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Hydrological risks and water management in the transition of underground block cave mining: a case study of Deep Ore Zone–Deep Mill Level Zone transition

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Abstract

The East Ertsberg Skarn System (EESS) is located in the Ertsberg Mining District in Papua, Indonesia. It includes the historical Gunung Bijih Timur (GBT), Intermediate Ore Zone (IOZ) and Deep Ore Zone (DOZ) mines, while currently the operational focus is on the Deep Mill Level Zone (DMLZ) mine. This strategic shift aims to reach deeper ore reserves and optimise resource management within the EESS, although it also introduces significant hydrological challenges and risks associated with deep underground block cave mining. The transition phase is critical for helping ensure the sustainability of deep mining activities.

PT Freeport Indonesia's (PTFI) operational area experiences very high rainfall, with certain weather stations recording over 5,000 mm of rainfall per year. This intense rainfall, coupled with the operational complexity of managing several inactive mines overlaying the DMLZ mine, such as the DOZ mine, creates unique challenges. These include managing regional groundwater inflows to prevent rainfall infiltration into the existing surface subsidence, and existing DOZ mine water from causing flooding or triggering wet muck spills into the DMLZ mine. Effective water management is therefore critical to mitigating operational risks and includes strategies such as surface water diversion, large-scale underground dewatering, caveline drilling and continuous monitoring of groundwater levels.

The practices and strategies implemented during the DOZ and DMLZ transition have valuable implications for deep mining operations globally, offering guidance for safe and efficient transitions in similar hydrological settings.

Keywords: *underground, block cave, transition, hydrology, hydrogeology, dewatering, hazard, management, drilling*

1 Introduction

Copper is essential for driving global economic advancement and is becoming increasingly important in the shift towards a low-carbon economy. The increasing need for copper is fuelled by its indispensable role in decarbonisation technologies, including electric vehicles, renewable energy systems and advanced electronics. These technologies play a crucial part in drastically decreasing global carbon emissions. According to Freeport-McMoRan (2021a), the utilisation of copper might potentially lead to a reduction of world carbon emissions by 16% by the year 2030. As these technologies progress, the important role of copper is projected to become even more critical, highlighting the requirement for mining operations that are both efficient and sustainable. The Deep Ore Zone (DOZ) mine, located at elevations ranging from 3,456 to 3,125 m in the Ertsberg Mining District (Figure 1), has consistently played a significant role in PT Freeport Indonesia's production of copper and gold. Production from the DOZ ore deposit started in 1989 and ended by the end of 2021. Average daily ore milled from the DOZ underground mine was 8,700 metric tons (M/T) in 2021, 20,900 M/T in 2020 and 25,500 M/T in 2019 (Freeport-McMoRan 2021b). Since stopping mining

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operations at DOZ, PTFI has redirected its efforts towards the extraction of copper and gold from deeper underground ore deposits such as the Deep Mill Level Zone (DMLZ) mine. The DMLZ mine is located 500 m below the DOZ and operates in the same geological complex.

Effectively controlling water is a crucial operational obstacle in most underground mining operations but is especially so at PT Freeport Indonesia (PTFI), where the region encounters significant precipitation — over 5,000 mm annually — resulting in considerable hazards related to water infiltration and groundwater flow. These hazards can lead to severe operational disturbances, such as floods and wet muck events in the mines, which are a risk to both safety and productivity.

To address these risks, PTFI has implemented advanced water management and mitigations systems that comprise containment, drainage, borehole drilling and thorough monitoring of groundwater levels.

These actions are essential not only for maintaining the safety and efficiency of the mining operations, but also for ensuring safe production in deep underground excavations. The objective of this paper is to discuss the water management methods implemented throughout the transition from DOZ to DMLZ in the East Ertsberg Skarn System (EESS), with a particular focus on the practical elements and the hazards associated with water in caving environments. The study aims to analyse the efficacy of these tactics to offer useful insights that can improve the sustainability and safety of deep mining operations. This paper aims to provide useful insights for PTFI water management strategies in deep cave mining operations to the wider deep mining community.

2 Methodology

2.1 Study area

The study specifically examines the DOZ and DMLZ mines, which are part of the EESS in Papua, Indonesia (Figure 1). The landscape is distinguished by steep topography and high rainfall, presenting distinctive difficulties for mining operations.

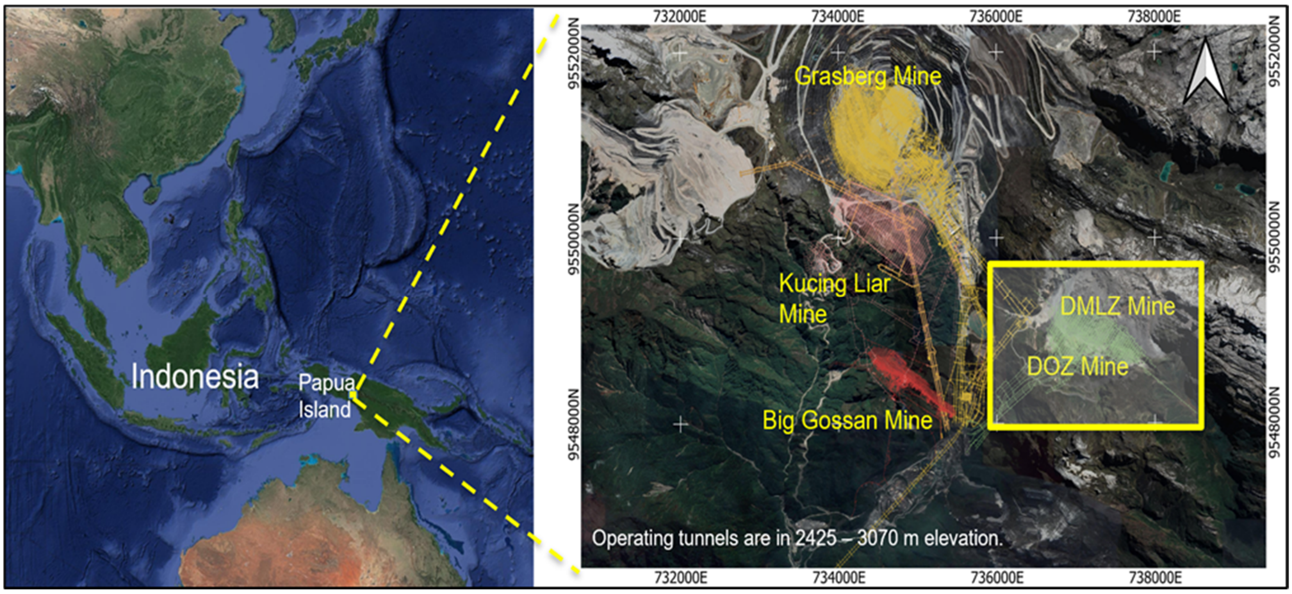
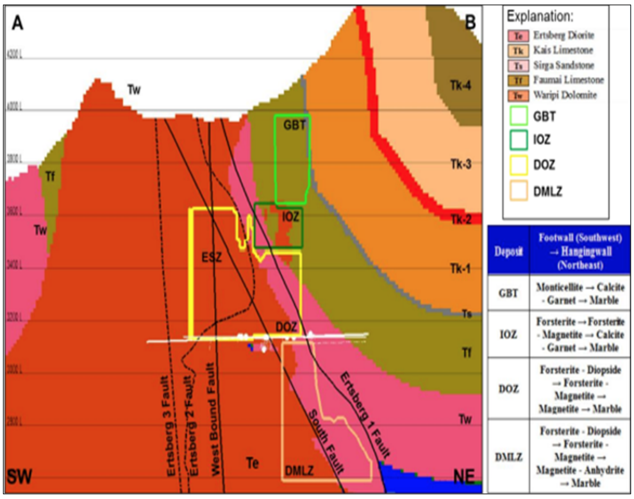


