days on which $\Delta h_i = 0$. That is, $t_1$ and $t_2$ with the same water elevation. This implies that:

$$q_{t_1,t_2} = \frac{1}{t_2 - t_1 + 1} \sum_{i=t_1}^{t_2} p_i \quad (3)$$

# 3 Results and discussion

Based on data collected since 2000, several lessons were learnt from observations, data collection and projects implemented to reduce ingress into the mine voids and to pump and treat mine water to maintain water below the ECLs. The lessons learnt can be placed into one of four categories:

1. Application of the regulation to avoid government responsibility.
2. Prevention of pollution is cheaper than treatment of the pollution.
3. Mine water evolves during flooding of the mine voids.
4. Regional integration is essential to manage mine water for interconnected mines.

## 3.1 Regulatory framework for mine water management

Before 1991 there was no regulation that enforced mining companies to use responsible mining methods. Early legislation focused on surface rehabilitation. The primary emphasis of mining was on its economic gains (Swart 2003; Damar-Fakir et al. 2017). Therefore, mining companies complied with the minimum requirements and adopted a reactive approach, leaving the South African government with an enormous social and environmental legacy. Environmental problems in the Witwatersrand Basin became pronounced in the late 1900s as the number of mines decreased substantially. This has resulted in the enactment of several regulations, policies and guidelines between 1996 and 2009, as shown in Table 3, focusing on the 3 facets of mine water management: prediction, prevention and remediation (PPR).

**Table 3 The regulatory framework developed in response to environmental challenges caused by mine closure, based on prediction, prevention and remediation (Matsumoto et al. 2016)**

| Year | Regulatory framework | Prediction | Prevention | Remediation |
|---|---|---|---|---|
| 1997 | *Water Service Act* | | X | |
| 1998 | Constitutional Right: Section 27(1)(b)<br>*The National Water Act* No. 36 of 1998 | | X | X |
| 1998 | *National Environmental Management Act* 107 | X | X | X |
| 2002 | *Mineral and Petroleum Resources Development Act* 28 of 2002 | X | X | X |
| 2006 | Mine and Environmental Management Guidelines | X | X | X |
| 2008 | *National Environmental Management: Waste Act* | X | X | X |
| 2008 | Regional Mine Closure Strategies | X | X | |

The detailed legislative framework could not be applied retrospectively to hold mines that profited from mineral resources accountable. This means the environmental liability rested on the South African government. The interconnectedness of the mine voids in the Witwatersrand Basin required strong coordination between institutions to address the environmental legacy.

## 3.2 Prevention of pollution is cheaper than the treatment of pollution

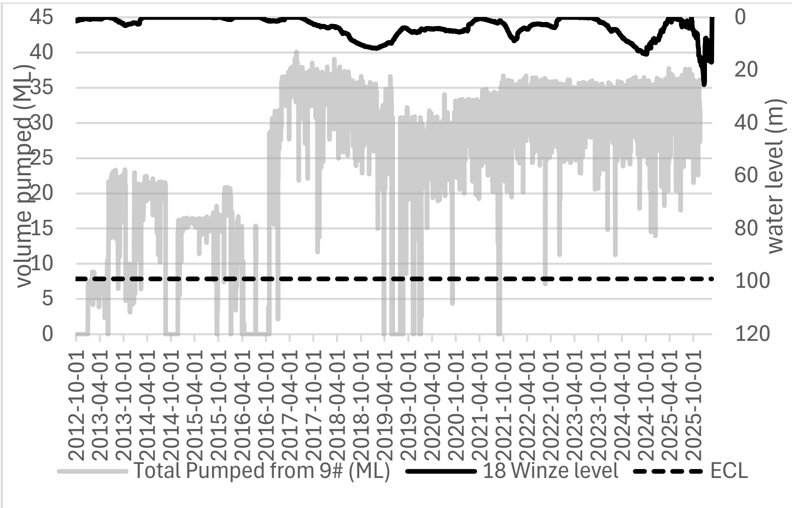
The intervention for the mine water problem in the Witwatersrand Basin was a reactive approach. The ToE was established in 2010 following widespread mine closures in the late 1990s and 8 years after mine water discharged into the environment in the Western Basin (McCarthy 2010, 2011; Matsumoto et al. 2016; Damar-Fakir et al., 2017; Ramugondo et al. 2023). This means that the mine water level in the Western Basin was already above the ECLs.

