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Evolution of wet muck inflow risk management at El Teniente: lessons learned and current practices

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Abstract

The management of wet muck inflows at El Teniente underground operations has evolved significantly over the past three decades. This paper provides a historical review of risk management practices, consolidating lessons learned from wet muck inflow events and operational strategies for hazard mitigation.

The analysis is organised in three parts: an initial stage dominated by reactive actions following fatal accidents and large-scale inflow events; a second stage characterised by preventive closures; and a third stage focused on tele-operation, predictive models to estimate high-risk zones and guidelines for safe production.

The main aspects addressed include the development of risk classification frameworks, the introduction of predictive models to identify high-risk conditions, operational trials that supported the development of production guidelines and, finally, the current production management system used to mitigate personnel exposure.

Today these practices are an integral part of El Teniente's underground production system. They enable the recovery of previously restricted sectors and contribute in a sustained manner to the mine's overall output.

Keywords: *wet muck, inflow, caving operations, risk management, tele-operation, predictive modelling*

1 Introduction

Wet muck inflows represent one of the most persistent and high-consequence operational hazards in block caving mines. These events involve the sudden inflow of saturated fine material into production drifts, often with high momentum, which pose a safety hazard to personnel and infrastructure. Although wet muck behaviour has been documented in some caving operations worldwide, the long history of risk management at El Teniente, under a wide range of operational conditions, makes it a particularly valuable case for understanding the phenomenon.

Over the course of its operational history, inflow occurrences at El Teniente have caused equipment entrapment, damage to underground infrastructure and, in some cases, fatal accidents. Initial interpretations associated these events primarily with surface water accumulation and thaw-related infiltration. However, subsequent investigations demonstrated that the mechanisms governing wet muck behaviour are strongly influenced by internal cave dynamics, vertical connectivity between abandoned upper levels and active drawpoints, and disturbances induced by extraction. As such, the phenomenon cannot be adequately managed through surface-based interventions alone.

Over the last three decades, El Teniente has transitioned from reactive responses following large-magnitude inflows to a proactive risk-based operational framework. This evolution has included basin-scale hydrological assessments, geotechnical characterisation of fine material, identification of operational drivers such as extraction uniformity and draw-rate variability, tele-operated trials in high-risk sectors, the development of predictive tools and standardised planning guidelines. The combination of these elements now enables

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controlled extraction within sectors that were previously considered inoperable due to high wet muck hazard potential.

This paper presents a consolidated overview of the development, validation and implementation of the wet muck management system currently in use at El Teniente. Emphasis is placed on operational learning and the integration of empirical evidence, multi-parameter risk classification tools and tele-operation to minimise exposure while sustaining production operation. The aim is to provide a reference for caving operations based on operational experience, highlighting practices that have demonstrated effectiveness on industrial scale.

2 Background and problem definition

The occurrence of wet muck inflows at El Teniente has been documented for more than three decades and remains one of the most disruptive underground mining hazards. The phenomenon is characterised by the sudden release of saturated fine material through drawpoints, often mobilised with enough energy to inundate production, haulage and service drifts, block access routes, and damage equipment and infrastructure. Historically, these events have generated high-consequence impacts, including five fatal accidents in the late 1980s, 1990s and 2000s, which prompted extensive investigations and operational responses across the mine.

In the 1980s and 1990s, wet muck inflows were primarily interpreted as the result of surface water infiltration, snowmelt and ponding above the cave (Codelco 1989, 2008). This assumption guided much of the initial risk management approach, with mitigation efforts focused on surface drainage, containment structures and monitoring of cave-induced subsidence depressions. Later, however, detailed reconstructions of major inflow events revealed that these events were not only governed by preferential flow paths. Instead, internal cave geometry, pre-existing excavations in abandoned upper levels and the presence of highly saturated fine material within the cave column played key roles in driving the behaviour.

As production expanded into deeper mines, several operational patterns emerged. Inflow events tended to occur in areas with:

- vertical connectivity to upper abandoned mines
- A high proportion of broken, fine-grained ore
- localised water inflows not correlated with surface events
- extraction sequences that produced uneven draw between adjacent drawpoints.

These observations revealed a critical limitation in the original conceptual model: wet muck was not simply a hydraulic or surface-driven issue, but a coupled geomechanical-hydraulic process influenced by internal cave dynamics and operational decision-making. Addressing the hazard therefore required a shift from surface-oriented mitigation to an integrated framework based on underground characterisation, operational discipline and predictive assessment.

Figure 1 provides the temporal evolution of wet muck inflow incidents. It indicates that although the number of recorded events has increased markedly in recent years, the spatial extent of individual inflows has progressively decreased. Recent events typically affected 9 m average lengths from 2022 to 2025, compared with those documented from 1989 to 2021 affecting 41 m average lengths, in line with the evolution of wet muck production management practices.