Figure 1 Location of the Deep Mill Level Zone and Deep Ore Zone mines in Papua, Indonesia

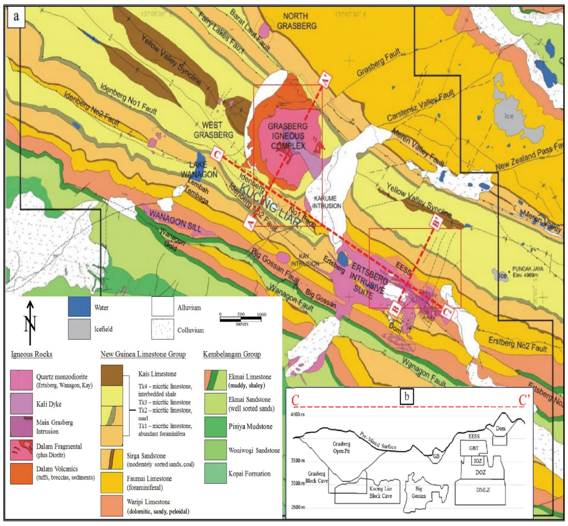
2.2 Geology

The EESS is a copper-gold deposit located on the northeastern edge of the 2.7-million-year-old Ertsberg Diorite. This diorite intruded along the southern side of the Yellow Valley Syncline and is associated with skarn mineralisation. The deposit has prominent copper-gold skarn replacement mineralisation, accompanied by porphyry-style stockwork and sheeted vein mineralisation in specific regions. The Ertsberg Diorite is a significant geological formation that contains several important skarn ore deposits, such as the original Ertsberg (Gunung Bijih) skarn, the Dutch of Mountain (DOM) skarn and the Big Gossan skarn. Another notable characteristic is the West Hanging Valley skarn, located at a high altitude where diorite and sedimentary rock meet, possibly indicating an elongated roof pendant.

The process of geological stratification starts with sedimentary rocks from the Cretaceous period located deep underground, and then progresses upwards via different formations from the Tertiary period until it reaches the surface. The Kembelangan Ekmai Formation comprises the Ekmai shale, Ekmai limestone and Ekmai sandstone. Located above these formations are the Tertiary formations, which consist of the Waripi Formation, characterised by dolomitic limestone with anhydrite nodules. This is followed by the Faumai Formation, which is composed of thick-bedded limestone, and then the Sirga Formation, which is made up of quartz-carbonate sandstone (Figure 2a).



(a)



(b)

Figure 2 **(a) Schematic geologic cross-section showing Gunung Bijih Timur, Intermediate Ore Zone, Deep Ore Zone and Deep Mill Level Zone; (b) Regional geology within the study area**

Lastly is the Kais Formation, a limestone formation notable for its abundant fossils. The EESS area is delineated by the west-northwest oriented characteristics of the Yellow Valley Syncline and the steeply inclined reverse faults such as the Ertsberg (Figure 2b). These flaws have made it easier for the Ertsberg Diorite to enter and for the crucial hydrothermal fluids to assist in the formation of porphyry and skarn minerals along this boundary.

2.3 Hydrology

The DOZ and DMLZ mines are in a location characterised by exceptionally high levels of precipitation, with an annual rainfall ranging from 5,000–6,000 mm as recorded by the local DOM station and GBT rainfall station (Figure 3). The region's river systems exhibit narrow, profound channels that expand and become shallower in more gradual landscapes. The flow of the river is mostly influenced by rainfall, which causes it to increase greatly during precipitation and decrease swiftly thereafter (Figure 4).

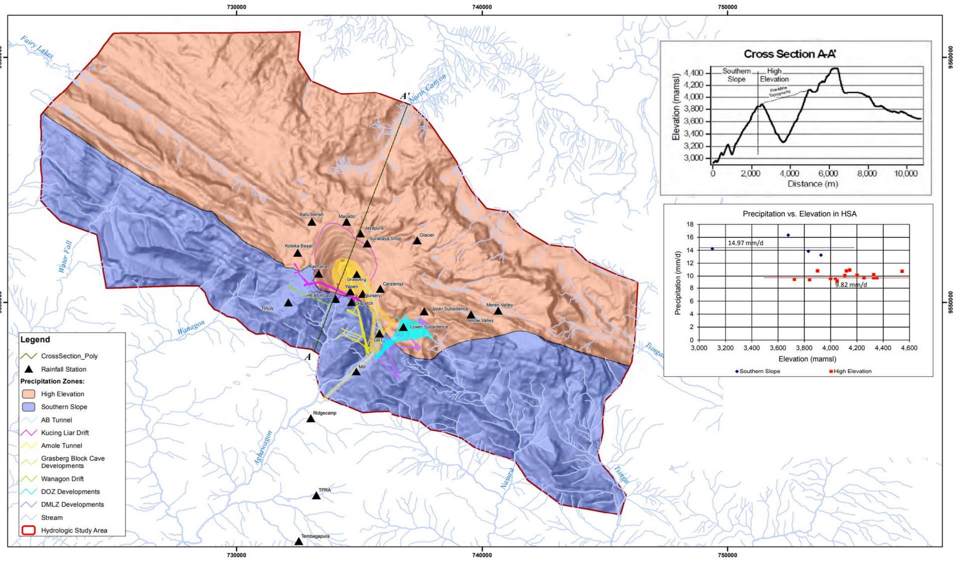


Figure 3 Location of the rainfall station and distribution of precipitation zones (SRK Consulting 2017)

