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Subsidence backfilling operation of Padcal: a unique case in block caving

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Abstract

The Padcal Mine in Benguet, Philippines is one of the world's longest continuously operating block caves, having transitioned from open pit to underground caving in 1963, and operates under high rainfall, steep topography and thick unconsolidated overburden. Progressive cave growth under these conditions produced large subsidence craters, creating direct hydraulic and material connectivity between surface water, loose overburden and active drawpoints. This led to recurring mud rush events, drawpoint instability and loss of cave confinement.

Unlike conventional block cave operations that allow subsidence craters to evolve freely, Padcal has implemented a long-term strategy of systematic subsidence backfilling using waste rock to offset surface subsidence and control water infiltration. This paper documents how subsidence backfilling has been integrated with draw control and mud rush risk management in a mature, deepening cave.

Subsidence backfilling strategy, rainfall response and drawpoint behaviour are analysed to demonstrate how Padcal caving operations suppresses fines migration and stabilises cave flow to avoid catastrophic mud rush events.

The Padcal experience provides a rare, field-scale demonstration of engineered subsidence control in block caving and offers directly transferable guidance for caves operating in high rainfall or infrastructure-constrained environments.

Keywords: *block caving, subsidence management, crater backfilling, mud rush, draw control*

1 Introduction

Block caving is a highly efficient underground mass mining method (Laubscher 1994), yet it inherently induces failure and drawdown of the overlying rock mass, culminating in surface subsidence. In conventional block cave operations in arid environments or beneath competent capping rock, subsidence craters are typically fenced off and allowed to evolve freely (Brown 2003). However, the Padcal Mine presents a unique geomechanical and hydrological environment that renders this passive approach unviable.

Operating in a tropical climate characterised by extreme precipitation and typhoons (https://climateknowledgeportal.worldbank.org), Padcal's subsidence zone acts as a large-scale catchment. The resulting hydraulic connectivity between the surface crater and the active extraction level has historically driven catastrophic fines migration, resulting in drawpoint instability and mud rushes (Butcher et al. 2005). To counteract these phenomena, Padcal pioneered an engineered subsidence backfilling strategy. By systematically depositing waste rock into the subsidence crater, the mine creates a controlled geotechnical buffer to minimise surface water inflow into the subsidence crater thereby reducing infiltration into the muck pile. This paper outlines the methodology, mechanisms, and operational impacts of this

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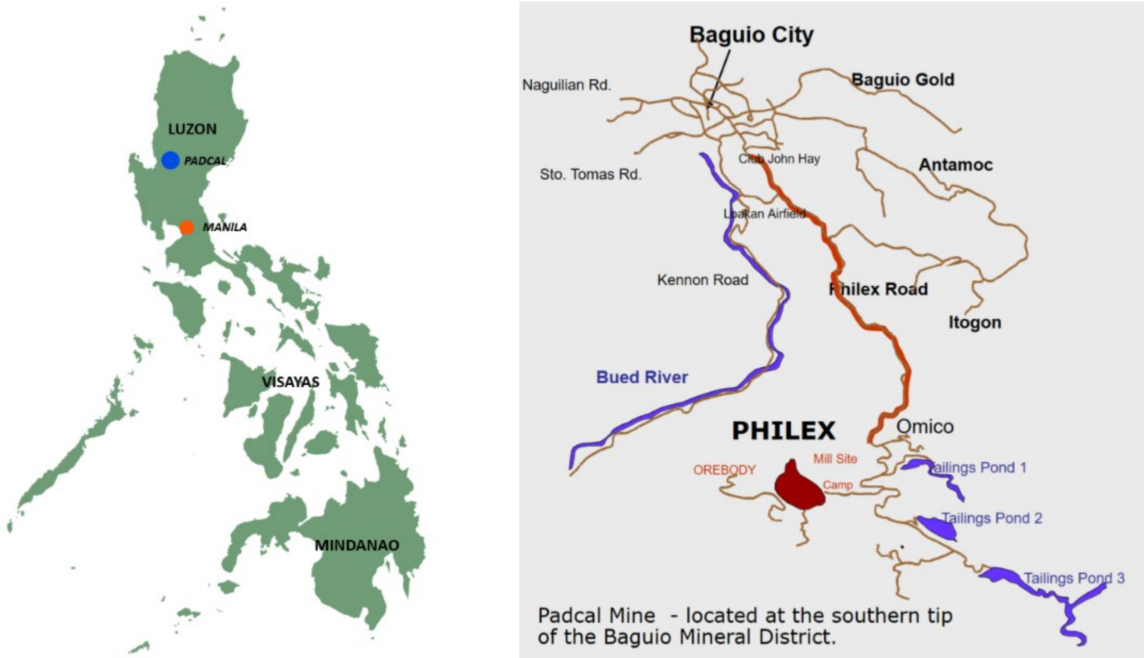
backfilling strategy, establishing a framework for managing subsidence in high rainfall, deep-lift caving environments.

2 Geologic and environmental setting

The Philippines is an archipelago situated in Southeast Asia, bound by the Philippine Sea to the east and the South China Sea to the west. The regional climate is a tropical monsoon system characterised by pronounced wet and dry seasons and significant annual precipitation due to its location in the equatorial region of the Northern Hemisphere and its exposure to the Pacific typhoon belt (https://www.pagasa.dost.gov.ph). The Padcal Mine is located within the Cordillera Central mountain range, straddling the municipalities of Tuba and Itogon in the Province of Benguet, Cordillera Administrative Region. Access to the mining site from Baguio City is provided via the 21 km-long, all-weather paved Kias-Philex provincial road (Figure 1).



(a) (b)

Figure 1 Geographical context of the Padcal operation. (a) National map of the Philippine archipelago highlighting the operation's location within the mountainous terrain of northern Luzon relative to the national capital, Manila. (b) Regional map of the southern Baguio Mineral District, detailing the primary logistical access routes

2.1 Topography and geography

The Padcal Mine is geographically situated within the Cordillera Central mountain range of northern Luzon, an area defined by heavily dissected, high-relief terrain. Surface elevations in the immediate mine vicinity average approximately 1,100 m above sea level. The pre-mining topography was characterised by steep, structurally controlled slopes, deep V-shaped ravines and narrow ridgelines. Historically, prior to the commencement of large-scale mining, the area was heavily logged for commercial sawmill operations. This deforestation, combined with the pronounced mountainous geomorphology, naturally drove a high-velocity dendritic drainage system, promoting rapid surface water run-off and minimising natural groundwater retention.