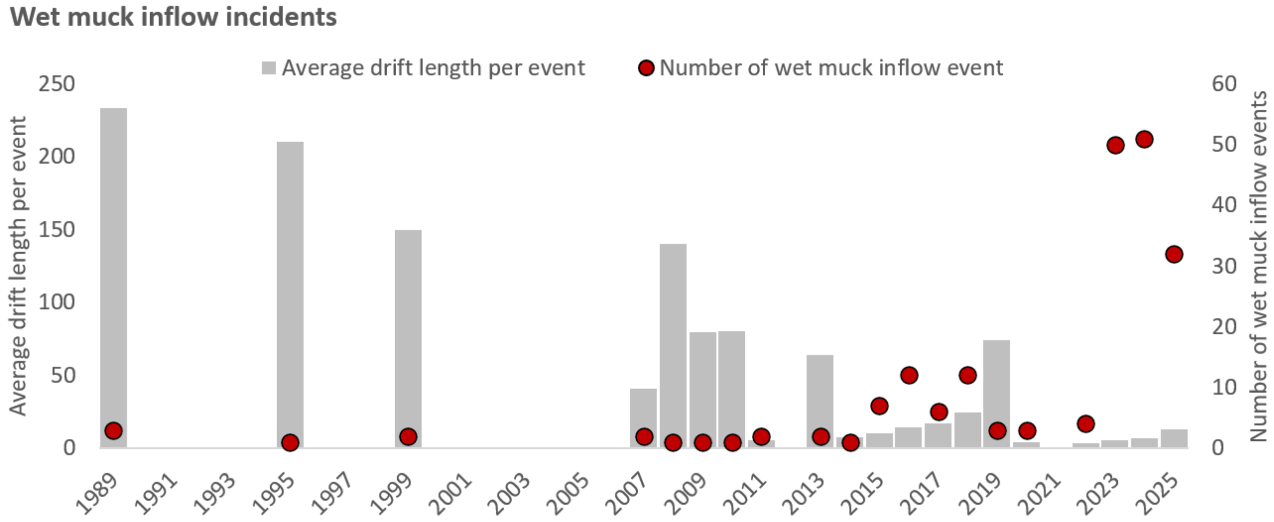

Figure 1 Length of drifts covered by wet muck inflows from 1989 to 2025

3 Early operational challenges

During the initial period of documented wet muck activity, inflow events were generally treated as isolated operational incidents, and management efforts focused on addressing visible surface conditions rather than internal cave processes. In the 1990s, production areas located beneath surface-scale geometric singularities, as localised depressions and water pooling, were identified and characterised accordingly, reflecting the prevailing interpretation of wet muck inflows as a surface-driven phenomenon as shown in Figure 2. This interpretation was supported by documented instances of rapid surface pool drawdown coincident with inflow events, providing evidence of a hydraulic connection between surface water accumulation and the cave (Codelco 2008). Control measures implemented during this period included drainage and water diversion works, the monitoring of subsidence-related depressions and, in several cases, the filling or partial infilling of surface singularities to reduce water accumulation and infiltration above the cave footprint. Figure 3 shows an example of water accumulation in a crater depression, together with a plan view identifying the hazard zone for mud inflow in relation to the projected footprint of the underground mine.

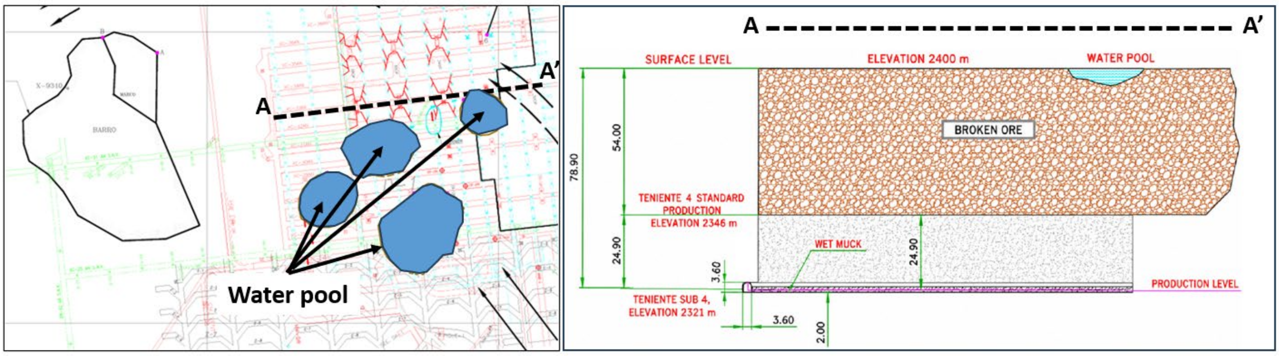

Figure 2 Example of production areas located beneath geometric singularities at surface at Ten Sub4 mine (1995)