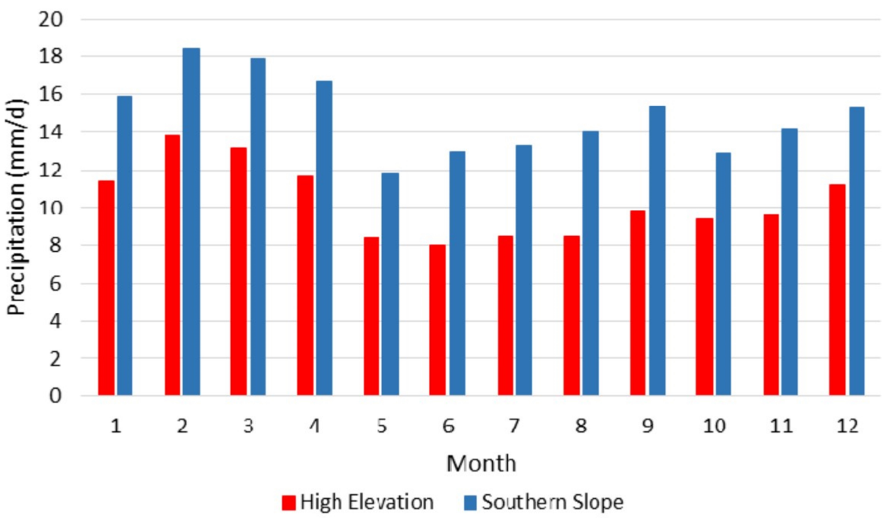


Figure 4 Monthly average precipitation data (SRK Consulting 2017)

Management of hydrological mechanisms presents some difficulties due to the heterogeneous infiltration rates observed across the area. Specifically, the collapsed zones exhibit rates as high as 1,000 mm/day, while the fractured zones have rates of only 10 mm/day.

Extensive hydrogeological research and modelling of the EESS have been conducted since 2003. These studies have resulted in thorough conclusions that were given in the DOZ 50K (Freeport-Indonesia 2007).

The hydrogeology of the region is intricate, with multiple hydrogeological units that impact the flow of water into the DOZ and DMLZ block cave mines:

- rainwater absorption. Rainwater is primarily absorbed directly in the caving zones, which has a considerable impact on the movement of water

- formation flows. Water is discharged from the Kais and Faumai Formations at the points where fault zones meet these geological units. These formations are essential as they provide significant amounts of water throughout the mining operation
- seepage and fault zones. There is direct leakage observed from the fractured diorite units, and at the boundaries between diorite and skarn, into the fracture zones. It is especially noticeable during mining operations. When break zones overlap with the West Fault Zone and East Fault Zone, these fault zones serve as pathways for water flow. The latter, in particular, is known for its ability to facilitate significant water drainage as it is connected to the Nasura Basin.

The upgraded regional model (Figure 5) completed in 2017 integrates the hydrological findings to offer a full and detailed depiction of hydrogeological units and their interactions with the mines within the EESS. The update of the model was crucial in assisting with understanding potential water inflows into drifts and caves. Understanding and then managing that water was crucial to limiting operation risks.

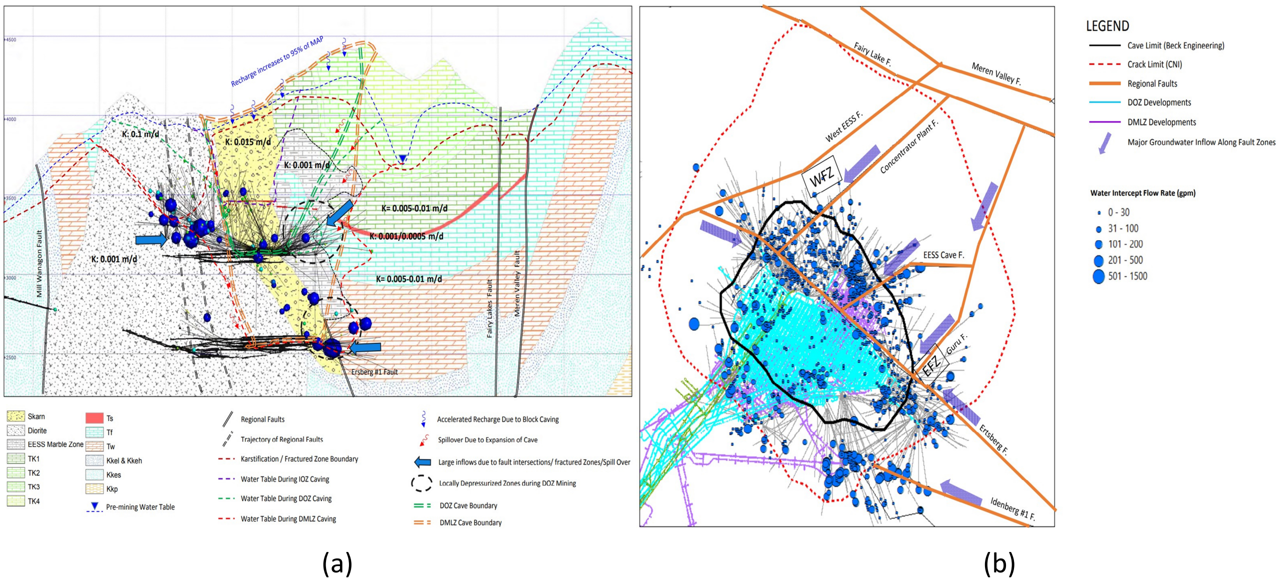


Figure 5 Conceptual hydrogeologic model of the East Ertsberg Skarn System (SRK Consulting 2017): (a) Section view; (b) Plan view

3 Deep Mill Level Zone case study

The hydrological risks associated with caving under an existing block cave can be separated in three different phases as follows.

- phase one — initial phase of cave formation. During the earliest stage of cave development the primary sources of groundwater are the initial interaction with permeable geological structures such as faults and fractures. As a result a localised depression in the form of a cone is created near the cave, leading to a reduction in water levels. The influxes mostly occur in regions characterised by strong transmissivity, such as the upper sections of the Kais limestone and prominent faults like the Ertsberg #1 Fault
- phase two — expansion of the cave and interaction. During the second stage the cave expands and meets with additional porous geological formations, leading to a higher influx of groundwater and a subsequent increase in volume. The cone of depression widens and strengthens, affecting a larger area and resulting in a more significant decrease in the watertable. During this phase, cracks develop in carbonate and intrusive rocks, enhancing the connectivity between groundwater systems and facilitating greater water flow

- phase three — interacting with the DOZ cave. The third stage is characterised by engagement with the DOZ cave and is impacted by the intrusion of rainfall. During this stage there is a significant increase in the amount of groundwater flowing into the area as a result of the combined effects of both cave systems. The DOZ/DMLZ cave creates steep cones of depression which extend the drawdown influence over a greater distance from the mining area. The merging of the two cave systems, along with the impact of rainfall seepage, lead to complex underground water flow routes, necessitating the implementation of more sophisticated monitoring and management techniques.

In the case of DMLZ the risks associated with each phase are described below, along with their associated mitigations.

3.1 Cave establishment before interaction

3.1.1 Groundwater level

The intricate geological configuration intersected during the cave establishment, comprising fault zones with high permeability, limestone with karst features and fractured rock formations, was conducive to high groundwater inflows. Without the implementation of dewatering drilling, the DMLZ mine was expected to encounter considerable inflows of groundwater up to 1,520.78 litres per second (l/s) during the post-caving stage (SRK Consulting 2017), representing an unacceptable risk for mining activities. This prompted apprehension regarding the occurrence of floods and wet muck events, both of which have the potential to significantly compromise operational safety and efficiency.