However, as the underground block caving operation matured and extraction deepened, the cave back ultimately propagated to the surface, resulting in breakthrough and continuous subsidence. The resulting macro-topographic depression entirely disrupted the natural topographical contours. Surrounded by steep catchments, this subsidence sink now intercepts vast volumes of regional run-off that would otherwise shed away from the site, fundamentally transforming the local geography into an artificial hydrological basin (Figure 2). Unmanaged, such macro-catchments in mature caving operations pose severe operational risks, as surface water rapidly infiltrates the fragmented rock mass and saturates the underlying cave column (Brown 2003; Butcher et al. 2000). To mitigate the catastrophic risk of water ponding and the subsequent inundation of extraction horizons, Padcal implemented a strategic engineering intervention, actively managing the subsidence crater to isolate surface waters from the cave column below.

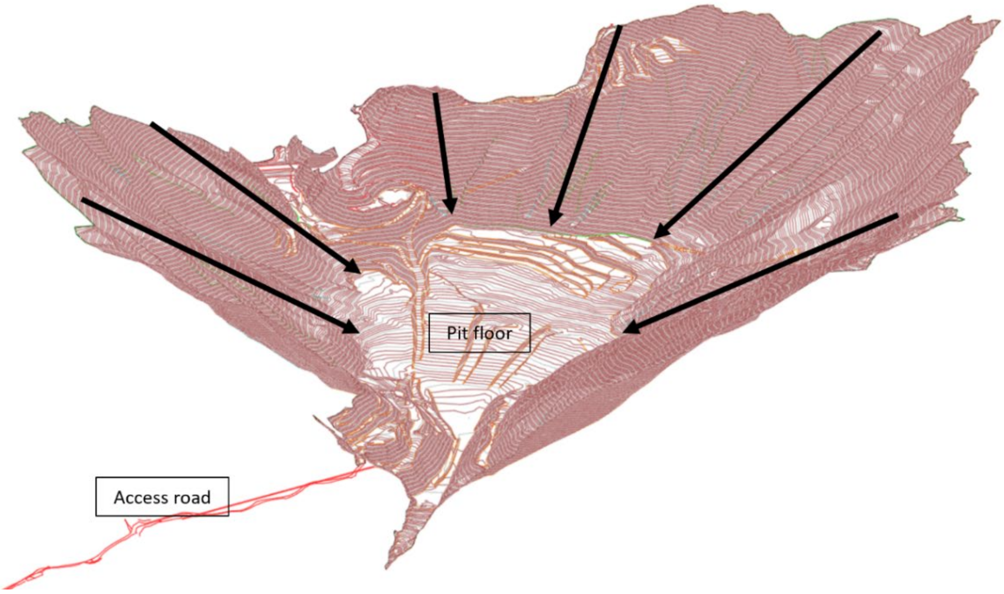


Figure 2 Current subsidence topography. Detailed view of the artificial hydrological basin created by continuous subsidence. The figure highlights the convergence of regional run-off towards the pit floor especially during high precipitation periods

2.2 Orebody geometry, geology and mining layout

The Padcal operation exploits the Sto. Tomas II orebody, a classic copper-gold porphyry system located within the southern Baguio Mineral District. Geometrically, the deposit manifests as a massive, sub-vertical pipe-like body measuring approximately 500 × 550 m laterally, with an established vertical extent of 730 m. Mineralisation is strongly structurally controlled by the northeast-trending Albian Fault system – a conjugate shear of the regional Philippine Fault Zone. The primary ore is hosted within a complex of heavily fractured, multi-phase diorite intrusions (dark and clear diorites) that were emplaced into the Palaeogene metavolcanics of the Zigzag-Pugo Formation (Figure 3).

From a rock mechanics perspective, the deeper extraction horizons of the diorite-hosted orebody exhibit moderate to high rock mass strengths, facilitating favourable and manageable caving fragmentation. Conversely, the upper structural domains and the overlying lithological capping have been subjected to intense meteoric weathering and epithermal alteration. This degradation has produced a thick, unconsolidated overburden heavily enriched in clays and fine particulate matter. In mature block caving environments, such expansive argillic zones represent a critical geomechanical hazard; when saturated by the surface water ingress, these fines rapidly lose shear strength and mobilise, forming the primary physical mechanism for catastrophic mud rushes and wet muck events at the active drawpoints (Jakubec 2008; Vallejos et al. 2017).

To exploit this geometry safely and economically, the operation uses the block caving mining method, supported by a continuous operational history dating back to 1958 when the mine transitioned from surface open pit extraction to an underground slusher-type block caving system using finger raises. Extraction has systematically advanced downwards through the mineralised footprint across successive horizons, progressing from the upper 1170 mining level (ML) and 1020 ML slusher levels to fully mechanised block caving operations introduced from the 908 ML downward to the 798 ML, 782 ML and 760 ML horizons. Production horizons use an El Teniente drawpoint layout design coupled with a post-undercutting strategy to optimise early production and load-haul-dump (LHD) loader efficiency. Under the current production schedule, the declared life of mine (LOM) for Padcal is projected to extend to 2028, systematically recovering remaining reserves through active block extensions at the 798 ML and sublevel extraction drifts at the 760 ML.

