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Applicability of sublevel caving to small-scale orebodies: design and mixing analysis from the Jama Bor mine

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Abstract

This paper presents the application of the sublevel caving (SLC) mining method in the T4 orebody of the Jama Bor underground mine, with emphasis on dilution control and draw behaviour in a small, geometrically irregular deposit. The T4 orebody contains approximately 300,000 tonnes of ore, requiring a compact and carefully scaled SLC design. The adopted mining solution comprises a 3-level SLC layout adapted to the limited size of the deposit, irregular ore boundaries and constraints imposed by the existing underground infrastructure. The design explicitly addresses conditions that influence caving propagation, material mixing, dilution entry and ore recovery. Dilution and recovery were evaluated using a flow-based marker mixing assessment in the PCSLC module within GEOVIA Surpac. The analysis focused on material flow paths, ore-waste interaction, level interaction, and the sensitivity of the response to draw strategy and geometry. The results indicate that controlled dilution and stable recovery can be achieved at a small scale when draw rules and layout geometry are aligned. The case study demonstrates that SLC can be applied beyond large orebodies and can represent a technically viable mining method for smaller and geometrically complex deposits.

Keywords: *sublevel caving, small-scale orebody, dilution control, marker mixing*

1 Introduction

Sublevel caving (SLC) is a mass mining method that relies on the gravity flow of blasted ore while the hanging wall caves in to fill the void, enabling continuous production without maintaining large open stopes. Campbell (2022) shows that SLC performance is not fixed; recovery and dilution vary widely between operations and are strongly governed by draw control practice, sequencing, and how well the layout geometry fits the orebody and cave mechanics. Despite this, SLC is still often treated as a method reserved for large orebodies where dilution can be absorbed by production scale. That assumption is risky for small deposits because they have less geometric buffer to tolerate boundary-driven mixing, and development errors or poorly tuned extraction percentages can consume the value proposition early. At the same time, modern planning tools and improved understanding of gravity flow, including marker studies and empirical calibration methodologies, have expanded the practical design envelope (Quinteiro & Nordqvist 2022; Khodayari & Diering 2022). From a practitioner's standpoint, SLC is not simply a method with dilution risk; it is a gravity-flow system in which dilution is an expected phase of draw. As ore is extracted, caved material progressively replaces it, and the draw column evolves from an ore-dominated regime towards increasing ore-waste interaction. Standard descriptions of caving flow emphasise that early draw tends to deliver relatively clean ore, while continued draw gradually mobilises more caved waste into the flow zone (Heslop 2010; Campbell 2022). The operational question is therefore when and how that transition is managed. The study uses the T4 orebody as a case context and focuses on design adaptation for scale and geometry, together with a primary cave sublevel caving- (PCSLC-) based marker mixing assessment that makes dilution

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entry mechanisms explicit. The working hypothesis is that small-scale SLC behaves as a boundary-controlled flow system in which draw strategy is the primary driver of mixing behaviour.

2 Geological constraints and flow implications

The T4 orebody is situated in the central part of the Bor deposit within a fault zone and is hosted by altered andesite and pyrite-type mineralisation. Published descriptions by Vojinović et al. (2025) indicate intense alteration close to the orebody, transitioning outward to weaker alteration and fresh andesites. Documented alteration styles include pyritisation, silicification, kaolinisation, chloritisation and sulphurisation. From a geotechnical and mining engineering viewpoint, the alteration pattern matters because it creates contrasting behaviours: mineralised and silicified zones may be mechanically stronger while kaolinised and sulphatised gypsum-bearing zones can be weak, fractured and stability-limiting around openings and faulted contacts. The production horizon considered in this study is defined by the −30, −45 and −60 m levels. These conditions drive 2 design imperatives for a small-scale cave: keep the footprint compact and development efficient; and anticipate that flow and dilution may be strongly boundary-controlled, especially where weak altered rock promotes early caving and horizontal and vertical mixing, i.e. gravity-driven migration of loose or fine material along damaged contacts. The T4 layout must also account for existing underground infrastructure (Vojinović et al. 2025).