3.1.2 Dewatering drilling

The groundwater dewatering drilling at DMLZ (also referred to as far-field dewatering drilling) has proven to be quite successful in substantially reducing water levels to the extraction level footprint and reducing groundwater inflows into the DMLZ cave by employing strategic diamond drilling and targeted dewatering methods. The graph depicting groundwater level monitoring (Figure 6) reveals significant declines in water levels, particularly in the East and West Zones. As an illustration, piezometer DZ225-04H-04 (located in the East Zone) experienced a decline in elevation from around 2,950 metres above sea level (masl) to 2,879 masl by 31 October 2023, resulting in a fall of more than 70 m. Piezometer DZ225-03H-02 (in the West Zone) saw a decrease in elevation from about 2,900 to 2,651 masl, resulting in a reduction of close to 250 m (Figure 6). In addition, the flow monitoring data shows that the total water inflow at the active production zones consistently stayed below 31.5 l/s, even during periods of intense rainfall (Figure 7).

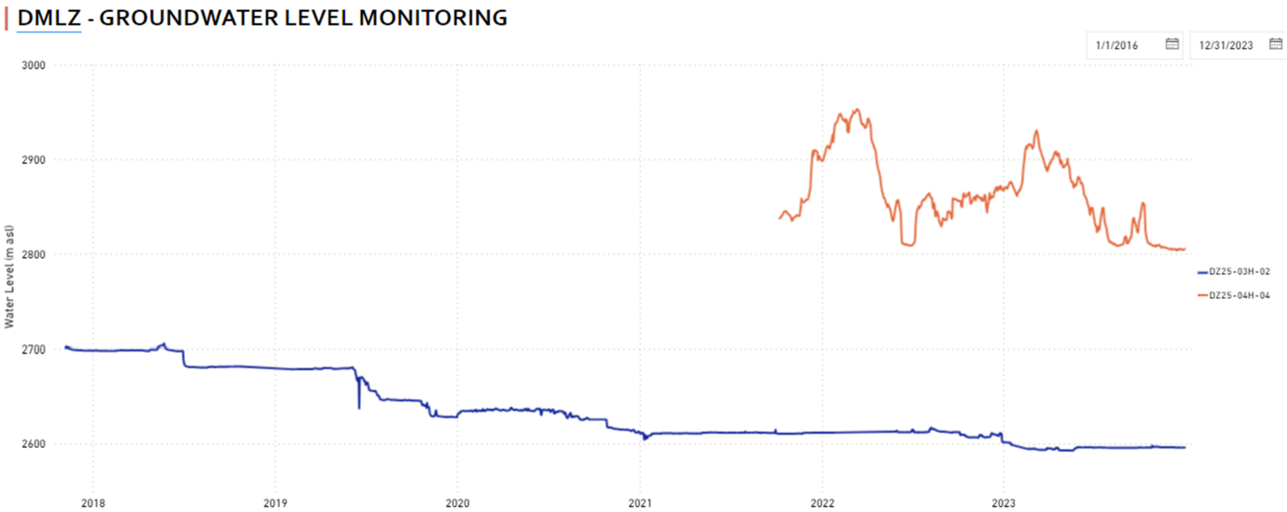


Figure 6 Deep Mill Level Zone groundwater level monitoring

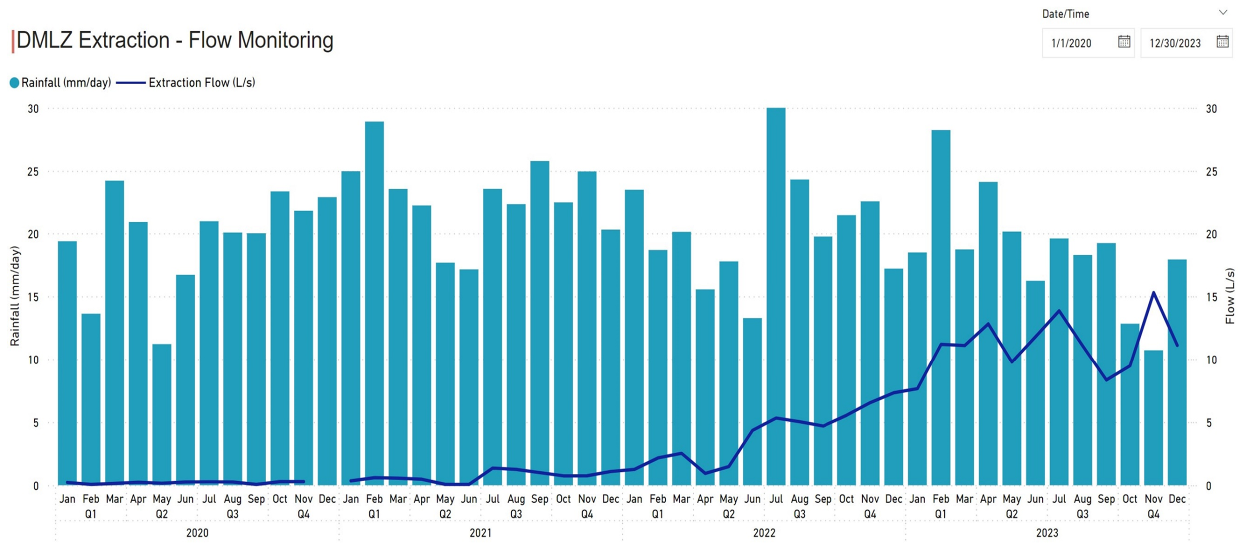


Figure 7 Deep Mill Level Zone extraction flow monitoring

This dewatering program comprised 18 drill sites specifically designed to target fault zones and aquifers, resulting in a decrease in pore pressure and water levels. The dewatering efficiency against set targets was measured through continuous monitoring using vibrating wire piezometers and real-time data modifications. The consistent upkeep of the dewatering system additionally contributed to the ongoing success. The substantial decrease in water levels has greatly reduced water-related disruptions such as flooding, enabling secure and uninterrupted mining operations at DMLZ during the establishment of the DMLZ cave.

3.2 Deep Mill Level Zone cave breakthrough with the Deep Ore Zone mine

3.2.1 Deep Ore Zone and Deep Mill Level Zone interaction

The DOZ mine has always been a wet mine with inflows reaching up to 37.86 l/s. Associated drifts were also considered wet considering the amount of dewatering drilling undertaken in the past. Further to this, the northern part of the DOZ contained the DOZ J4-drift and DOZ Tebai Dam, both overlaying the DMLZ future cave. They were constructed as a water supply drift and a water dam, respectively, to collect and divert residual water from the production area (Figure 8). In 2021, the DMLZ cave started interacting with some of the DOZ mine's existing drifts, including the Tebai Dam (Figure 9).