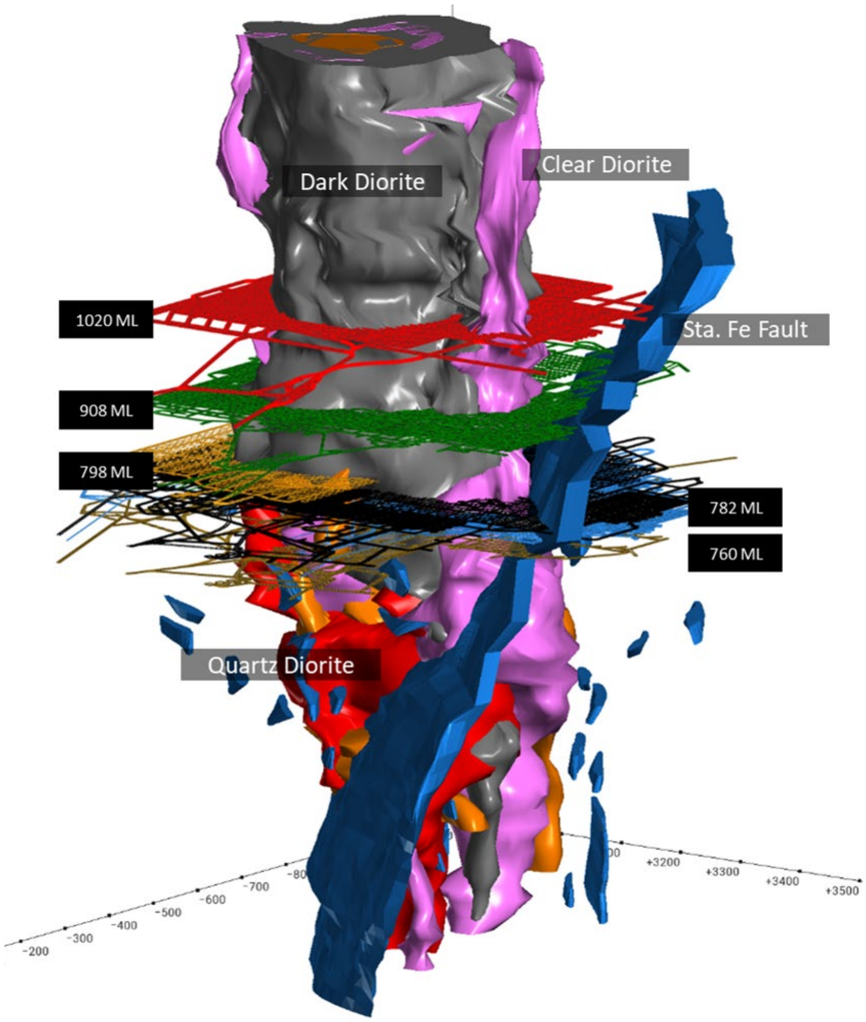


Figure 3 Three-dimensional isometric geological model of the Sto. Tomas II copper-gold porphyry deposit. The projection illustrates the sub-vertical, pipe-like geometry of the orebody, which spans approximately 500 m × 550 m laterally and extends 730 m in depth. The model delineates the multi-phase intrusive complex – highlighting the mineralised Dark Diorite and Clear Diorite phases – as well as the major, steeply dipping structural fault plane (blue) that dictates local rock mass behaviour and cave propagation

2.3 Climate

The climatic conditions at the Padcal operation represent one of the most extreme hydrological environments encountered in any active block cave globally. Situated within the Cordillera Central, the region is subjected to a protracted Southwest Monsoon (Habagat) season and high-frequency cyclonic events – on average, 20 cyclones per year originating from the Pacific typhoon belt. Consequently, the regional location of the Padcal site experiences intense and sustained meteoric recharge, with annual precipitation routinely exceeding 3,000–4,000 mm (https://www.pagasa.dost.gov.ph). This seasonal cycle brings sudden, extreme water inflows, frequently exceeding 1,000 mm of rain in a single month. While the main monsoon season runs from June to August, heavy rains often stretch as late as November (Figure 4). From a rock mechanics standpoint, this massive water saturation is the primary trigger for underground mud rushes, making engineered surface backfilling and drainage systems critical for safe operations. To quantify this environmental extreme, Table 1 contextualises the local precipitation metrics at Padcal against both the regional climatic baseline and the broader Philippine national average.

Beyond the baseline precipitation volumes, the hydrological risk at the Padcal operation is compounded by dynamic, macro-climatic processes unique to the Philippine archipelago. The site's mountainous topography is subjected to different weather systems, characterised by increasing inter-annual variability and a documented rise in severe cyclonic events. Table 2 outlines these primary climatic drivers and their recent historical trends, highlighting how shifting meteorological patterns continue to exacerbate the potential for rapid transient water ingress into the underground extraction horizons.

Table 1 Comparative average annual precipitation demonstrating the severe hydrological environment of the Padcal operation relative to regional and national baselines

Environmental baseline	Average annual rainfall (mm)	Primary data source
Philippine national average	2,348	World Bank Group (GFDRR) (https://climateknowledgeportal.worldbank.org)
Baguio City (Regional Normal)	3,824	PAGASA (1991–2020 Climatological Normals) (https://www.pagasa.dost.gov.ph)
Padcal Mine	4,500	Padcal Mine monitoring

Table 2 Major macro-climatic drivers and recent meteorological trends exacerbating the hydrological risks at the Padcal operation (data derived from https://climateknowledgeportal.worldbank.org)

Major climate processes	Impacts on climate
Northeast monsoon	Rainfall (November to February)
Southwest monsoon	Rainfall (June to August)
El Niño	Associated with droughts
Low pressure over Pacific or South China Sea	Tropical cyclones