### *3.2.1 Implementation of pumping and treatment of mine water*

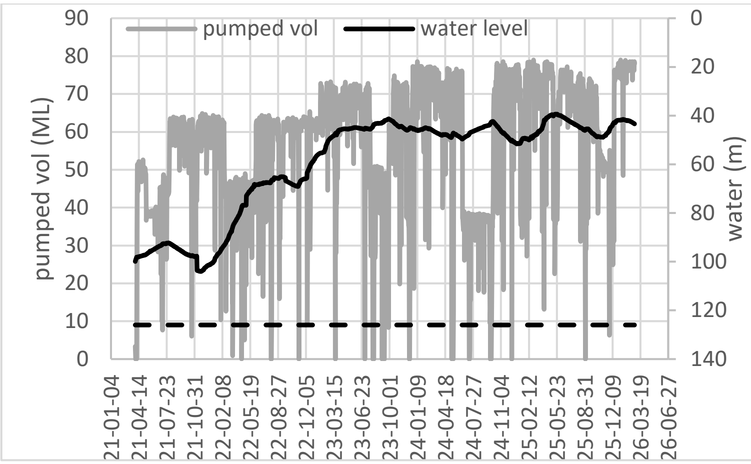
The water levels in the 3 basins (Western, Central and Eastern) relative to the set ECL and the associated pumping volumes are shown in Figure 5. The volume pumped from the Western Basin has been consistent at about 35 ML/d. Ingress in the Western Basin is well correlated with rainfall, with heavy rainfall events generally resulting in substantial increases in the ingress rate, most likely due to direct ingress into open pit mine workings. This has resulted in flooding of the mine workings up to the discharge level.

The monthly average pumped volume for the Central Basin has been lower than recommended by the ToE to the Inter-Ministerial Committee of at least 60 ML/d. Pumping rates increased to above 60 ML/day in 2023, as shown in Figure 5. Examination of reported pumping rates shows that they are lower than the ingress rates, resulting in water levels in the Central Basin continuously increasing. As a result, in May 2025 the water was discharged to the environment. Currently, the water level in the mine void is at around 40 m below the pumping shaft. This is higher than the ECL set by the Interministerial Committee in 2011 of 126 m).

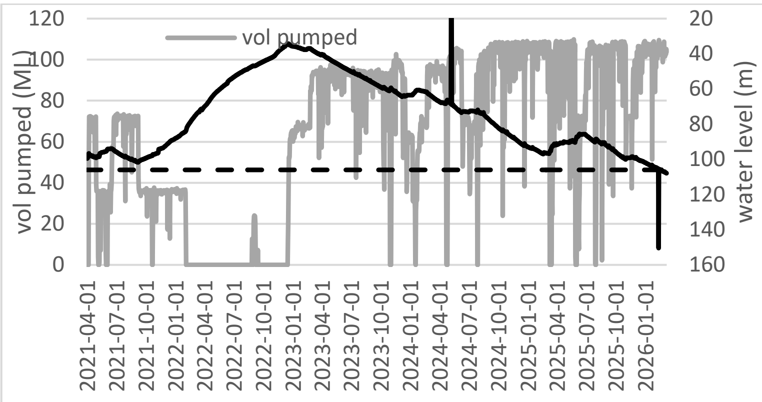
In the Eastern Basin, the effects of a pump breakdown from February 2022 to January 2023 are clear in the water levels shown in Figure 5. After pumping resumed in January 2023, pumping has consistently lowered the water level in the mine void. The current water level is just below the recommended ECL.




(a)




(b)




(c)

**Figure 5 The pumped volumes and associated water levels relative to the set environmental critical levels (ECL) in the: (a) Western Basin; (b) Central Basin; (c) Eastern Basin**

### *3.2.2 Implementation of ingress control measures*

Ingress control measures only reduce the direct inflow of surface water into the mine void. This is because these measures are implemented by closing shafts and redirecting water away from geological structures that allow direct surface water inflow into the mine void. In the Eastern Basin, an ingress measure has been successfully implemented; the Van Ryn Canal, as shown in Figure 6. The Van Ryn Canal directs water away from an ingress area that is directly above the mine void.