Vojinović et al. (2025) describe T4 as a structurally controlled orebody hosted within a pronounced tectonic corridor, with tectonic contacts to surrounding altered andesite. In such settings, faults and associated damage zones are more than geological background: they can influence where caving initiates and how it propagates, and they can provide preferential pathways for horizontal mixing of weak, fine material into the draw column. The same published T4 description reports fractures within and near the orebody that may be infilled by sulphides, sulphates and quartz, which is consistent with a mechanically heterogeneous rock mass where some intervals are blocky and others are crushed or friable. Once ore-waste interaction begins, damaged contacts can become rapid pathways for waste inflow. Vojinović et al. (2025) document T4 as a small and irregular orebody, leaving a limited geometric buffer between production drawpoints and waste-producing boundaries in the altered andesitic host rock. In flow terms, this reduces the draw height available before the draw column intersects tectonic contacts, damaged wall rock or caved material migrating from outside the ore envelope. It also means that neighbouring draw columns can begin interacting over a short vertical interval, making the system sensitive to local overdraw and sequencing effects. The practical implication is that dilution entry is likely to be controlled by boundary proximity and contact behaviour, so the draw strategy must explicitly manage column growth and interaction rather than relying on scale-based averaging. The mining context adds additional design limits. The T4 layout is integrated with existing underground workings, including protective stand-offs and pillars around infrastructure that must remain stable during extraction (Vojinović et al. 2025). In a compact cave, these constraints can limit footprint placement, reduce the number of available drawpoints and force locally non-ideal spacing or orientation. Together, tectonic contacts, mechanically contrasting alteration and infrastructure stand-offs support the framing used in this paper: small-scale SLC at T4 is best treated as a boundary-controlled flow system in which disciplined draw control is the main practical lever for delaying boundary-driven dilution.

3 Sublevel caving layout design and flow control strategy

A 3-level SLC layout with 15 m vertical spacing has been documented as the baseline development concept for T4, comprising the −30, −45 and −60 m levels relative to the local mine data (Vojinović et al. 2025). The design logic is straightforward but critical for a small orebody: short sublevel spacing reduces ring height and tends to limit the vertical distance over which mixing can develop before ore-waste contacts migrate into the draw.

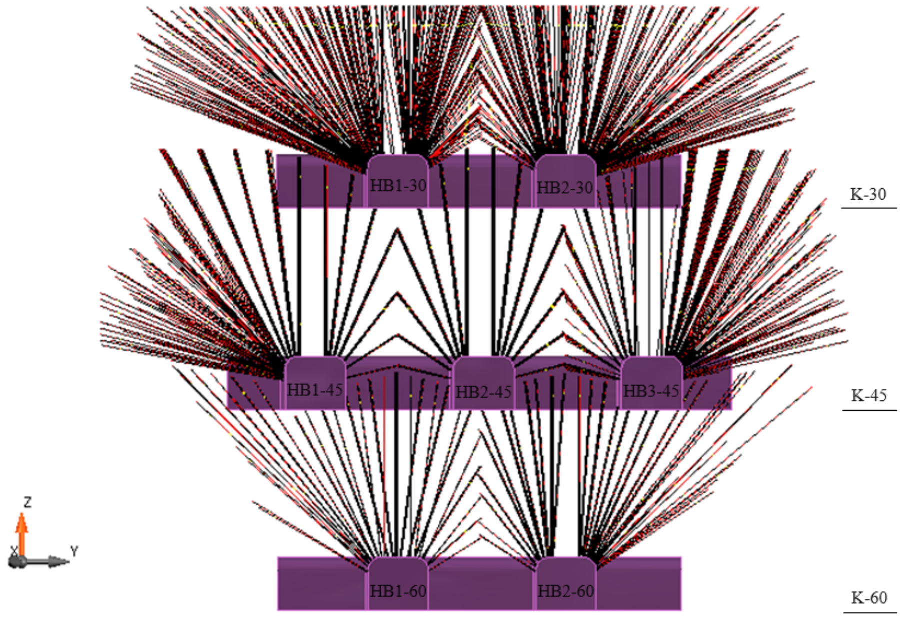


Figure 1 Vertical cross-section of drifts and ring design for the T4 sublevel caving layout (Vojinović et al. 2025)

For T4, Vojinović et al. (2025) describe a chessboard arrangement of slot drifts and drilling drifts yielding a rhomboidal ore block configuration. Slot raises of 2 x 2 m are developed at drift ends. Fan rings are drilled along slot drifts at 1 m intervals, while rings from drilling drifts are spaced 2 m apart. Drilling height is set by the upper sublevel, and drilling width is constrained by the orebody contour. This geometry is consistent with classical SLC design intent: keep drawpoint spacing dense enough to manage isolated draw zone overlap and limit early dilution while retaining practical drill-and-blast implementation.