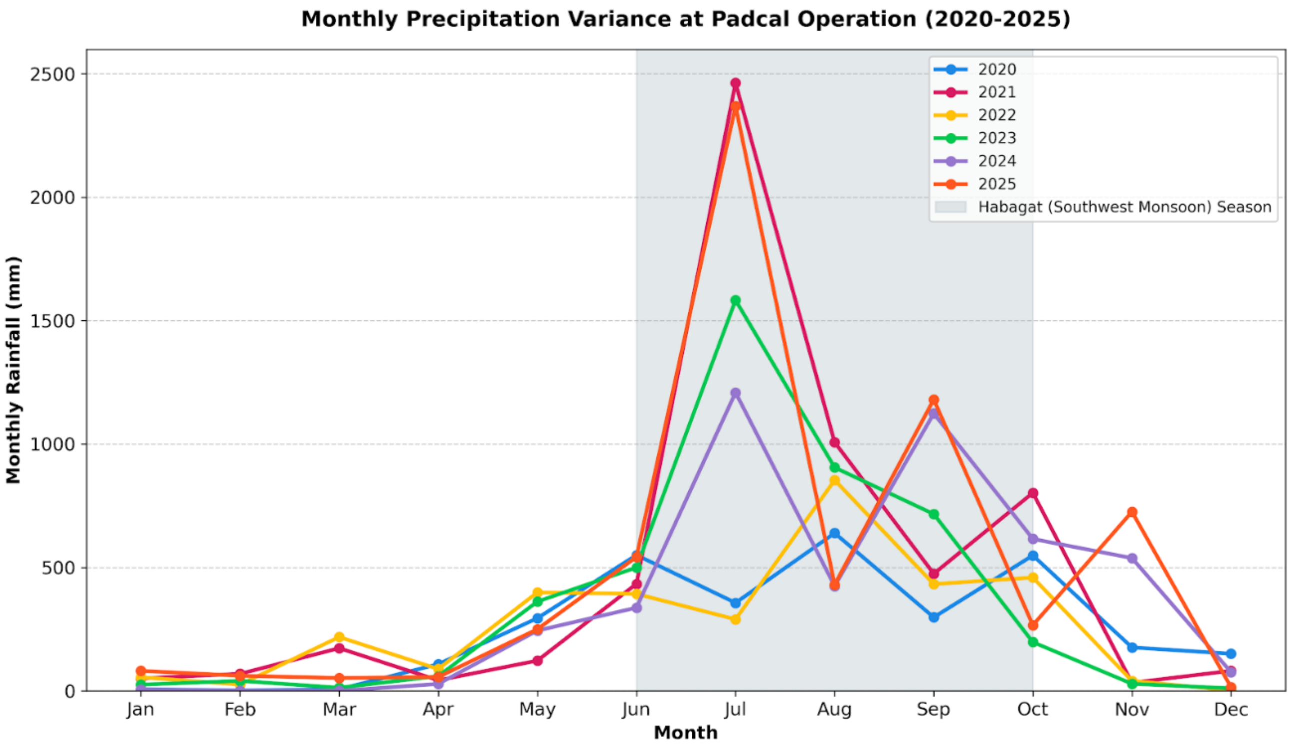


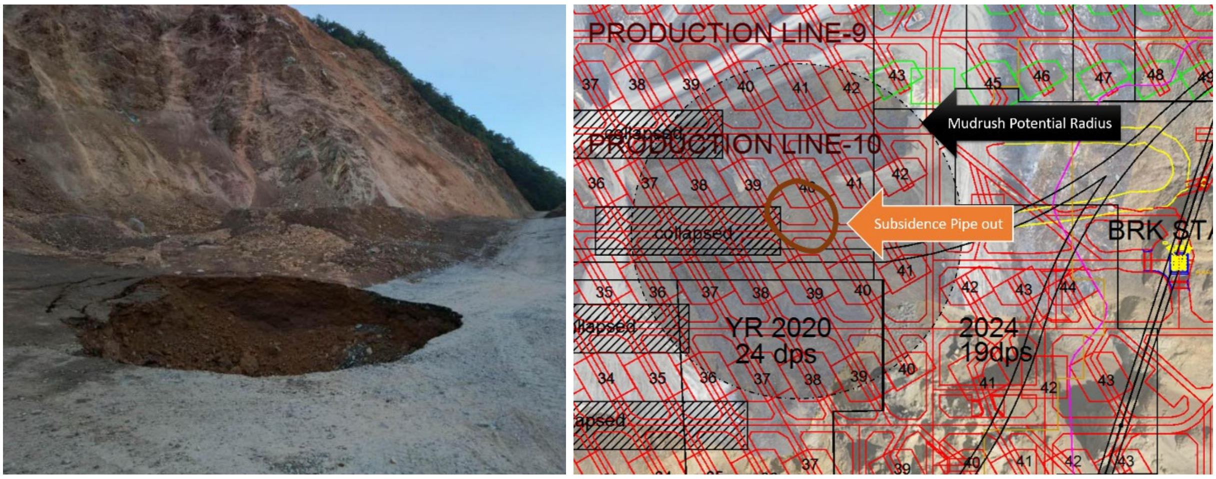
Figure 4 Multi-year analysis of monthly precipitation variance at the Padcal operation (2020–2025). The empirical data illustrates the extreme seasonal cyclicity and severe volumetric shock-loading driven by the protracted Southwest Monsoon (Habagat) season (June–August)

3 Draw control

Based on the monitoring data and field observations, mine management implemented a series of geotechnical interventions to mitigate the seismic risks, maximise ore extraction and recover the headings.

3.1 Mud rush and pipe-outs correlation

At the Padcal Mine, the occurrence of mud rushes – the sudden, uncontrolled ingress of saturated, fine-grained material – is intrinsically linked to the formation of 'pipe-outs', which are localised failure zones that establish a direct hydraulic and material connection between the surface subsidence crater and the extraction horizon. Empirical data collected in 2025 demonstrate a critical spatial correlation where surface pipe-outs typically manifest as mud rush events within a 50 m-radius danger zone on the extraction level or even more. In cases of any detection of a surface pipe-out, the immediate suspension of draw from all vertically coincident and adjacent drawpoints within the danger zone are mandated and will remain inactive until engineered backfilling is completed to restore the cave's filter bed and structural confinement (Figure 5).



(a) (b)

Figure 5 Spatial correlation between surface pipe-out and heightened underground mud rush risk area. (a) In situ photograph of an active surface pipe-out within the subsidence crater averaging 15 m depth, 6 m width, and 1,500 m^3 in volume based on 2025 data. (b) Vertical projection of pipe-out onto the extraction horizon, highlighting the 50 m high-risk radius which is subject as drawpoint cancellation zone

Analysis of the 2025 hydrological and geomechanical data reveals a pronounced temporal hysteresis between peak precipitation and severe inflow events. During the Southwest Monsoon (Habagat) season, which delivers maximum rainfall between July and August (sometimes lasting until November), immediate drawpoint manifestations are predominantly limited to low-severity mud rushes – widely recognised in caving literature as 'mud pushes' – which are classified on site as 'slight blowouts' (Figure 6). These minor events act as early indicators of increasing moisture content within the fragmented ore.

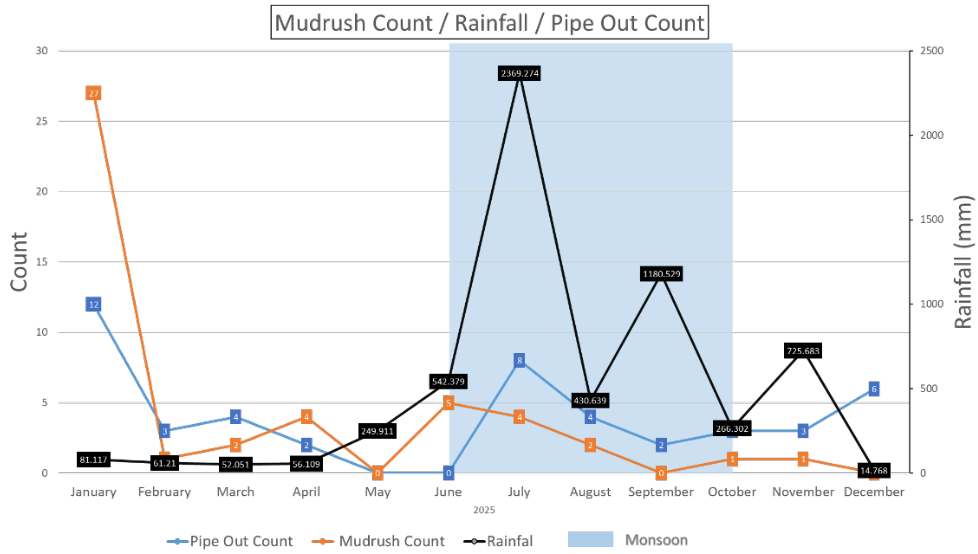


Figure 6 Temporal correlation between monthly rainfall and the frequency of inflow events (mud rushes and pipe-outs) at the Padcal Mine in 2025. The data illustrate the pronounced hydro-geomechanical lag between peak monsoon precipitation and maximum event severity

However, the data demonstrate a critical 2–3 month lag, with severe mud rushes and major pipe-outs peaking between October and January. This delay empirically quantifies the time required for meteoric water to percolate through the heterogeneous muck pile. As the water descends, it accumulates within flow-restricted, fines-rich zones, creating localised saturated 'plugs' that migrate towards the extraction horizon, often leaving unsaturated conditions above and below the ‘plug’ of water. The eventual fluidisation of the fines results in a delayed, but higher-severity, hazard profile.