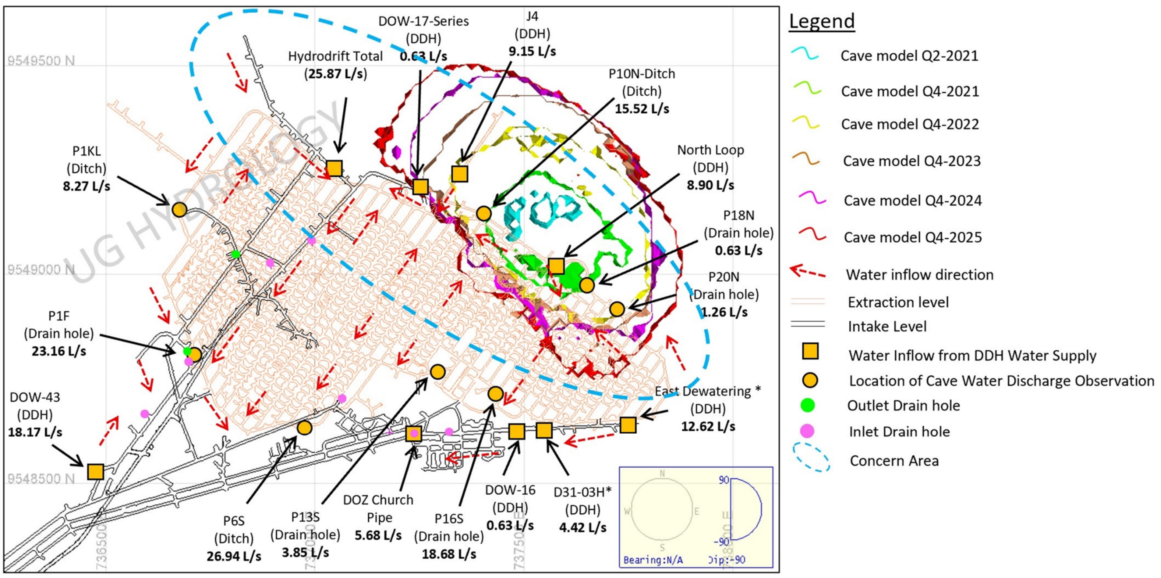


Figure 8 Water influx from the Deep Ore Zone area into the Deep Mill Level Zone cave

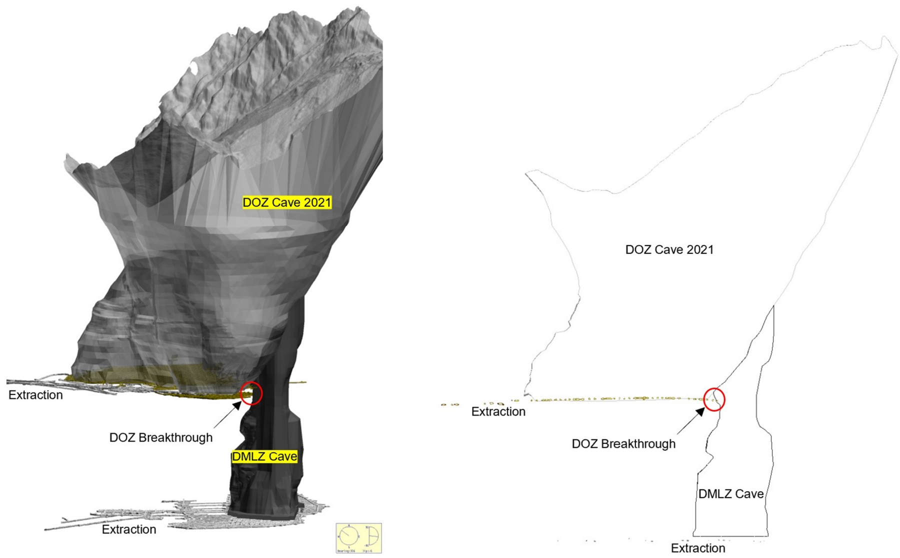


Figure 9 Deep Ore Zone and Deep Mill Level Zone interaction

A considerable reduction in water flow was observed from monitoring locations around the dam. The water was observed flowing towards mine-induced cracks and vanishing. By June 2021 a complete absence of water flow was observed and up to 22.9 l/s (Figure 10) was missing from the area. A similar amount of water was documented at the DMLZ extraction level following the breakthrough, indicating that the water from the DOZ drift was now reporting to the DMLZ extraction level through the DMLZ cave or yield zone.

This was confirmed by both geotechnical observations and modelling work showing the yielding zone interacting with the DOZ drifts. In addition to flooding, having water inflows of considerable magnitude at the DMLZ extraction through a more mature DMLZ cave considerably increased the risk of wet muck or mud rush. Mitigations were then implemented to reduce these risks.

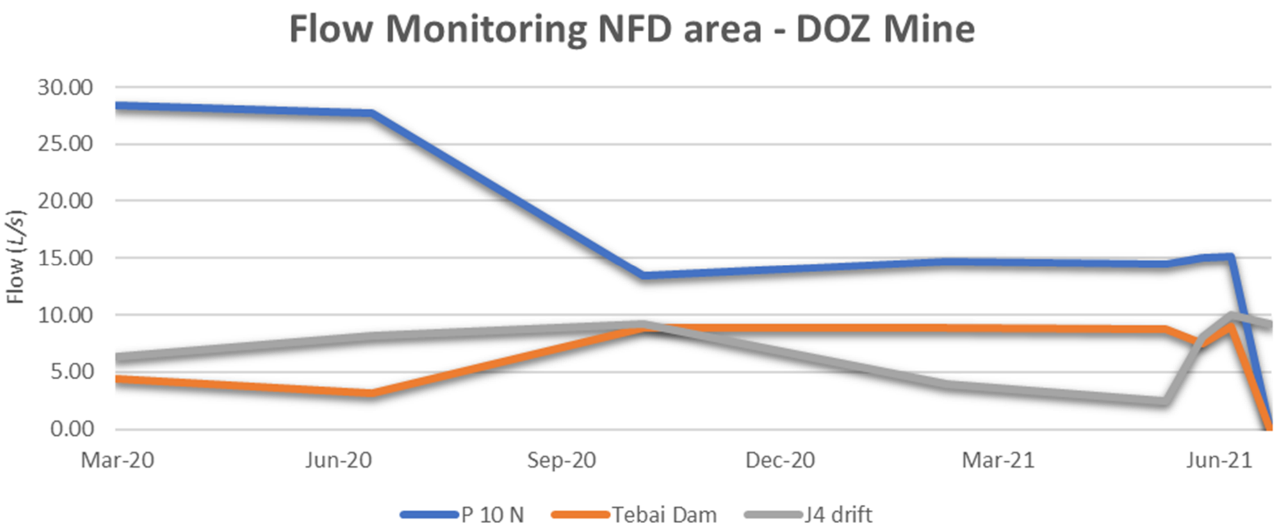


Figure 10 Flow rate at North Fringe Drift (NFD) during Deep Ore Zone and Deep Mill Level Zone cave breakthrough