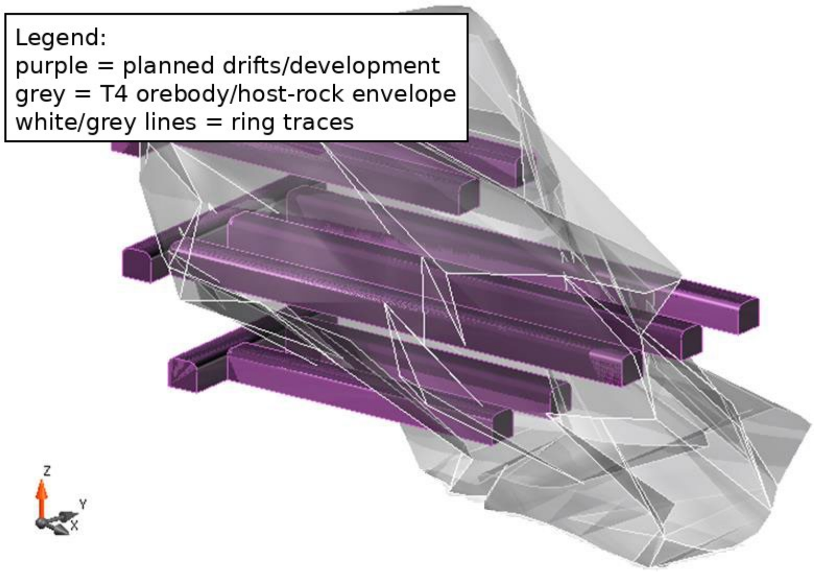


Figure 2 T4 orebody development model showing planned development drifts, ring traces and the orebody/host-rock envelope (Vojinović et al. 2025)

In the PCSLC model snapshot used for this study, the layout is summarised as 3 levels (−30, −45 and −60 m), seven drifts and 140 rings. These values are used as the baseline layout scale for the comparative design alternatives in Table 1. The alternatives were evaluated qualitatively in terms of development intensity, draw-control practicality and mixing risk, and quantitatively through the flow and mixing assessment described below.

Large-mine examples show that sublevel height can be increased in major operations, such as LKAB, but small orebodies and complex geometries generally prioritise flow control over scale (Quinteiro & Nordqvist 2022). Footprint evaluation tools for SLC similarly emphasise sensitivity to tunnel spacing, face shape, sequencing and draw strategy (Diering & Breed 2018).

Table 1 Design alternatives considered for a small, irregular sublevel caving footprint

Parameter	Option A compact control	Option B baseline	Option C reduced development
Vertical level spacing	12 m (4 levels)	15 m (3 levels)	18 m (3 levels, higher rings)
Primary intent	Maximise draw control; reduce per-ring height	Balanced control versus development	Minimise development; fewer levels
Indicative ring height	Low	Moderate	Higher
Expected dilution behaviour	Lowest early dilution; slower dilution growth	Moderate; manageable with strict draw rules	Higher early dilution risk; stronger sensitivity to boundary irregularity
Expected recovery behaviour	Higher selectivity: may leave value unless extraction increased later	Stable recovery baseline	Recovery can be high, but often at cost of dilution
Development complexity	Highest	Moderate	Lowest
Suitability for T4 constraints	Good if development time/cost acceptable	Best overall fit	Higher risk for small irregular boundary

Vojinović et al. (2025) describe a structured extraction sequence for the T4 orebody consistent with standard SLC practice. As illustrated in Figure 3, the process begins with slot development, which provides the free face required for controlled blasting. Production rings in the slot drifts are completed first, after which blasting progresses into the production drifts. Ring blasting is performed sequentially, with each blast followed by draw and loading of broken ore before advancing to the next ring. The overall extraction sequence follows a top-down progression from the upper to the lower levels.

The PCSLC draw strategy snapshot formalises this sequence through a flat-front extraction concept, level-specific extraction targets and a shut-off criterion applied at the lowest level. This approach is consistent with SLC planning principles in which extraction percentage acts as a primary control variable governing flow behaviour (Villa & Diering 2010; Campbell 2022). As extraction increases, particularly at deeper levels, the draw column extends vertically and promotes interaction with overlying material. This enhances mixing and accelerates dilution ingress because deeper draw can mobilise waste and previously mixed material into the active draw zone.

The applied draw strategy is defined through level-dependent extraction targets combined with a flat-front extraction approach. Extraction at the upper production level (−30 m) is limited to approximately 40% to preserve grade and delay early dilution entry. The intermediate level (−45 m) is extracted more intensively, to approximately 80%, because it represents the primary production horizon with the highest in situ metal content.