Furthermore, operational observations indicate a significant latency in the vertical propagation of these hazards. Surface pipe-outs often take several days to manifest at the extraction horizon. This delay is attributed to complex internal arching and flow tortuosity within the caved rock mass, which can temporarily suspend liquefied material and mask the active hazard from underground personnel, reinforcing the need for predictive spatial modelling.

3.2 Draw control best practices

To mitigate the inherent risks of block cave instability and mud rushes, Padcal employs a rigorous, audit-based draw control protocol. This system transitions draw control from a simple grade-management tool into a primary geotechnical defence mechanism. By integrating real-time field observations with a dynamic database, the operation ensures that extraction rates are strictly aligned with the physical state of the muck pile.

3.2.1 Systematic audit and monitoring protocols

The cornerstone of Padcal’s strategy is a twice-daily audit of all active drawpoints. This standardised process ensures that every extraction point is evaluated against five critical geotechnical parameters. Data are captured using a standardised coding system (Table 3), which are then uploaded into the Drawpoint Condition Database to inform the subsequent shift’s draw orders.

Table 3 Standardised drawpoint condition classification parameters and their geomechanical significance

Parameter	Classification codes	Geotechnical significance
Moisture Content	D (dry), W (wet), DW (dripping), FW (flowing)	Primary indicator of saturation and mud rush potential
Fragmentation	F (fine), M (medium), C (coarse), VC (very coarse)	Assesses cave maturity and risk of ‘pipe-out’ or chimneying
Dilution	FR (fresh), SD/MD (slight/mod), HD (high), BO (brown)	Identifies ingress of waste or backfill material
Fluidisation	FL (significant fluidised ore)	Triggers immediate regulated draw or suspension of draw orders
Structural State	CB (concrete brow), DB (damaged), WC (constricted)	Evaluates the physical integrity of the extraction horizon

3.2.2 Data-driven decision support and technical mitigation

3.2.2.1 Moisture monitoring

Figure 7 illustrates an example of drawpoint moisture monitoring for a given area/block. Drawpoints exhibiting ‘flowing water’ (FW) or ‘fluidised ore’ (FL) are audited daily for immediate recommendation for temporary or even permanent cancelation to allow for pore-pressure dissipation but still varies depending on actual audit.

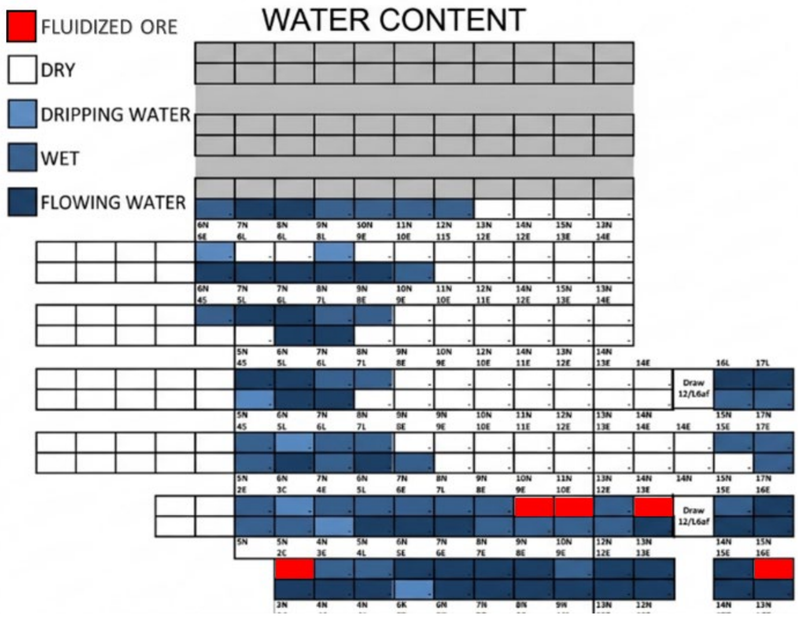
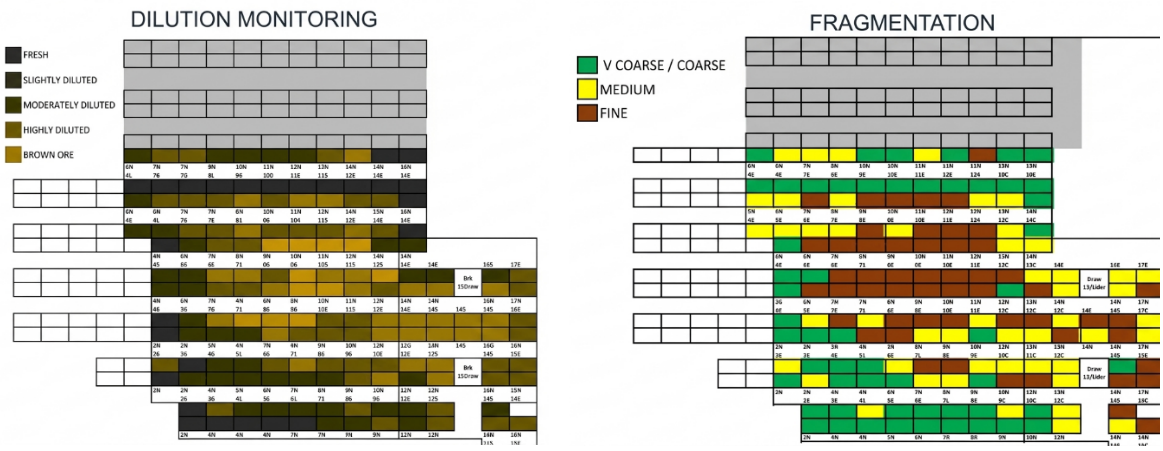


Figure 7 Example mapping of drawpoint water content. High-saturation zones (dark blue) and fluidised ore (red) are cross-referenced with surface hydrogeological data to identify critical periods of meteoric recharge and cave ingress

3.2.2.2 Mass balance and pipe-out prevention

To prevent isolated draw cones and differential displacement within the cave column, fragmentation and dilution data (Figure 8) are used to adjust draw profiles. A sudden influx of fine 'brown ore' (BO) signifies a direct connection to the subsidence zone, necessitating a draw suspension to restore local muck pile stability.