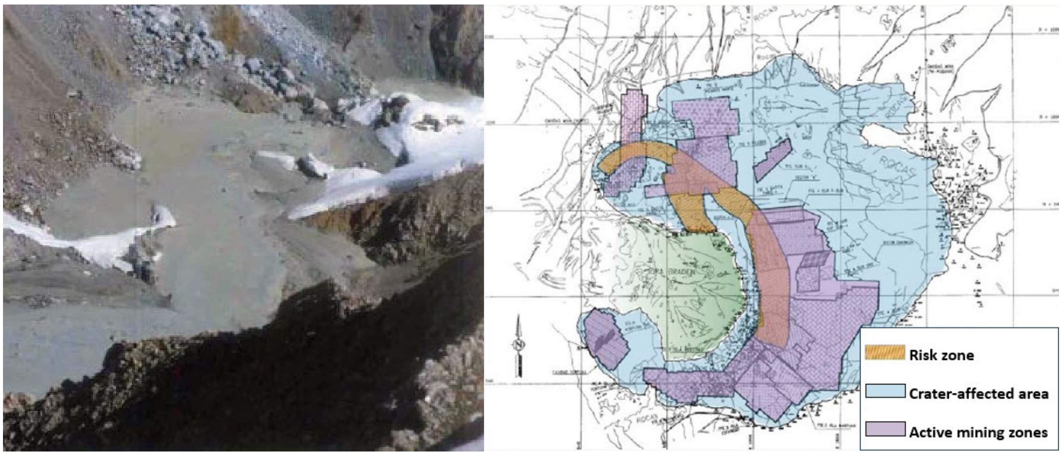

Figure 3 Example of surface water accumulation above the cave footprint and corresponding identification of the risk zone and underlying production areas (1995)

3.1 Reinforced use of underground controls and area restrictions following the 2007 accident

The fatal wet muck inflow accident that occurred in 2007 at Regimiento mine (Ten 4 Reg) marked a turning point in the understanding and management of the phenomenon at El Teniente, as it was not directly associated with surface water accumulation or surface geometry. Unlike most previous inflow events, which occurred at short vertical distances to surface (generally less than 100 m) and were commonly linked to direct surface connectivity, the 2007 accident took place at a vertical distance of approximately 449 m from surface.

No surface water pools or distinct crater depression were identified above the inflow location. However, increased moisture conditions were observed in Regimiento mine drawpoints following the abandonment of the Isla mine. This suggests that internal water flow paths within the cave were modified. The proposed mechanism is that fine material was supplied by the broken ore mass associated with the abandoned Brechas level, while the redistribution of water was driven by the cessation of extraction at Isla LHD level, promoting the development of internal flow paths and ultimately enabling the inflow event, as illustrated in Figure 4.

As a result, management efforts began to shift from predominantly surface-based controls towards measures focused on underground conditions and operational practices. These early controls included stricter restrictions to affected areas, increased emphasis on drawpoint closures and isolation, and the introduction of more conservative extraction practices in zones identified as susceptible to internal wet muck mobilisation.

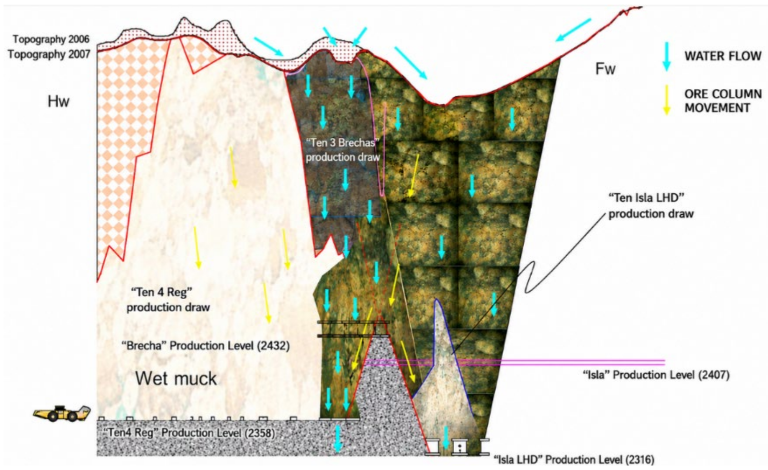

Figure 4 Conceptual hypothesis of the wet muck inflow mechanism associated with the 2007 fatal accident. Fine material was supplied by the broken ore mass of the Brechas level, and the redistribution of water was driven by the cessation of extraction at Isla load–haul–dump level, promoting the development of internal flow paths and enabling the inflow event at Regimiento mine

4 Risk management through drawpoint closure and risk identification

During the first half of the 2010s, as wet muck inflow conditions became more widespread across several production mines, operational management at El Teniente was increasingly characterised by conservative control measures focused on risk identification and exposure reduction by drawpoints closure. Affected areas were assessed using qualitative and semi-quantitative risk characterisation tools, commonly structured through criticality matrices that incorporated standardised observed moisture conditions by systematic inspections.

Based on this risk characterisation, implemented through the criticality matrix (Codelco 2016) shown in Figure 5, drawpoints identified as high risk were generally closed, either temporarily or permanently; thus becoming the principal control to prevent personnel exposure and uncontrolled inflow development. Drawpoints with wet muck were operated under 'limited' operational class (yellow and red colours in Figure 5), while drawpoints affected by wet muck inflow events were closed.