At the lowest level (−60 m), extraction is governed by a shut-off grade criterion rather than by a fixed extraction percentage. In practice, this results in localised over-extraction as material is drawn beyond the nominal level capacity to recover ore remaining from upper levels before drawpoints are closed. This mechanism links production levels and promotes multi-level interaction within the draw column.

The strategy therefore uses deeper extraction as a recovery driver while accepting the associated increase in dilution caused by enhanced vertical mixing and boundary interaction.

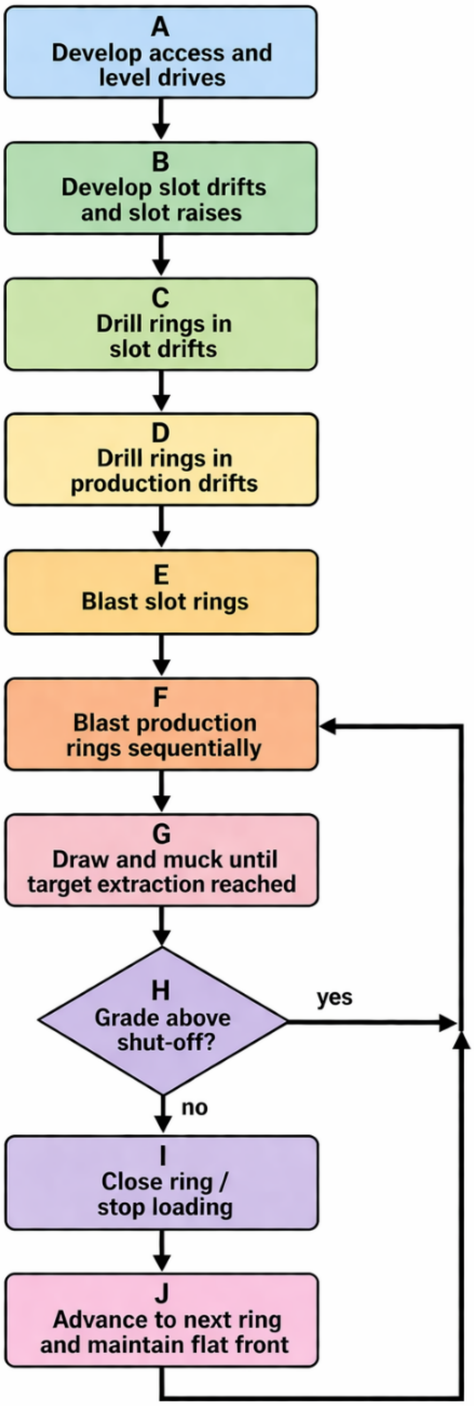


Figure 3 Sublevel caving schedule algorithm used to define slot development, ring blasting, draw and shut-off logic

The flow and mixing analysis are based on the PCSLC planning framework, which integrates mine design, material flow modelling and production scheduling into a single workflow. As shown in Figures 4, 5 and 6, the workflow enables generation of drifts and rings, transformation of ring geometry into computational cells and assignment of material properties derived from the block model. It also incorporates reconciliation of ring volumetrics, definition of dilution sources and scheduling based on development constraints and extraction strategies.

This approach follows established PCSLC methodology for SLC mine planning (Villa & Diering 2010) and is consistent with template-mixing and marker mixing concepts used in caving tools (Khodayari & Diering 2022).

The objective is not to reproduce particle-scale granular mechanics. Rather, the objective is to predict ring response under defined flow conditions and to compare the sensitivity of alternative draw strategies. Model credibility therefore depends on clear assumptions, calibration checks and sensitivity analysis. This is particularly important in small and geometrically irregular orebodies, where boundary effects and multi-level interactions can dominate dilution entry.

Figure 4 shows the geometric foundation of the PCSLC model. Ring volumes are explicitly defined and constrained by the orebody shape through solid trimming. This step is important in small and irregular deposits because the simulated extraction units must reflect real geological boundaries rather than idealised geometries. By preserving the spatial limits of each ring, the model captures asymmetric interaction between the ore and surrounding waste, which is a key driver of boundary-controlled mixing.