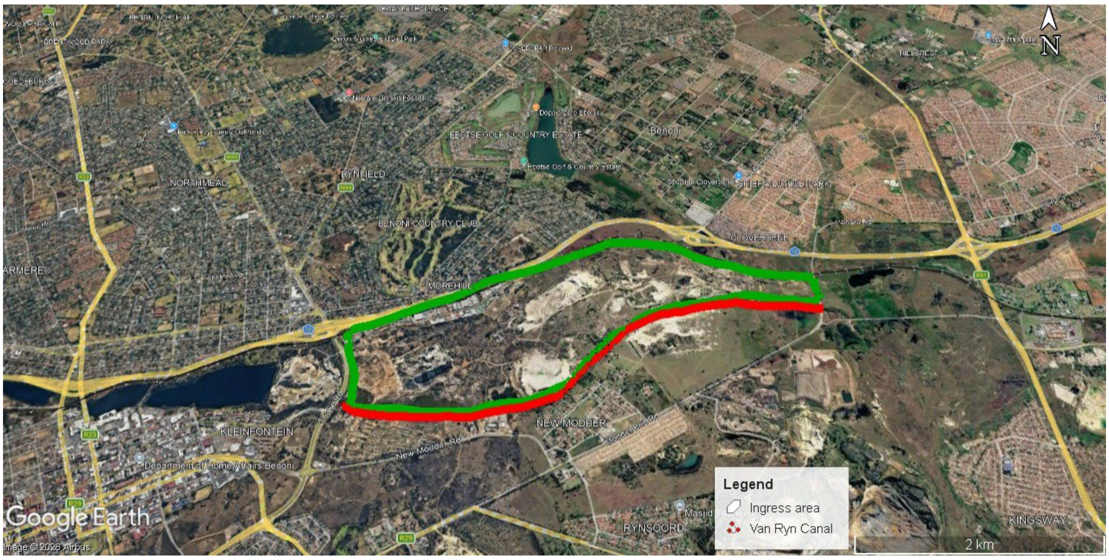



**Figure 6. The locality of the Van Ryn Canal relative to the ingress area**

After the implementation of this ingress control measure, water inflow into the Eastern Basin was reduced from about 75 ML in 2019 to about 50 ML in 2021 and 35 ML in 2022, as shown in Figure 7. This translates to 15-40 ML/day prevention of surface water ingress.

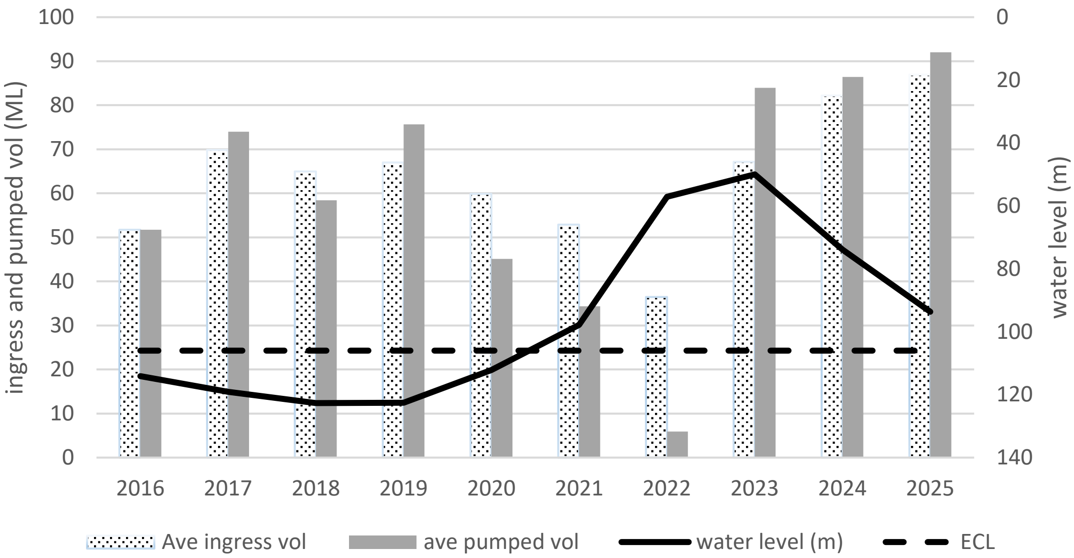



**Figure 7 Changes in water levels relative to environmental critical levels (ECL) and the associated average (ave) ingress and pumped volumes in the Eastern Basin**

From the data shown in Figure 7, water ingress has risen again, and pumping increased from 2023 to 2025. Ingress volumes can be reduced by preventing surface water from entering the mine voids. But as the water level is drawn down further, ingress from groundwater increases due to the head pressure from shallow aquifers.