3.2.2 Deep Ore Zone water diversion to prevent its entry to the Deep Mill Level Zone cave

As the production rate of the DMLZ mine increased so did its expansion to the north, leading to a more pronounced connection with the overlaying DOZ drift including the DOZ West Hydro Drift. To mitigate further water entering the DMLZ cave a dedicated drilling plan was developed to intersect DOZ water for the yet-to-be-impacted DOZ West Hydro Drift and divert up to 5.05 l/s of water away before it entered the DMLZ cave. The original project proposal included six boreholes drilled from the intake level of the DOZ mine towards the western part of the NFD. The six boreholes drilled were 50–70 m long, with an inclination ranging from 48° to 72°. Each hole was expected to yield 0.63–2.52 l/s. The program was successful, with five out of the six holes intersecting the DOZ West Hydro Drift of DOZ (Figure 11 and Table 1).

Table 1 Summary of the dewatering drilling process for the Deep Ore Zone extraction level

Hole ID	Location	Length (m)	Initial flow (l/s)
DZ31-07H-04	DOZ WID	70.2	0.63
DZ31-07H-03	DOZ WID	58.5	0.76
DZ31-07H-02	DOZ WID	67.6	0.50
DZ31-07H-01	DOZ WID	26.6	–
DZ31-07H-05	DOZ WID	54.9	2.52
DZ31-07H-0101	DOZ WID	50.2	0.63

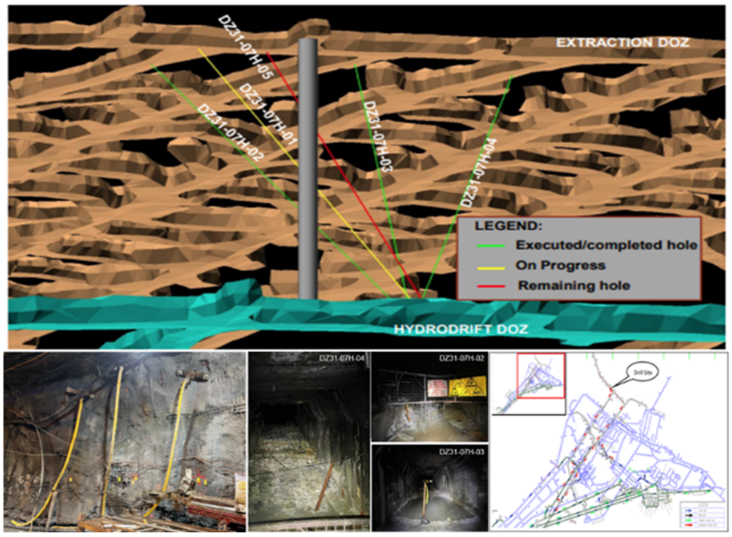


Figure 11 Drilling procedure from the Deep Ore Zone West Hydro Drift to the Deep Ore Zone extraction level

Lasting roughly two weeks, this project required a significant level of precision during drilling to mitigate the potential for deviation. A hexagonal chrome barrel was used with a slow drilling speed of 20 m per day to reduce deviation. After successfully drilling through to the West Hydro Drift all HQ pipes were left inside the hole, with perforated pipes placed to mitigate the collapse of the borehole.

The drilling of five dewatering holes in the West Hydro Drift of the DOZ effectively captured and diverted water, leading to a significant decrease in water intake to the DMLZ production area. The total initial water flow gathered through these openings reached a maximum of 5.05 l/s and further reduced the risk of flooding and wet muck.

3.3 Deep Mill Level Zone cave and Deep Ore Zone cave interaction

3.3.1 Effects of the Deep Mill Level Zone cave connecting with the Deep Ore Zone cave

After the DMLZ cave was connected with the DOZ cave it began to be significantly affected by rainwater. The intrusion of rainwater into the DOZ cave was now an additional pathway for water to enter the DMLZ cave, hence increasing the probability of a sudden influx of water into the mining area. To manage this, advanced real-time monitoring systems were enhanced to detect changes in water flow and the impact of rainfall.

Piezometers were used to measure hydraulic pressure and the amounts of water below the surface. Additional drilling was conducted near the cave region to effectively manage and reduce the flow of water into the DMLZ production area. In addition, surface water diversion techniques were employed to control the precipitation on the surface prior to its infiltration into the cave systems. This effectively decreased the total amount of water entering the mining areas and enhanced operational safety.

3.3.2 Surface water diversion

Prior to the DMLZ cave breakout into the DOZ mine in 2017, the major objective of surface water management was to build and upkeep diversion drains surrounding the EESS subsidence area. A 1.5-km drainage system was constructed on the southern side of the EESS subsidence area to redirect rainfall run-off from important places such as the DOM, the fracture diorite and subsidence zones. This system is capable of effectively handling up to 63.10 l/s of run-off water. As of 2023, the surface water management strategy had been extended to cover a catchment area of almost 3,809,118 square metres in the DOM region. Out of the total area, 47% (1,780,810 square metres) was effectively redirected from the subsidence zone to assist the Open Pit Lama (OPL) reservoir and mud removal initiatives. Passive inflow into the DOZ-DMLZ mine was contributed by the remaining 53% of the catchment area. The main enhancements involved the establishment of drainage systems that were equipped with geomembrane and concrete linings. These measures were implemented to reduce the amount of water seeping into areas prone to sinking. Proposals were made to conduct regular inspections and implement ongoing improvements to the catchment area to maintain efficient water diversion and effectively manage any alterations in surface run-off pathways. PTFI's integrated initiatives demonstrate its holistic strategy in surface water management, guaranteeing the stability and security of mining operations while mitigating the hazards linked to water infiltration into mining zones. Systematic drainage review is carried out, specifically in the southern channel region, to redirect water away from areas yet to be encroached by the subsidence (Figure 12). This involves the annual revision of the catchment area Quarterly maintenance inspections are conducted and include evaluation of the surface run-off locations, drainage ditches' debris and sedimentation in check dams to ensure precise recording of surface run-off pathways.