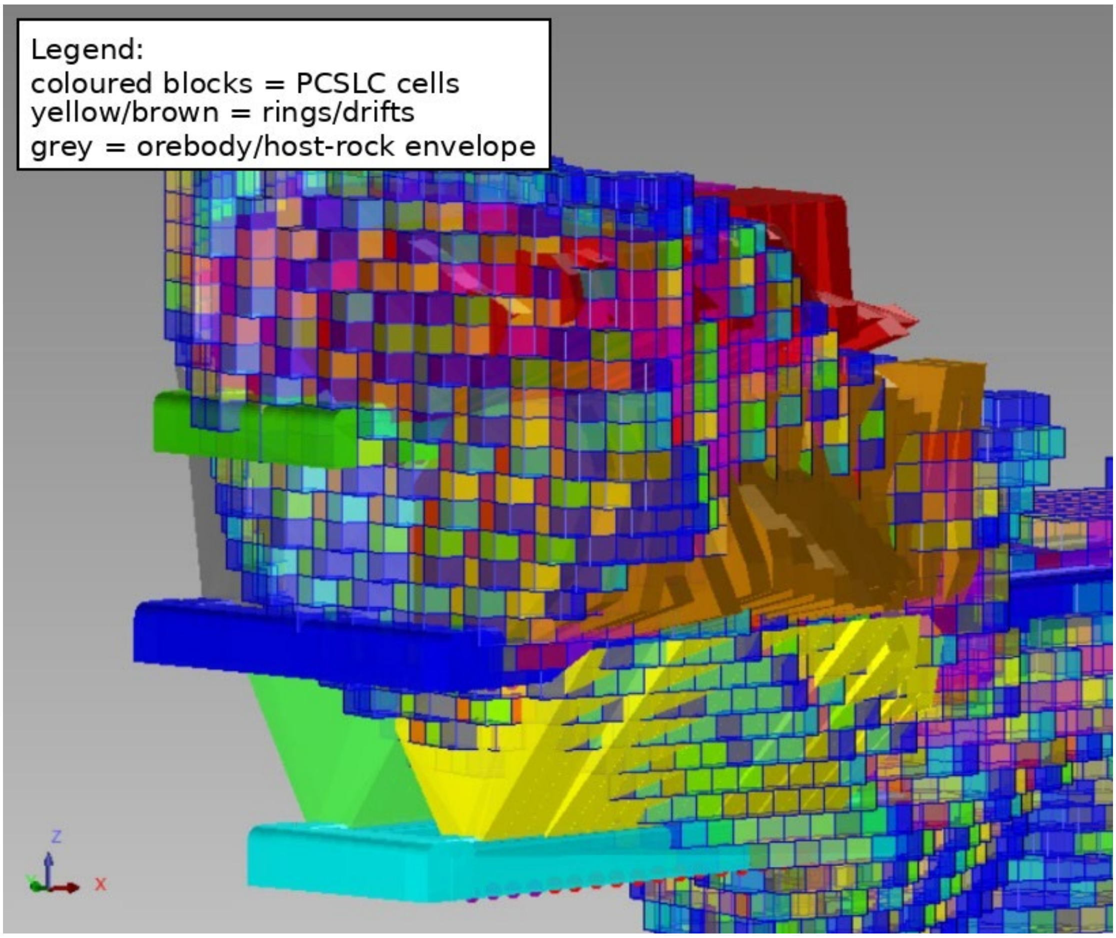


Figure 4 Primary cave sublevel caving (PCSLC) economic mining cells and trimmed production ring blocks for the T4 model. Colours represent modelled PCSLC cell copper grade; yellow/brown elements indicate rings and development, and grey surfaces indicate the orebody/host-rock envelope

Following the geometric definition of the model, the extraction process is first represented through the distribution of material drawn from each level, as shown in Figure 5. The figure shows how the applied draw strategy controls the relative contribution of individual levels to the overall extraction process. In this multi-level SLC system, the distribution is controlled by both layout geometry and the extraction percentages assigned to each level. Figure 6 extends the analysis by showing the origin of extracted material, distinguishing between material sourced from in situ rings and material introduced through mixing and dilution processes. Figure 5 shows how much material is extracted from each level, whereas Figure 6 shows where that material originates. Comparing these 2 views highlights the transition from targeted extraction to mixed flow conditions as extraction increases.