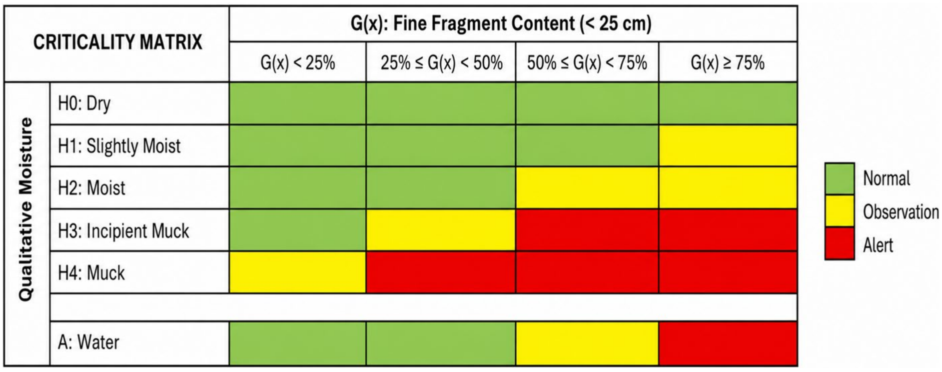

Figure 5 Criticality matrix used to qualitatively assess wet muck risk based on moisture condition and fine material content. Colour coding indicates normal (green), observation (yellow) and alert (red) conditions, supporting drawpoint classification and operational decision-making

This approach represents a shift from pre-2007 practices, where hazard assessments were primarily based on crater local depressions and water pooling, under the assumption that wet muck inflows were directly controlled by surface water accumulation. Following the 2007 fatal accident, greater emphasis was placed on direct observations at the drawpoints, recognising that surface conditions alone may not adequately indicate the location or likelihood of inflow events within the underground mine.

To support this approach, a multidisciplinary risk management committee was established, integrating operational, engineering, planning and safety perspectives to periodically review risk conditions and oversee the investigation of wet muck events and the definition of associated corrective actions and guidelines.

In parallel, routine monitoring of cave behaviour and surface flow conditions was maintained, providing key inputs for planning decisions, including constraints on mine planning through a reduction in the extractable reserve envelope.

4.1 Studies on material characterisation and physical mechanisms enabling wet muck failure

As wet muck conditions became more prevalent across multiple production sectors, a series of technical studies were undertaken to improve the understanding of the material behaviour associated with wet muck inflow events. These studies focused on the characterisation of the broken ore, particularly the fine fraction, and on the identification of the physical mechanisms governing its mobilisation under saturated conditions. This work was developed progressively, as part of the accumulated operational learning documented in the lessons-learned process, and not as a direct outcome of individual inflow investigations.

Material characterisation efforts highlighted the critical role of fine material content and moisture state in governing wet muck behaviour. Observations and test results indicated that as the proportion of fines increased and saturation levels rose, the broken ore exhibited a transition from gravity-driven granular flow to a behaviour dominated by undrained conditions, where pore water pressure played a central role in reducing effective stress and material strength (Castro et al. 2017). This condition promoted static liquefaction, resulting in a flow failure once local confinement was lost. Under these conditions, extraction-induced disturbances play a central role, where changes in draw rate, draw imbalance or localised loss of confinement associated with extraction can trigger rapid downward mobilisation of saturated fine material, resulting in high-mobility wet muck inflows. This interpretation is consistent with most analysed events, which typically occur during active extraction or immediately following extraction activities.

These findings provided a physical basis for differentiating material states and for supporting subsequent developments in risk classification, planning constraints and the formulation of operational and planning guidelines. Importantly, the focus of these studies was not to eliminate wet muck behaviour, but to understand the conditions under which it transitions from stable extraction to uncontrolled mobilisation.

4.2 Identification of operational triggers for wet muck inflow

Overall, these observations confirm that wet muck inflow is a multivariable phenomenon. While extraction-related disturbances act as the immediate trigger defining the timing of events, inflow occurrence depends on the concurrent presence of unfavourable material conditions, elevated moisture content, high fines content, and internal cave geometry and connectivity. Wet muck inflows therefore result from the interaction between operational disturbances and pre-existing geological and hydromechanical conditions, rather than from any single controlling factor.

As part of the progressive formalisation of operational controls, draw rate emerged as a key variable requiring standardisation in wet muck-prone areas. Operational experience showed that uncontrolled or highly variable draw rates increased the likelihood of triggering wet muck inflow events, particularly under conditions where saturated fine material was present within the broken column (Codelco 2019). In response, explicit draw rate limits were defined for areas where extraction continued with onboard LHD operators, with the aim of reducing the magnitude of extraction-induced disturbances during active draw in areas with identified risk. These controls primarily involved capping the maximum draw rate while also imposing operational continuity requirements, whereby each drawpoint was to be extracted within a defined time interval (typically every three days). In practice, this established an indirect lower bound on draw, ensuring both controlled extraction rates and consistent drawpoint activity. In parallel, the abandonment sequence was actively managed to avoid isolated draw, maintaining production only in drawpoints with at least three active neighbouring drawpoints.