## 3.3 Mine water evolution

The raw data from the HDS plants provides actionable insights for decision-making by answering data analytics questions as follows (Sharda et al. 2024):

- Descriptive data analysis: What happened?
- Diagnostic data analysis: Why did it happen?
- Predictive data analysis: What will happen?

### *3.3.1 Descriptive data analysis*

Descriptive analysis of the raw data from the Eastern Basin HDS treatment plant shows that water quality evolves post closure, as shown in Figure 8. The data from the 3 basins show similar trends.

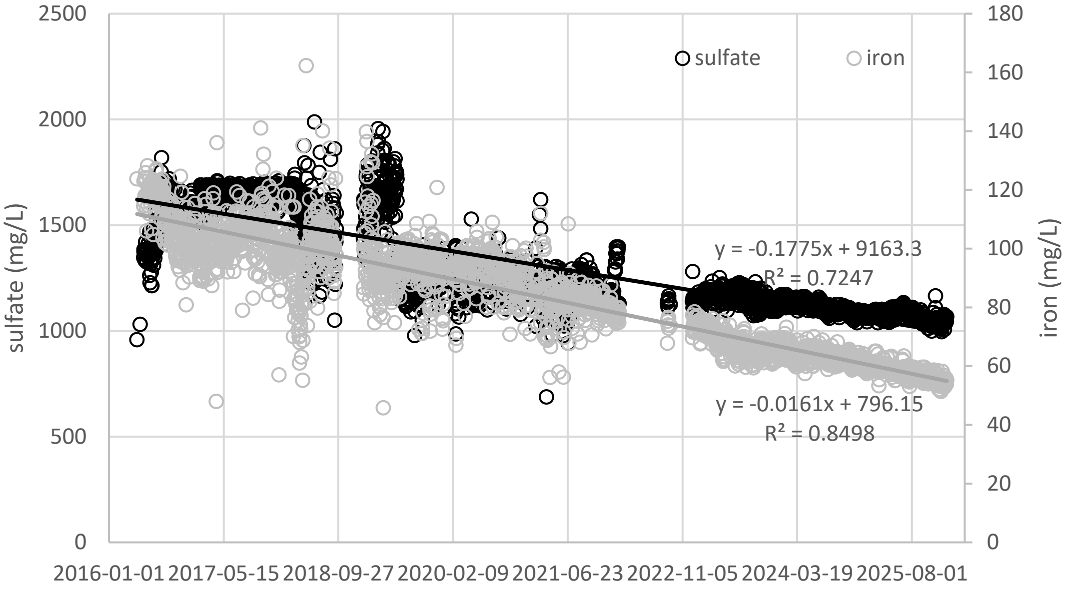



**Figure 8 The evolution of mine water in the Eastern Basin since the commissioning of the high-density sludge mine water treatment plant**

### *3.3.2 Diagnostic data analysis*

The evolution of the water chemistry in the mine voids situated in the Eastern Basin can be attributed to the following:

- During the treatment of mine water through the HDS treatment system, the resultant sludge is disposed of in the mine voids. This has residual alkalinity, which causes in situ neutralisation of pH and improves water quality.
- Long-term acidity generation in mine void water has been known to have two components: vestigial and juvenile acidity (Younger 1997).

The vestigial component relates to the geochemical trauma which occurs as abandoned mine voids are allowed to fill with water for the first time, taking ferrous and ferric hydroxy sulphate salts (intermediate products of pyrite oxidation) into solution. The dissipation of vestigial acidity is primarily controlled by the hydraulic retention time of the flooded mine system and will generally be achieved within 40 years (Younger 1997). The mines in the Witwatersrand Basin stopped being mined in the early 2000s and were left to flood. The secondary products of pyrite oxidation [$FeSO_4.7H_2O$, $FeSO_4.4H_2O$, $FeSO_4.H_2O$ and $Fe^{2+}.Fe_4^{3+}(SO_4)_6(OH)_2.20H_2O$)] were dissolved, resulting in water quality characterised by low pH and high sulphate and metal concentration. From 2012 when the treatment plants were commissioned, geochemical trauma had occurred and vestigial acidity was depleted.