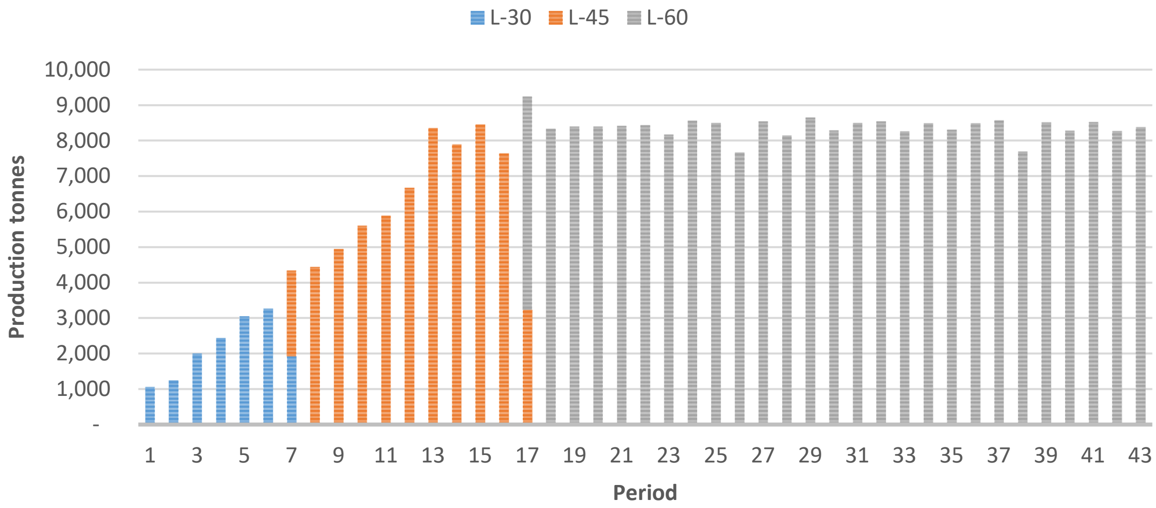


Figure 5 Tonnage extracted per level by schedule period: X-axis – schedule period/month; Y-axis – tonnes. Bar colours denote the −30, −45 and −60 m production levels

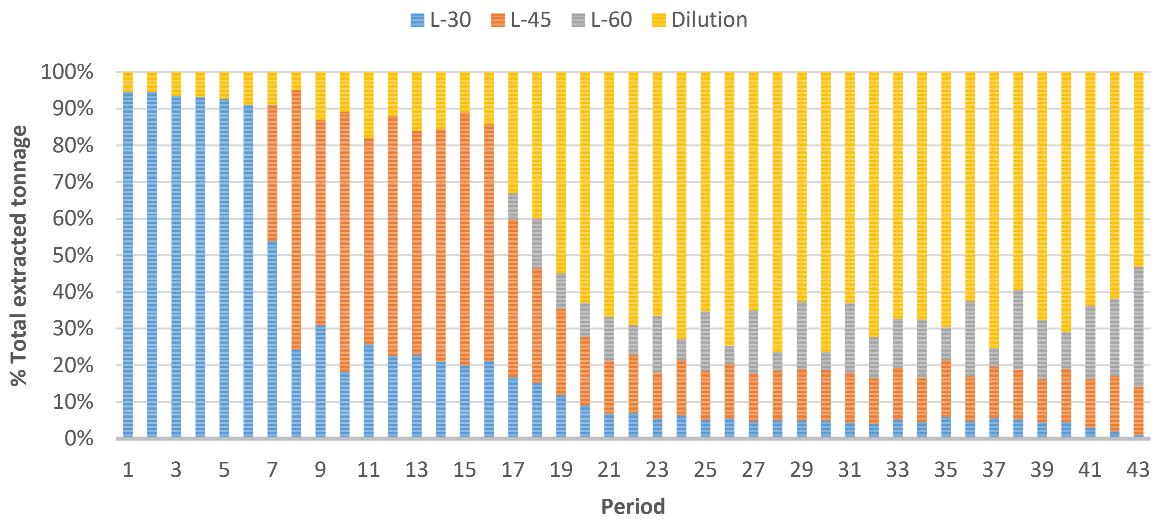


Figure 6 Tonnage composition by material origin: X-axis – schedule period/month; Y-axis – percentage of total extracted tonnage. Colours denote material from the −30, −45 and −60 m levels and dilution material

3.1 Marker mixing approach

To make ore-waste interaction transparent, a marker-based mixing representation is used conceptually. Discrete markers associated with ore and waste domains are tracked through depletion steps in the draw columns, rather than only tracking fractional material mixing. This is aligned with marker mixing concepts used in GEOVIA caving tools, where markers are tracked through draw columns and multi-lift linkages can be represented by absolute 3D position (Khodayari & Diering 2022). In practice, markers and production monitoring, such as bucket-weight proxies or recovered markers, can be used to quantify draw width, waste dilution and recovery components, which is particularly important in complex geometries (Quinteiro & Nordqvist 2022).