5 Managing wet muck risk through remote operation

This section describes the practical implementation of remote operation as the primary control for managing wet muck inflow risk. It presents the progressive validation of this approach through industrial trials, the role of modelling as a decision–support tool and the development of the current wet muck management system. Emphasis is placed on how these elements were integrated to enable controlled extraction under wet muck conditions while eliminating direct personnel exposure.

5.1 Diablo Regimiento: industrial trials

The first large-scale industrial application of the wet muck management approach was conducted in the Diablo Regimiento mine, which provided a controlled environment to validate operational concepts derived from accumulated learning. This sector presented extensive wet muck conditions, a history of inflow events and abandoned reserves, and strong internal connectivity within the cave column, making it a representative test case for evaluating new extraction strategies under wet muck risk.

The trial production area was located within a sector previously abandoned due to wet muck conditions, with approximately 88% of the area classified as ‘alert’ and the remaining 12% as ‘Observation’, according to the criticality matrix shown in Figure 5. In addition, the nearest active extraction areas were located at least 400 m away, effectively defining an isolated production quadrant. The trials were designed to assess whether extraction could be safely resumed under wet muck conditions by eliminating direct personnel exposure and applying disciplined operational controls. Extraction was conducted exclusively using remotely operated LHDs, allowing production to continue while accepting the potential occurrence of wet muck inflow as an inherent system response. Operational rules developed during earlier stages – such as draw rate control, coordinated extraction and access restrictions – were applied and observed under real production conditions.

Trial production initially commenced in quadrants 1 to 4 (Figure 6); however, due to the use of a single LHD, maintaining continuity across all areas proved difficult and the trial was reduced to quadrants 1 and 2. After eight months, six inflows occurred; the last burying the LHD and resulting in a five-month suspension. Following resumption, only three events occurred over 17 months, indicating that production in a smaller, well-utilised area reduces inflow frequency.

Figure 6 Diablo Regimiento trial area

A total of nine inflow events were recorded, with an average distance of 46 m on the drift. Notably, all events originated from only three drawpoints, indicating a higher likelihood of recurrence in previously affected drawpoints.

An 8-hour daily no-extraction period was implemented for re-entry activities, with all events occurring either during active extraction or within this window. This confirmed that an 8-hour exclusion period was adequate.

The trials confirmed that wet muck expression could not be fully prevented under certain material and hydraulic conditions, particularly in drawpoints classified as 'Alert' in Figure 5, which were characterised by high fine content and elevated qualitative moisture levels. However, its consequences could be managed through the removal of operators from the production level.

From an operational perspective, the Diablo Regimiento trials demonstrated that controlled extraction under wet muck conditions was technically feasible. Exposure was eliminated and operational discipline was maintained. While production rates during the initial trial phase were lower than in conventional sectors, the experience generated critical operational data and confidence in the control framework. These lessons directly informed the subsequent scale up of the wet muck management system and its integration into routine production planning.

5.2 Development of a predictive models for wet muck inflow risk

Based on the accumulated operational experience and the identification of key material and operational variables, a statistical predictive model was developed to estimate the likelihood of wet muck inflow occurrence. The model is based on a multivariable formulation that integrates operational parameters, material condition indicators and spatial attributes of the cave system, providing a probabilistic risk score at drawpoint, using a logistic regression method (Castro et al. 2025).

Model parameters were calibrated against the historical record of wet muck inflow events in the underground mine. The predictive model integrates variables from multiple sources, including operational data and simulation outputs, providing a probabilistic estimate of inflow occurrence at the drawpoint level based on a multivariable logistic regression framework. Risk categories are defined by applying cut-off thresholds to the model outputs, allowing the probabilistic results to be translated into operational controls. Granulometry and lithology are derived from flow and fragmentation simulations, while moisture represents the only parameter measured directly in the field. The variables and data sources considered in the predictive model are summarised in Figure 7, grouped into four main categories: historical draw parameters, fragmentation and lithology, water and wet muck conditions, and surface topography.