The ongoing juvenile acidity (from ongoing pyrite oxidation) remained the only source of pollution in the water. The generation of this kind of acidity is very slow as it requires $O_2$ availability and bacterial catalysis:

$$FeS_2 + \frac{7}{2}O_2 + H_2O \xleftrightarrow{bacteria} Fe^{3+} + 2H^+ + 2SO_4^{2-} \quad (4)$$

In the flooded mine voids, $O_2$ ingress to facilitate pyrite oxidation is minimised. In conjunction with in situ neutralisation of the disposed sludge back into the mine void, this resulted in improved water quality.

### 3.3.3 Predictive data analysis

The treatment plant in the Eastern Basin was designed to handle acidic water with high metal concentrations. The water quality in the mine voids is showing gradual improvement (with circumneutral pH and low concentration of metals). Therefore the treatment plants became inappropriate as the water continued to improve. Long-term, sustainable mine water management, such as passive treatment, should be considered if the trends observed in this study continue.

Based on the data on Figure 8, the regression analysis showed that the concentration of sulphate (Equation 5) and Fe (Equation 6) follow linear relationships:

$$y = -0.1775x + 9163.3 \; where \; R^2 = 0.7247 \quad (5)$$

$$y = -0.0161x + 796.15 \; where \; R^2 = 0.8498 \quad (6)$$

Based on the regression equations, the water quality in the Eastern Basin mine void was forecasted and the results are shown in Table 4.

**Table 4 Prediction of the mine void water quality data up to potable water quality with respect to sulphate and iron concentration in mg/L**

| y (sulphate) | x (year) | y (iron) | x (year) |
|---|---|---|---|
| 1,000 | 2025/11/29 | 45 | 2027/09/25 |
| 800 | 2028/12/30 | 35 | 2029/06/07 |
| 700 | 2030/07/16 | 25 | 2031/02/18 |
| 600 | 2032/01/30 | 15 | 2032/10/31 |
| 500 | 2033/08/16 | 10 | 2033/09/07 |
| 400 | 2035/03/02 | 5 | 2034/07/14 |
| 300 | 2036/09/16 | 4 | 2034/09/14 |
| 250 | 2037/06/24 | 2 | 2035/01/17 |
| 200 | 2038/04/02 | 1 | 2035/03/20 |
| 150 | 2039/01/09 | 0.5 | 2035/04/20 |
| 100 | 2039/10/17 | 0.25 | 2035/05/05 |
| 50 | 2040/07/25 | 0.2 | 2035/05/08 |
| | | 0.1 | 2035/05/15 |

Predictive analytics showed that the concentrations of sulphate and Fe will be below the potable guideline limits of 250 mg/L in about 2037 and 0.1 mg/L in about 2035. Mine void water quality improves over time under controlled conditions but requires continuous monitoring and adaptive management.

### 3.4 Lessons learnt

Based on the management of interconnected underground mine voids in the Witwatersrand Basin, several lessons have been learnt. These lessons are based on observations of the implemented project to manage mine void water and on data analysis from continuous monitoring. The following 3 lessons have been learnt and can be considered for project planning for post closure of interconnected mines:

1. Regulation is important to avoid burden shifting. The transition from a historically weak regulatory environment to a comprehensive legislative framework (1996–2009) significantly improved governance of mine water management. However, the inability to apply these frameworks retrospectively resulted in the transfer of environmental liabilities to the state. This highlights a fundamental gap in mine closure governance: regulatory systems must incorporate financial provisioning, enforceability and post-closure accountability mechanisms to prevent future legacy burdens. The Witwatersrand case demonstrates that regulatory frameworks are most effective when implemented proactively rather than reactively.

2. Management of mine water in interconnected voids requires integrated efforts. The interconnected nature of mines in the Witwatersrand Basin invalidates site-specific approaches to mine closure. Planning should be done during the operation to establish a coordinated water management project. This should involve all key stakeholders, including AMD treatment plant operators, government departments, communities and research councils. Consider the community's acceptance of the projects to prevent vandalism and/or misuse of the infrastructure by illegal miners. The planning should use the water management infrastructure during mine operations as the baseline for post-closure mine water management projects.