(a) (b)

Figure 8 Example distribution of (a) drawpoint dilution and (b) fragmentation. Fine-grained material (brown) indicates localised failure zones or 'pipe-outs' where vertical channels connect the surface directly to the extraction horizon

3.2.2.3 Subsidence management

The management of the subsidence zone is critical to maintaining underground stability. The integrated approach of backfilling to manage voids and direct surface run-off is explained further in Section 4.

4 Systematic subsidence backfilling strategy

To address the root cause of hydraulic and material connectivity within the cave, Padcal implements an active engineered backfilling strategy. The primary objective is to prevent the accumulation of water within the subsidence zone, thereby reducing the quantity of seepage through/saturation within the muck pile. Success is governed by four key effectiveness criteria: maintaining a −4% to −7% pit floor gradient, adhering to a 4:1 extraction-to-backfill mass ratio, ensuring zero water ponding and facilitating effective flow towards the main canal with minimal siltation as shown in Figure 9.

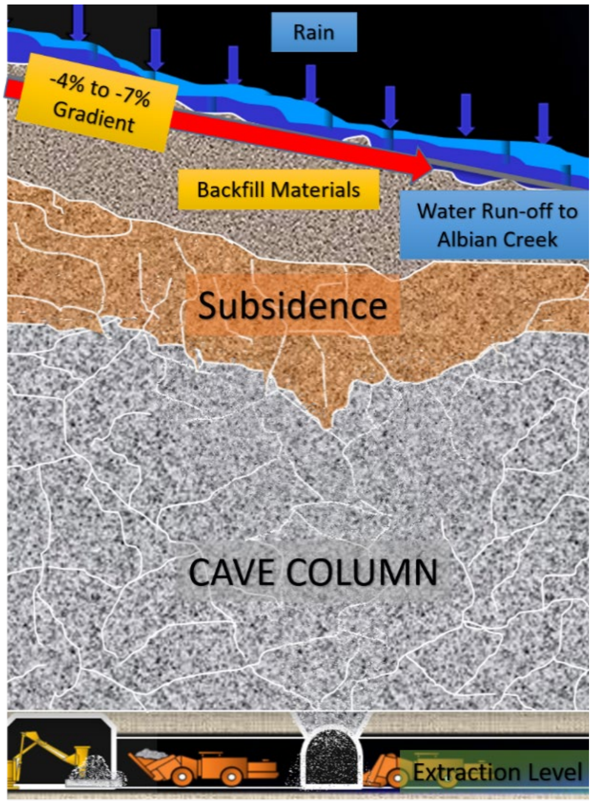


Figure 9 Conceptual cross-section of the systematic backfilling strategy at Padcal. The diagram illustrates the integration of the −4% to −7% engineered surface gradient for rapid surface run-off towards Albian Creek

4.1 Operational framework and equipment scaling

Backfilling execution follows a highly synchronised earthmoving strategy designed proportional to the underground draw rate. Padcal maintains a strict volumetric replacement ratio of 0.250 metric tonnes of surface backfill for every metric tonne of ore extracted. To sustain this balance, a dynamically scaled equipment fleet is used to navigate regional climatological constraints (Table 4).

Table 4 Seasonal fleet allocation and functional requirements for surface backfilling and drainage maintenance operations

Equipment type	Dry season	Wet season	Functional purpose
Dozer	5	4	Spreading, ripping and slope benching
Backhoe	4	3	Excavation from creeks and silt ponds
Dump Truck	12	10	Haulage (550–750 m optimised distance)
Loader	1	1	Unit loading and material handling
Grader	1	1	Precision floor profiling (−4% to −7%)
Compactor	1	1	Surface stabilisation and filter bed density

Materials are aggressively sourced from internal circular handling streams, including the deepening of discharge creek beds, mountain slope benching, eroded slopes ‘talus’ and road improvements. During dry months, accumulated sediments from the Subsidence Silt Pond and Albian Canal are dredged and hauled back to the pit floor to restore capacity before the monsoon.

4.2 Geotechnical and hydrological controls

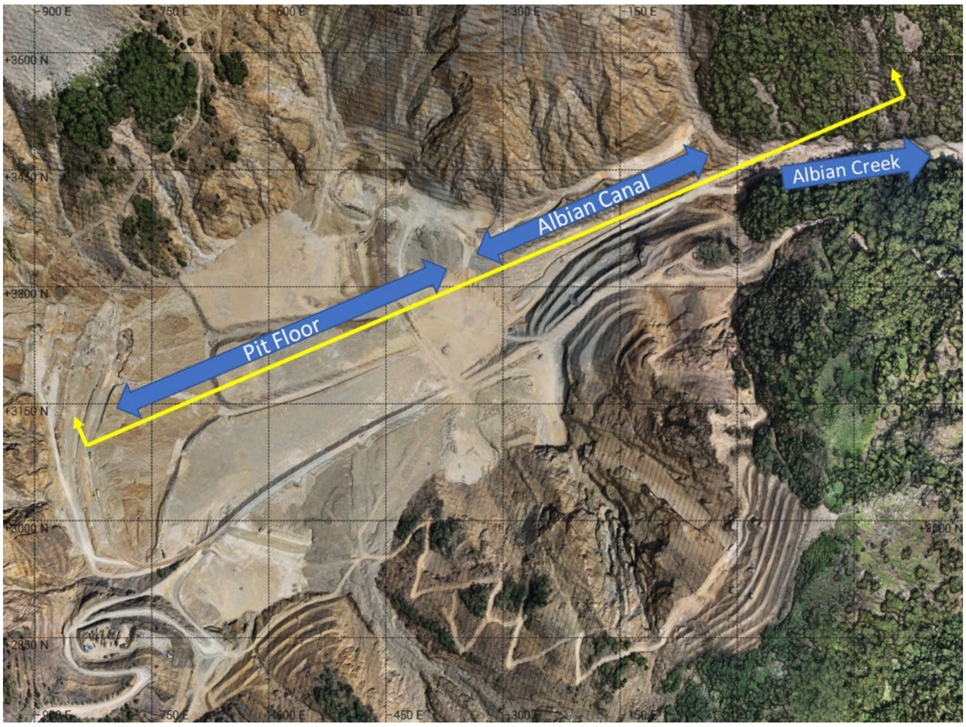
To maintain long-term geotechnical integrity, Padcal prioritises precision grading of the backfill surface to an engineered −4% to −7% gradient, effectively diverting run-off towards Albian Creek and away from the active cave footprint. This hydrological control is supported by rigorous seepage prevention, where surface cracks are sealed with backfill materials to inhibit vertical water migration. To prevent artificial damming and potential water outbursts, multi-disciplinary teams conduct regular ground and aerial inspections of discharge creeks to ensure they remain unobstructed. These physical interventions are validated by a strict monitoring and survey program, using annual topographic updates, monthly subsidence rate tracking via strategic post markers, and specialised surveys to identify localised ‘pipe-outs’ or depressions requiring immediate remediation.