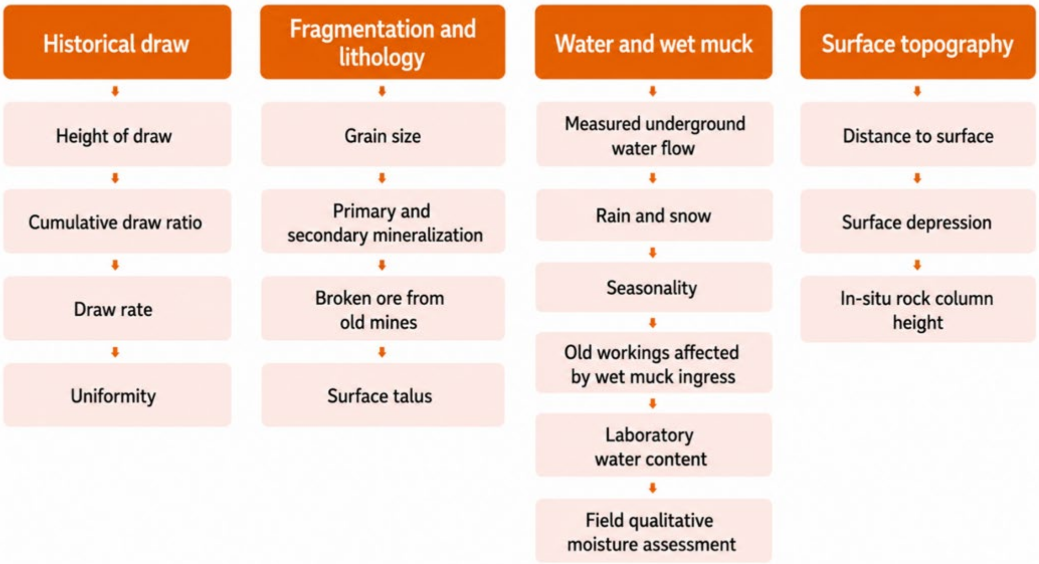

Figure 7 Schematic classification of variables evaluated to develop and calibrate the predictive model for wet muck inflow risk assessment

5.3 Operational guidelines and multisector implementation

The current wet muck management system (Codelco 2021, 2024) integrates the outcomes of industrial trials and predictive modelling into a structured control framework. The system combines spatial wet muck control polygons, risk-informed planning criteria using predictive models and remote extraction as the primary control, enabling consistent decision-making and controlled production in areas affected by persistent wet muck risk.

Remote operation constitutes the primary control measure for managing the consequences of wet muck inflow. By removing operators from the production level, this approach decouples personnel safety from inflow occurrence, allowing controlled extraction to proceed in areas affected by persistent wet muck conditions, even where inflow manifestation cannot be prevented. Examples of the remote operation infrastructure and field implementation are presented in Figure 8, illustrating both the physical isolation of production areas and the control systems used to operate LHDs from a remote control room.

Figure 8 Personnel barriers and remote production at integrated operations centre

Operational trials showed that extraction-induced disturbances play a central role in triggering wet muck events. Consequently, stabilisation periods were introduced as a mandatory component of the extraction cycle. These periods allow stress redistribution and pore pressure dissipation within the broken column following extraction or secondary breakage activities.

Isolation distances were defined to limit potential exposure to the maximum spatial extent of historically observed wet muck events. Rather than applying uniform isolation across entire panels, isolation strategies evolved towards focused zoning tied to drawpoint-level inflow risk ratings, allowing exclusion areas to be selectively defined around high-risk drawpoints.

Wet muck risk management elements include:

- identification of high-risk drawpoints using a predictive model (Figure 9)
- definition of isolation distances based on an empirical event reach in each sector (Figure 10)
- dynamic adjustment of isolation according to operational triggers i.e. extraction and hang-up removal defined as disturbance
- stabilisation periods after disturbance at high-risk drawpoints (Figure 11).