3.2 Model inputs, assumptions and boundary conditions

A defined set of parameters was used to provide a consistent and interpretable modelling framework for the PCSLC assessment. The values used in the study include the 3 production levels (−30, −45 and −60 m), the layout scale of seven drifts and 140 rings, a scenario swell factor of 1.25, a top-of-column/hanging-wall external dilution source, and a conceptual calibration target based on the tonnage profile and dilution trajectory. These inputs provide a controlled basis for comparing draw strategies and identifying how extraction percentage and level interaction affect material movement and dilution mechanisms.

Where site-calibrated values were not available for publication in this manuscript, parameters are stated as scenario assumptions rather than accepted operational design values. This keeps the modelling basis transparent and prevents unsupported precision. The approach is appropriate for comparative sensitivity assessment, but the resulting values should not be interpreted as final reserve, schedule or reconciliation results. The full set of inputs is summarised in Table 2.

Table 2 Flow and mixing model inputs used for the T4 small-scale sublevel caving assessment

Parameter group	Value used	Basis
Levels modelled	−30, −45 and −60 m	Three-level structure documented for T4 and used in the PCSLC snapshot (Vojinović et al. 2025)
Layout scale	7 drifts and 140 rings	Baseline PCSLC model summary used for comparative assessment
Swell factor	1.25 (scenario assumption)	Used as a sensitivity input in the absence of a publishable site-calibrated swell value; caving flow response is sensitive to swell and marker movement (Khodayari & Diering 2022)
External material	Top-of-column/ hanging-wall waste replacement	Represents caved material entering the draw column from outside the ore envelope, consistent with PCSLC/template-mixing concepts (Villa & Diering 2010; Khodayari & Diering 2022)
Draw strategies	Conservative, balanced baseline and new draw strategy	Conservative and balanced cases are bounded sensitivity cases; the new draw strategy represents the modelled high-recovery end point
Analysis results	Tonnage, copper grade and dilution	Dilution, ore recovery and loss are used to assess draw strategies (per cent of extraction per level and shut-off value)

3.3 Model verification

The PCSLC assessment presented in this study is based on published T4 design information and PCSLC model results, including production schedules, flow-model outputs and ore recovery estimates. The objective was not to perform a full calibration and validation exercise, but to verify model consistency and evaluate the sensitivity of the predicted response to the principal variables controlling material flow and dilution.

Two verification and assessment steps were applied:

1. Internal model consistency was checked. Ring and cell volumetrics were compared with in situ ring-solid reporting to confirm that the model inventory remained internally consistent and that the extracted tonnage was compatible with the defined production geometry.
2. Sensitivity assessment of flow-control variables was completed. Model response was evaluated under different extraction strategies, with particular focus on extraction percentage and level

interaction as these parameters are widely recognised as primary controls on mixing behaviour, recovery and dilution entry in SLC systems (Villa & Diering 2010; Campbell 2022).

The purpose of this procedure was not to reproduce site-specific production performance but to establish a transparent and technically consistent basis for comparing draw strategies and identifying the mechanisms responsible for dilution ingress and recovery response in a small-scale, geometrically irregular orebody. Figure 7 presents a simplified visualisation of the flow response. The original PCSLC output contained many time-step images; it has been reduced here to 3 representative stages to show the intended interpretation more clearly. The panels show successive draw steps from the same simulation, not separate scenarios. The increasing grey/white material paths and changing marker distribution illustrate the progressive mobilisation of mixed material as draw advances.

- Early draw shows the original ring shape as a reference for display purposes; however, it does not accurately represent the actual drilled shape of the ring. Instead, it shows the material allocated per level for mixing visualisation purposes.
- Intermediate draw illustrates the extraction of the 2 levels based on the midpoint of the production schedule simulation.
- Late draw displays the extraction carried out at the end of the production schedule, describing the material extracted in each level and the remaining portion due to the extraction and flow model results.