3. Adapt mine water management according to the changes in the water quality. The project to manage mine void water in the Witwatersrand was a reactive approach that involved mainly pumping the water and maintaining water levels below the ECLs. This intervention is energy-intensive and costly. Complementary interventions should be considered to predict and prevent pollution, thereby avoiding costly remediation of the environmental impacts of mine water. Thus pumping and treating should be a transitional control measure. Adapting the mine water management strategy should be considered. These adaptations should be informed by the monitoring data and data analytics. This shows the importance of continuous monitoring of mine water and data analytics in mine closure management.

## 4 Conclusion

The management of mine water in interconnected underground mine voids, such as those in the Witwatersrand Basin, is complex post mine closure. This study shows that the absence of a robust regulatory framework creates loopholes for mines to evade liability for managing mine water post closure, shifting the burden to the government. The management of mine water in an interconnected system requires an integrated approach and an integration of management systems. An integrated approach involves the mine and all key stakeholders, while an integrated management system involves prediction, prevention and mitigation. This reduces costs and the environmental impact of mine water. The lessons learnt from the Witwatersrand Basin provide a reference for interconnected mine void systems.

## Acknowledgement

The authors acknowledge the contributions of the Council for Geoscience and the data provided by the Department of Water and Sanitation and the Trans Caledon Tunnel Authority. In addition, the authors acknowledge the Department of Mineral and Petroleum Resources for funding the project.

# References

Coetzee, H, Hobbs, PJ, Burgess, JE, Thomas, A, Keet, M, Yibas, B, … Maree, J 2011, *Mine Water Management in the Witwatersrand Gold Fields With Special Emphasis on Acid Mine Drainage*, report of Inter-Ministerial-Committee on Acid Mine Drainage.

Damar-Fakir, P, Sithole, Z, van Niekerk, AM, Dateling, J, Maree, JP, Rukuni, T, … Saunders, B 2017, *Mine Water Treatment Technology Selection: User Guide,* Water Research Commission, Pretoria.

Madzivire, G, Coetzee, H, Nkabane, L & Mahlaule, R 2026, *Long-Term Management of Mine Water in the Witwatersrand Goldfields*, Council for Geoscience, Pretoria.

Madzivire, G, Coetzee, H, Ravi, V, Vadapalli, K, Ligavha-Mbelengwa, L & Nolakana, P 2023, *Research on the Relaxation of Environmental Critical Levels of the Mine Voids in the Witwatersrand Goldfields*, Council for Geoscience, Pretoria.

Matsumoto, S, Shimada, H & Sasaoka, T 2016, 'The key factor of acid mine drainage (AMD) in the history of the contribution of mining industry to the prosperity of the United States and South Africa: a review', *Natural Resources*, vol. 07, pp. 445–460, https://doi.org/10.4236/nr.2016.77039

Mccarthy, T 2010, *The Decanting of Acid Mine Water in the Gauteng City-Region: Analysis, Prognosis and Solutions*, https://cdn.gcro.ac.za/media/documents/gcro_terence_mccarthy_amd__final_version.pdf

McCarthy, TS 2011, 'The impact of acid mine drainage in South Africa', *South African Journal of Science*, vol. 107, no. 5/6, pp. 1–7, https://doi.org/10.4102/sajs.v107i5/6.712

Ramugondo, S, Molapo, D & Coetzee, H 2023, *Active Mine Water Solutions: Implementation of Ingress Control Measures in Witwatersrand Goldfields*, Council for Geoscience, Council for Geoscience

Ramugondo, S, Molapo, D & Mahlase, B 2026, *Active Mine Water Solutions: Implementation of Ingress Control Measures in Witwatersrand Goldfields*, Council for Geoscience, Council for Geoscience

Sharda, R, Delen, D & Turban, E 2024, *Business Intelligence, Analytics, Data Science, and AI: a Managerial Perspective*, Pearson.

Sheridan, C, Bonner, R, Bruyns, L, Drake, D, Harding, K, Janet, JP, … Nabeela, S 2015, *Conceptual Project on Using the Pumping Scheme to Eliminate Acid Mine Drainage*, report to the Water Research Commission.

Swart, E 2003, 'The South African legislative framework for mine closure', *The Journal of The South African Institute of Mining and Metallurgy*, vol. 103, no. 8, pp. 489–492.

Younger, PL 1997, 'The longevity of mine water pollution: a basis for decision-making', *Science of The Total Environment*, vol. 194–195, pp. 457–466.