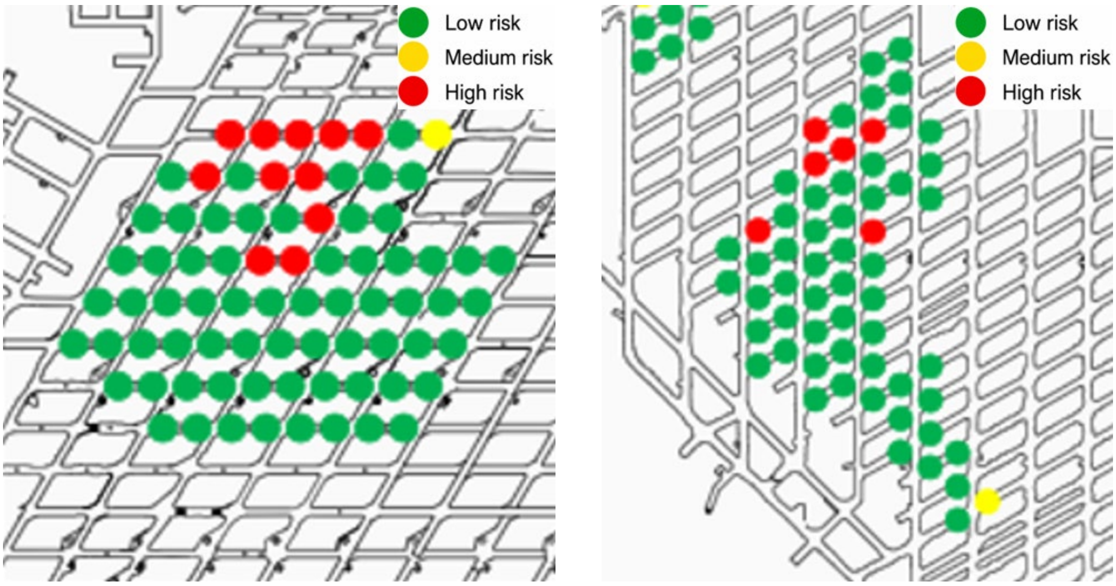

Figure 9 Example of predictive modelling classification for drawpoints

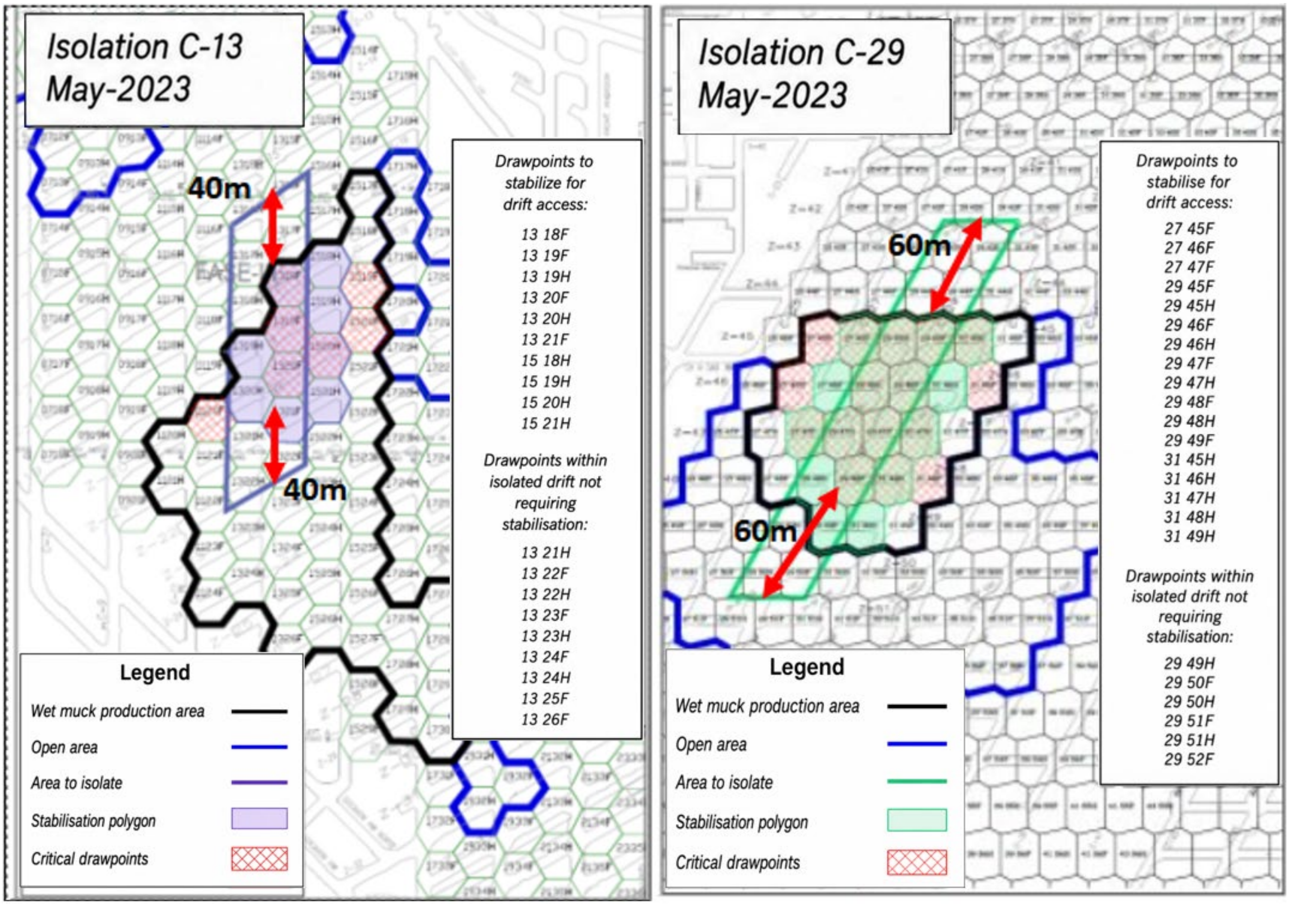

Figure 10 Example of isolation distances at wet muck drifts

Figure 11 Example of stabilisation monitoring based on time following a disturbance (mucking or hang-up removal)

Figure 12 shows the evolution of wet muck production across multiple mines, highlighting a sustained increase in extracted tonnage following the implementation of remote operation as the primary control.

Wet muck production progressively increased, particularly from the Diablo Regimiento and Dacita mines, while maintaining stable copper grades within the expected operational range. Importantly, despite the occurrence of more than 140 documented wet muck inflow events during this period, no incidents involving personnel exposure were recorded. This result confirms that remote extraction effectively decoupled production under wet muck conditions from worker safety, enabling sustained recovery of wet muck-affected reserves without compromising safety performance.