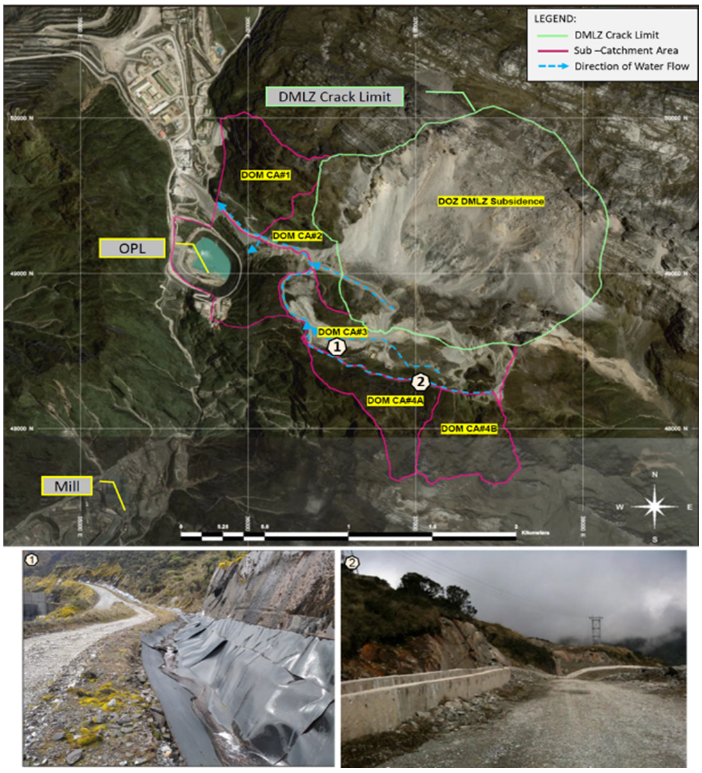


Figure 12 Drilling displays the process of flow routing in relation to the condition of the Dutch of Mountain (DOM) catchment and drainage

3.3.3 Caveline drilling

As discussed above, despite all of the efforts made to reduce rainfall run-off infiltration into the subsidence area, some water is still unable to be removed from the system. A novel plan was developed to try to capture cave flows from underground. The interactions between the cave system and the hydrological processes occur in the subsidence area, where surface water seeps through fissures left by precipitation, following paths around the edges of caves. (Figure 13).

Saturation zones form when water collects in broken-up, fine-grained strata. Strict water management is needed for production panels at the bottom to prevent flooding and guarantee safe operations, while effective dewatering produces dry panels.

The cave dewatering program encompassed 12 drill sites in the northern DMLZ undercut, aimed at capturing water flow originating from the J4-drift overlaying the DMLZ cave, before reporting the DMLZ drawpoints. The caveline dewatering holes were designed with lengths ranging from 13 to 45 m, with an inclination between 27° and 30° (Table 2).

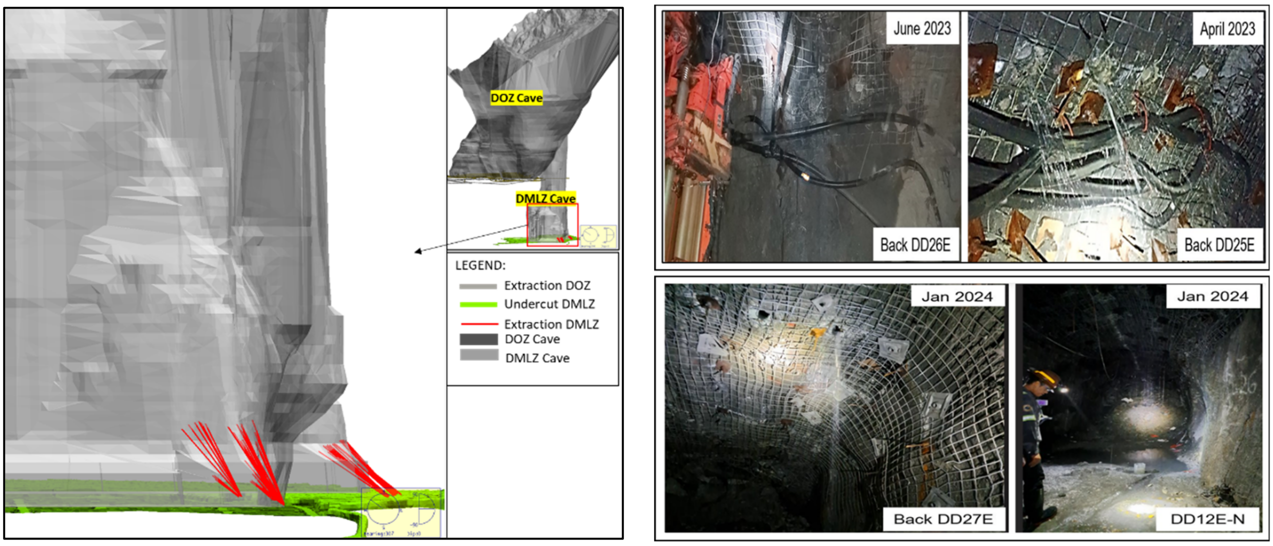
Table 2 Summary of the dewatering drilling process for the Deep Ore Zone extraction level

Hole ID	Location	Length (m)	Initial flow (l/s)
DD08W-N	DMLZ Undercut North	12–45	0.95
DD09W-N	DMLZ Undercut North	15–45	0.32
DD10E-N	DMLZ Undercut North	13–45	0.19
DD12E-N	DMLZ Undercut North	15–45	0.44
DD13E-N	DMLZ Undercut North	14–40	0.13
DD23W-N	DMLZ Undercut North	24–30	0.50
DD24E-N	DMLZ Undercut North	23–29	0.44
DD25W-N	DMLZ Undercut North	25–27	0.32
DD25E-N	DMLZ Undercut North	25–27	1.89
DD26E-N	DMLZ Undercut North	27–33	0.32
DD26W-N	DMLZ Undercut North	25–28	0.32
DD27E-N	DMLZ Undercut North	24–27	2.21

The estimated flow rate for each hole varied between 0.63 l/s and 1.89 l/s, and was determined by the underlying flow from J4-drift.

This project utilised a solo rig from the undercut level (Figure 13a). A solo rig was preferred due to the short length of holes, its fast drilling rate and its low cost. The total drilling for the project was 2,000 m and lasted about 20 days.

The project was successful, drilling from DD25E, DD24E and DD23W (undercut level), and intersected a significant amount of water (Figure 13b). As a result, PTFI was able to successfully reduce inflows observed for the drawpoint located directly underneath on the extraction level. The original flow rate of 8.39 l/s was greatly decreased to 2. /s through caveline drilling within one month of drilling at those sites (Figure 14). This effectively reduced the risk of wet muck.



(a) (b)

Figure 13 Caveline drilling: (a) Caveline drilling design; (b) Inspection and monitoring of caveline drilling site (2023–2024)

A

Panel	P#25		P#24		P#23	
D/P	W	E	W	E	W	E
1						
2	4.42	0	0.44	0.95	0.95	
3	0.06	0	0	0.63	0.95	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0.06	0	0	0	0

B

Panel	P#25		P#24		P#23	
D/P	W	E	W	E	W	E
1						
2	0.19	0.19	0.06	0.44	0.63	
3	0.19	0.06	0.19	0.76	0.13	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0.06	0	0	0	0

LEGEND:

- *High Discharge (>0.32 L/s)*
- *Low Discharge (0.06-0.32 L/s)*
- *Dry-Moist*

Figure 14 Diminished water flow following caveline drilling: (a) Water flow prior to caveline dewatering; (b) The diminished flow following caveline drilling

4 Result

4.1 Cave inflow implication

The connection between the DMLZ and overlaying DOZ cave in a high rainfall environment had substantial ramifications in regard to water management. By implementing proactive measures, both on the surface and underground, PTFI was able to mitigate these risks.