5 Mine dewatering strategy

To effectively mitigate the risk of subsidence and underground flooding, Padcal has implemented two primary dewatering strategies. These measures are designed to control water-related hazards – such as mud rushes and tunnel inundation – thereby preventing operational disruptions and, most critically, ensuring the prevention of fatal incidents.

5.1 Subsidence canal maintenance

To effectively isolate the underlying cave column from the region's extreme precipitation, Padcal employs a topographical management protocol. The deposited backfill material is actively contoured to maintain a strict positive drainage gradient of −4° to −7°. This slope prevents localised ponding and ensures that meteoric run-off is rapidly shed away from the permeable subsidence zone. This controlled run-off is subsequently captured by a canal. Continuous topographic monitoring is implemented to guarantee this canal maintains a strictly lower elevation than the crater invert (pit floor), preventing capacity reduction or backflow. Once intercepted, the water discharges via gravity into Albian Creek, downstream of the mine's active subsidence footprint. The strategic alignment of this canal, relative to the evolving subsidence footprint and the engineered drainage gradients, is illustrated in Figure 10.



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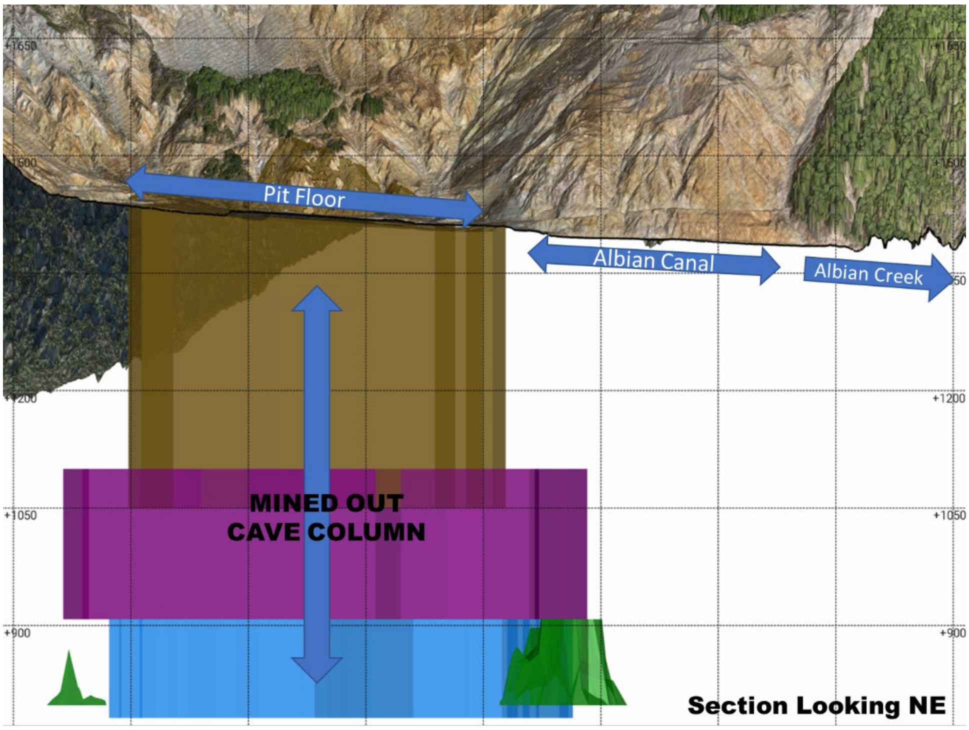

(b)

Figure 10 Longitudinal section of the subsidence management profile. (a) A plan view illustrating drainage flow path from pit floor, through Albian Canal and to Albian Creek. (b) Cross-section showing the actual −4° to −7° gradient, maintained to prevent water accumulation and ensure rapid meteoric discharge away from the cave column

5.2 745 ML underground drainage tunnel

Water from all underground openings is drained via strategically positioned drainage boreholes into dewatering drives, which are strictly maintained at a 0.5% negative gradient. These networks discharge into the mine's primary dewatering tunnel: the 745 m level (ML) drainage adit. Situated at the lowest elevation, this 4,000 m tunnel features a precise 0.2% gradient, establishing a massive, entirely gravity-fed dewatering capacity. This passive engineering design is highly strategic; it eliminates the reliance on mechanical pumping infrastructure, which is not only maintenance-intensive but vulnerable to typhoon-induced power failures.

Maintaining the hydraulic capacity of this gravity-drained system is critical, as percolating water continuously transports mobilised fines and debris into the network. To prevent flow restriction, the 745 ML adit undergoes routine desilting, and quarterly and monthly tunnel inspection during the extreme Southwest Monsoon (Habagat). This proactive maintenance sustains uninterrupted dewatering capacity. The massive scale of this underground inflow is quantified in Figure 11, which illustrates the direct correlation between annual surface precipitation and underground discharge rates at the 745 ML portal (2020–2025).