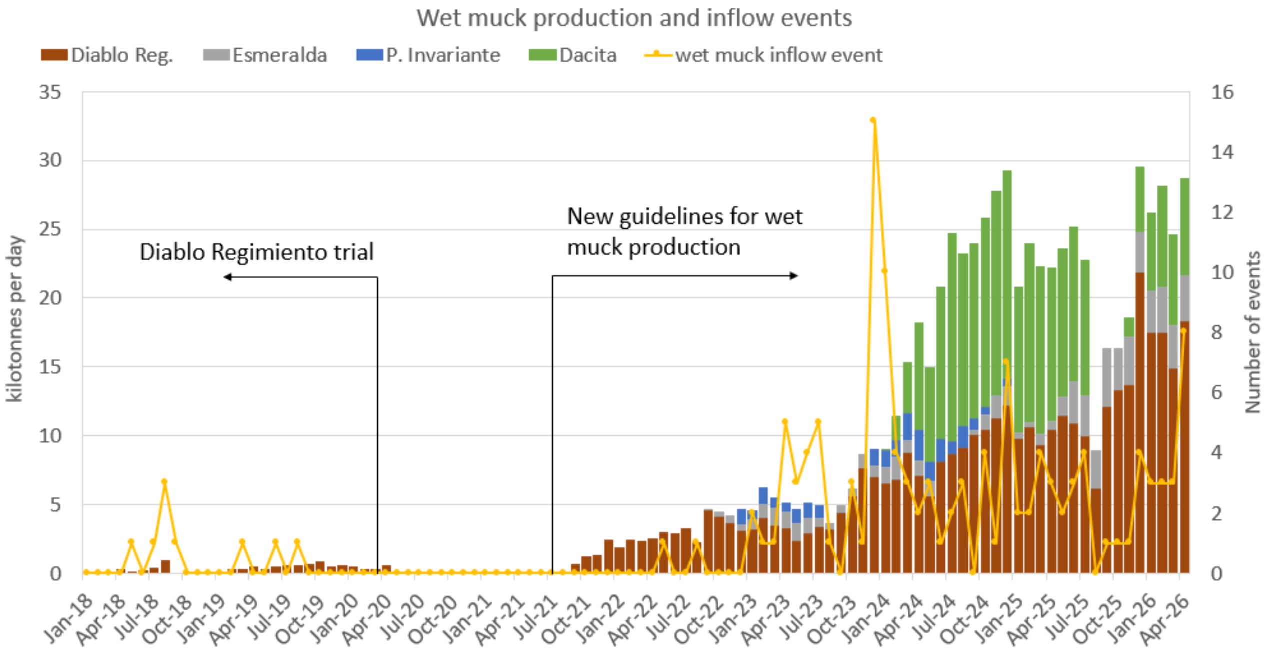

Figure 12 Wet muck production and wet muck inflow events

6 Conclusion

The experience at El Teniente demonstrates that wet muck inflow is an inherent phenomenon in large-scale caving operations, governed by the interaction between material condition, moisture state, internal cave geometry and operational disturbances. Over time, the understanding of this phenomenon evolved from surface-oriented interpretations, where inflows were primarily attributed to infiltration and surface water accumulation, towards a more comprehensive view that recognises the role of internal cave dynamics including fine content, moisture distribution and cave connectivity.

In parallel, risk management strategies evolved from conservative avoidance approaches to a control-based framework that enables continued production under wet muck conditions. This was achieved through improved identification of high-risk drawpoints and the implementation of control measures that eliminate personnel exposure, allowing extraction to proceed even in areas where inflow occurrence cannot be fully prevented.

Early management approaches based on drawpoint closure, limited operating states and reserve abandonment were effective in reducing immediate personnel exposure but imposed significant constraints on production and long-term resource recovery. Subsequent studies on material characterisation and physical failure mechanisms provided a technical basis for understanding wet muck behaviour, while operational analysis identified draw-related disturbances as the dominant trigger defining the timing of inflow events.

The formalisation of operational controls, including the standardisation of draw rate limits in identified elevated risk areas with onboard operators, represented an important step towards disciplined extraction under wet muck conditions. However, operational experience confirmed that these measures alone could not eliminate inflow occurrence under unfavourable material conditions, highlighting that personnel safety hazards cannot be eliminated through monitoring and control measure.

The implementation of remote extraction marked a critical step change in wet muck risk management. By removing operators from high-risk exposure at the production level, controlled extraction could proceed in areas affected by persistent wet muck conditions without personnel safety risk. Industrial trials and subsequent scale up demonstrated that wet muck production could be sustained without compromising safety, with more than 140 documented inflow events occurring without personnel exposure.

The current wet muck management system, which integrates spatial control polygons, predictive modelling and remote operation as the primary controls, provides a structured and transferable framework for governing wet muck risk at the planning and operational levels. While site-specific calibration remains essential, the principles developed at El Teniente highlight the effectiveness of combining system-level understanding, operational discipline and exposure elimination to manage complex inrush hazards in caving mines.

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