Advanced real-time monitoring systems were installed to more precisely and immediately detect changes in water flow. These systems used sensors and piezometers to quantify hydraulic pressure and subsurface water levels, furnishing vital data for prompt response and adaptation. Close and far-field dewatering drilling was carried out at selected locations around the mine at different elevations to efficiently manage and decrease groundwater and cave fracture flow.

Surface water diversion techniques were used to control the flow resulting from rainfall run-off and prevent it from entering the cave system. The diversion of surface water to specific drainage systems resulted in a substantial decrease in the amount of water entering the mining regions.

4.2 Wet muck management

The wet muck management solutions showed remarkable capability. The effective implementation of drawpoint water discharge and cave line drilling demonstrates proficient management of wet muck situations.

Although managing water infiltration following a DMLZ and DOZ cave breach is a complex operation, the occurrence of wet muck problems has been quite low. In 2019 the water flow reached a maximum rate of 0.32 l/s. There were 160 drawpoints completely dry, three that were slightly moist and 7 that were wet. There is a scarcity of documented occurrences of wet muck. In 2020 the water flow reached a rate of 0.28 l/s. During this time a total of 254 drawpoints were completely dry, 15 were slightly moist and 3 were wet. There is no recorded evidence of wet muck slides. In 2021 the water flow reached a maximum rate of 1.14 l/s, with a total of 321 dry, 18 moist and 9 wet drawpoints. Furthermore, there were two recorded instances of wet muck slides, although no harm or accidents resulted from these events. In 2022 the water flow reached a maximum of 4.92 l/s, along with a total of 341 dry drawpoints, 29 moist and 36 wet. Furthermore, there were six recorded occurrences of wet muck slide, however, no damage or incidents occurred as a result. In 2023 there was a significant increase in the water flow, reaching a level of 10.41 l/s. There 176 dry drawpoints, 53 moist and 41 wet. In addition there were four recorded cases of wet muck slide, however, no damage or incidents resulted from these episodes (Figure 15).

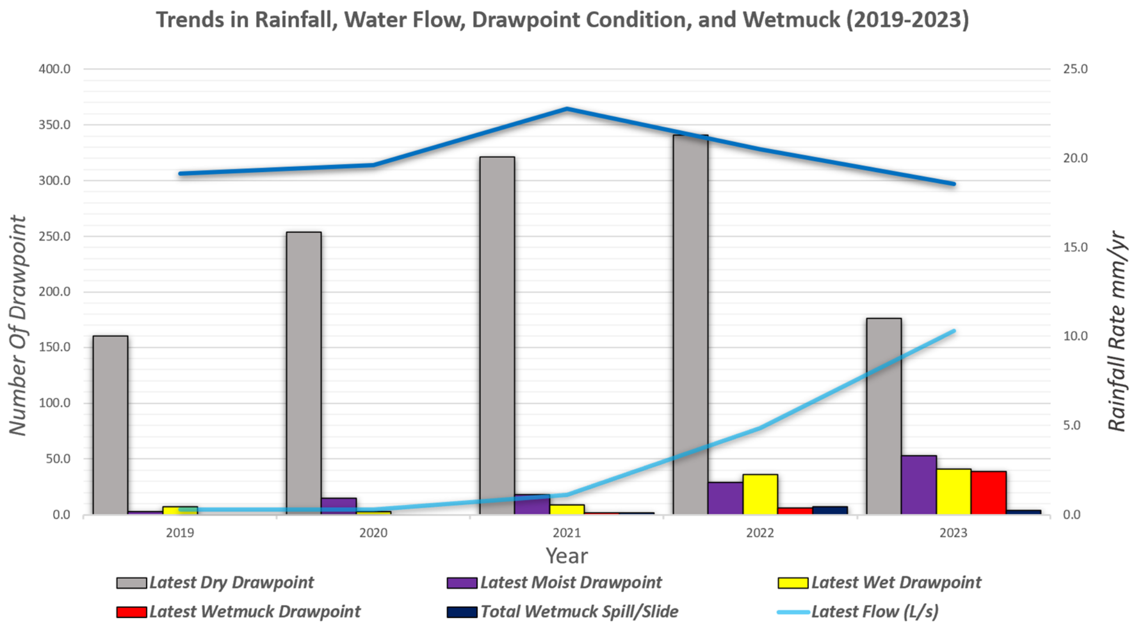


Figure 15 Trends in rainfall, water flow, drawpoint condition and wet muck (2019–2023)

4.3 Business interruption

The successful implementation of these water management strategies resulted in notable improvements in both safety and operational efficiency. The frequency of spills was negligible and there were no flooding events reported despite extremely large rainfall events, thus ensuring a safe and secure working environment.

The synergy of hydrologists, engineers and operations teams played a crucial role in upholding the integrity of the mining operations, guaranteeing the uninterrupted flow of business operations while prioritising safety and efficiency.

5 Conclusion

Utilising drilling techniques to manage water flow at the DOZ extraction level and DMLZ cave, along with surface water diversion, have demonstrated significant success in mitigating water infiltration in the DMLZ production area. Significant and prompt alterations in water flow were noticed as soon as the drilling was completed (far-field dewatering, cave line dewatering and targeted diversion drilling). This drilling and surface water diversion method effectively ensured that the overall water flow in the active production area remained below 31.55 l/s, even during periods of heavy rainfall.

Several important lessons were learned from this project. Early planning and coordination among hydrologists, engineers and operations teams proved crucial. Effective communication and collaboration helped in identifying potential water infiltration points and devising appropriate mitigation strategies. The adaptability of various drilling techniques was essential, with each method addressing specific challenges posed by the geological conditions and varying water infiltration rates. Implementing real-time monitoring systems was invaluable, allowing for continuous observation of water levels and flows, enabling timely adjustments to the dewatering strategies and ensuring immediate response to any changes in water infiltration. Additionally, the importance of surface water management cannot be overstated. Constructing and maintaining effective surface water diversion systems significantly reduced the amount of water entering the subsurface mining areas, especially during heavy rainfall. Continuous improvement and regular maintenance of the dewatering systems were essential, with regular inspections and updates ensuring optimal performance and longevity. Utilising data from real-time monitoring and historical records facilitated informed decision-making. The ability to analyse trends and predict potential issues allowed for proactive measures rather than reactive responses. Finally, balancing environmental considerations with operational needs was vital. The strategies implemented not only ensured the efficiency and safety of mining operations but also minimised environmental impact, promoting sustainable mining practices.

By incorporating these lessons learned, future projects can benefit from the experiences and strategies developed during the DOZ and DMLZ transition, ultimately enhancing the safety, efficiency and sustainability of underground mining operations.

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