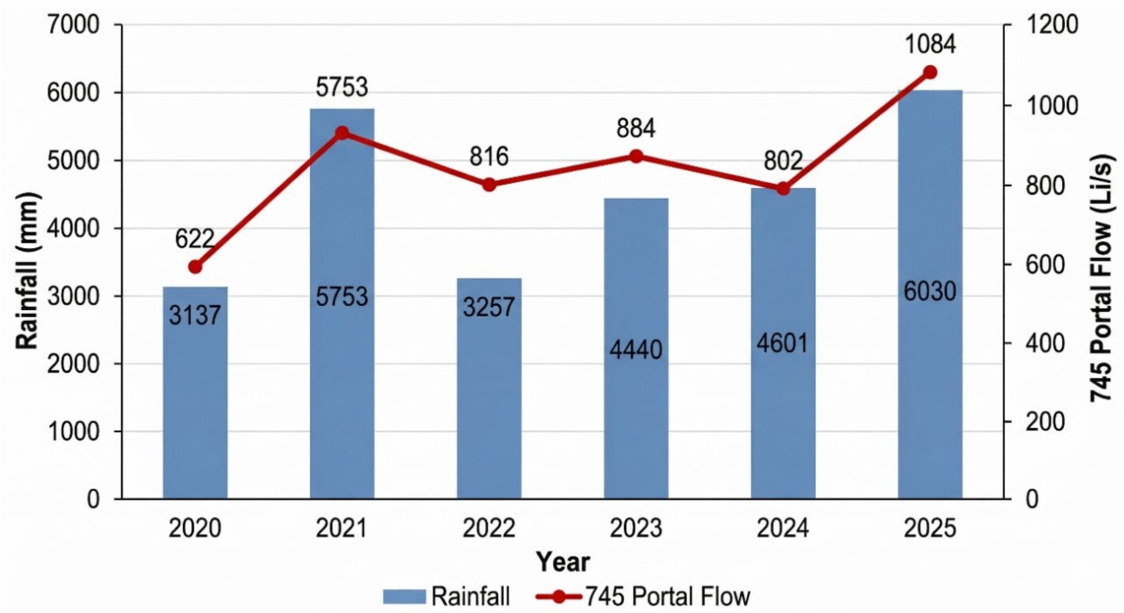

Figure 11 Hydrogeological correlation between annual surface precipitation (mm) and underground discharge rate at the 745 ML adit (L/s), 2020–2025. The data demonstrate the passive system's capacity to manage extreme meteoric recharge while highlighting critical periods of surface attenuation

6 Operational and socio-economic impacts

The systematic backfilling strategy has delivered three critical impacts: the mitigation of catastrophic mud rush events, the safe continuation of draw to maximise resource recovery, and the preservation of critical surface infrastructure traversing the subsidence zone. These impacts are discussed in the following subsections.

6.1 Mud rush control

The integration of systematic subsidence backfilling has yielded a demonstrable reduction in both the severity and frequency of mud rush events. While a lack of formal historical data from previous decades prevents a direct statistical comparison, accounts from senior personnel provide critical context. In the early stages of caving, the operation faced massive, sometimes fatal, mud rush events that caused major disruptions; these challenges served as the primary catalyst for developing the current backfilling strategy.

Today, by choking surface pipe-outs and promoting surface drainage from the subsidence zone, the infiltration of meteoric water has been heavily attenuated. The engineered backfill layer effectively increases the fluid residence time within the cave column, transforming hazardous, transient hydraulic surges into manageable, steady-state drainage at the extraction horizon. Although drawpoint blowouts are still experienced occasionally – particularly following the onset of the rainy season – the occurrence of massive, catastrophic mud rushes has been avoided. This results in significantly increased drawpoint availability and improved overall mine safety.

6.2 Dilution management and resource recovery

While subsidence backfilling provides essential hydrogeological stabilisation, it introduces a significant risk of early dilution if transported by preferential flow paths to the extraction level. In areas of high cave maturity, barren fines from surface backfill can migrate vertically to report prematurely to the extraction horizon, ultimately resulting in reduced resource recovery. Consequently, the primary objective of draw control at Padcal is to maintain a uniform draw profile to mitigate 'fingering' and prevent isolated pipe-outs, thereby maximising drawpoint life and ensuring the complete extraction of the ore reserve.

6.3 Surface infrastructure and social impact

The backfilling strategy also delivers a profound socio-economic benefit by preserving critical surface infrastructure. While backfill placement and grading are the primary tools for general subsidence management, mechanical compaction is also employed to stabilise critical surface infrastructure traversing the zone, which enables the maintenance of a vital transportation corridor directly traversing the active crater. This engineered thoroughfare is the primary public highway that connects isolated villages within the municipality of Tuba to the broader community and to the city of Baguio (Figure 12). By ensuring this road remains safe and passable despite the underlying caving, Padcal fulfils a critical environmental, social and governance (ESG) mandate, sustaining regional mobility and economic connectivity.

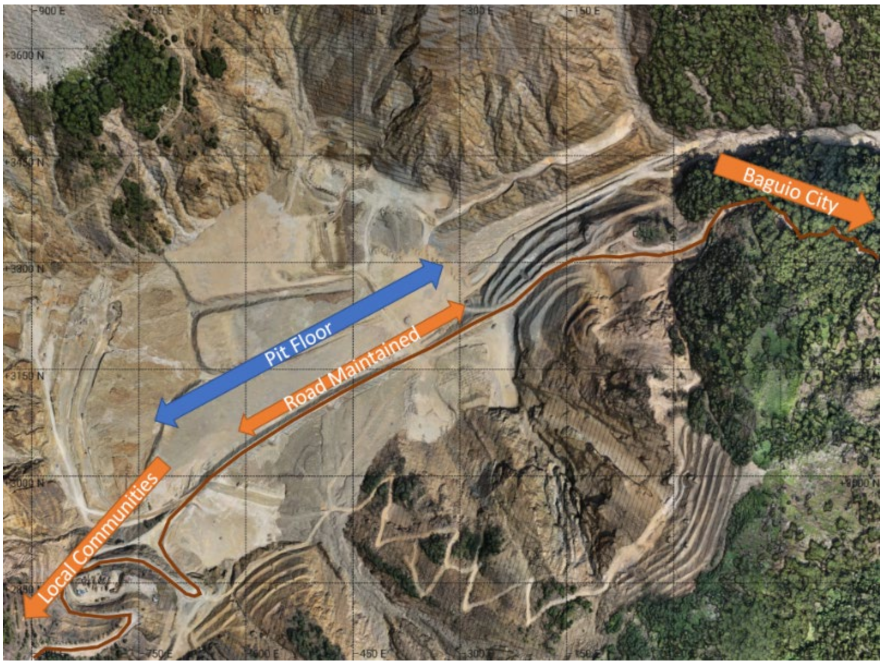

Figure 12 Surface view of the Padcal Mine subsidence pit floor and the actively maintained transportation corridor that provides continuous, all-weather access for both mine operations and the public

7 Conclusion

The six-decade operational history of the Padcal Mine demonstrates that subsidence backfilling can be used to limit underground inflow associated with a heavy precipitation environment and preclude catastrophic mud rush events. By systematically integrating waste rock backfilling with rigorous draw control, the operation has successfully established a buffer zone that suppresses fines migration and mitigates hydraulic connectivity between the surface crater and the extraction horizon.

The 2025 data confirm that while the Southwest Monsoon (Habagat) and associated tropical cyclones remain primary drivers of mud rush risk, the strategic infill of the subsidence zone effectively extends the lag time of inflow events and reduces their peak severity. This proactive management has been instrumental in preventing the catastrophic mud rush events experienced in the mine's earlier history. Ultimately, the Padcal operation represents a unique case study and provides a global benchmark for managing ‘wet’ block caves, proving that active surface management – specifically through reduction of infiltration and the buffering of inflows – is essential for sustaining production and safety as caving operations transition into deeper, higher-stress environments.

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