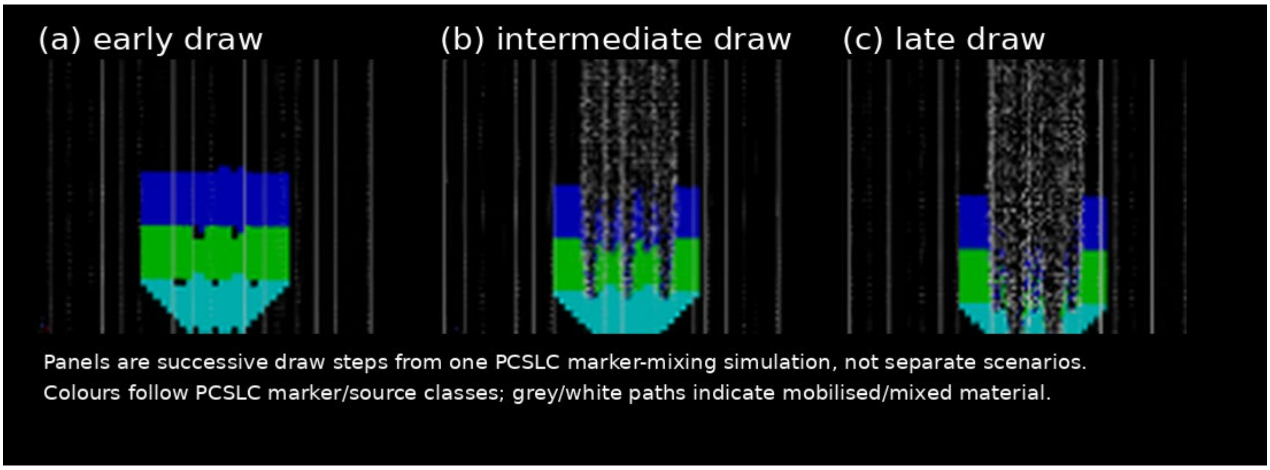


Figure 7 Representative primary cave sublevel (PCSLC) marker mixing response for the modelled draw strategy, shown from early to late draw. The panels are successive draw steps not different scenarios. Colours follow PCSLC marker/source classes and grey/white paths indicate mobilised mixed material

4 Results

Two draw strategies were analysed using different extraction profiles. Table 3 summarises the per cent of extraction used per level and overall results based on ore recovery and dilution.

The conservative draw strategy delivers a reasonable production profile over 23 months, maintaining ~8,000 tonnes per month. The grade profile describes the dilution ingress from upper levels, enabling good in situ metal recovery within the rings. Level -60 was extracting more than 400% to extract ore from the upper levels before the rings were closed due to the shut-off grade limit (Figure 8).

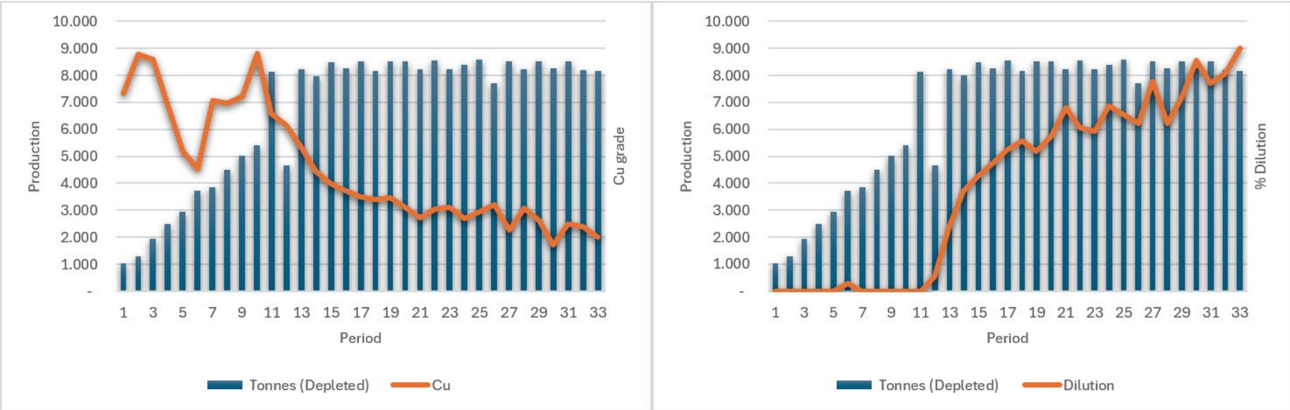


Figure 8 Results of a conservative run in terms of tonnage, copper grade and dilution

The new draw strategy produces a stable production profile that extends production for eight more months by increasing the extraction at each level and thus increasing the ore recovery due to extraction of in situ metal not extracted in the 2 levels above. The ingress of dilution has increased to 51% due to the high-grade material located in the rings and the over-extraction from -60 m level, which was done to access ore from the upper level before the rings were closed due to the shut-off grade limit (Figure 9).

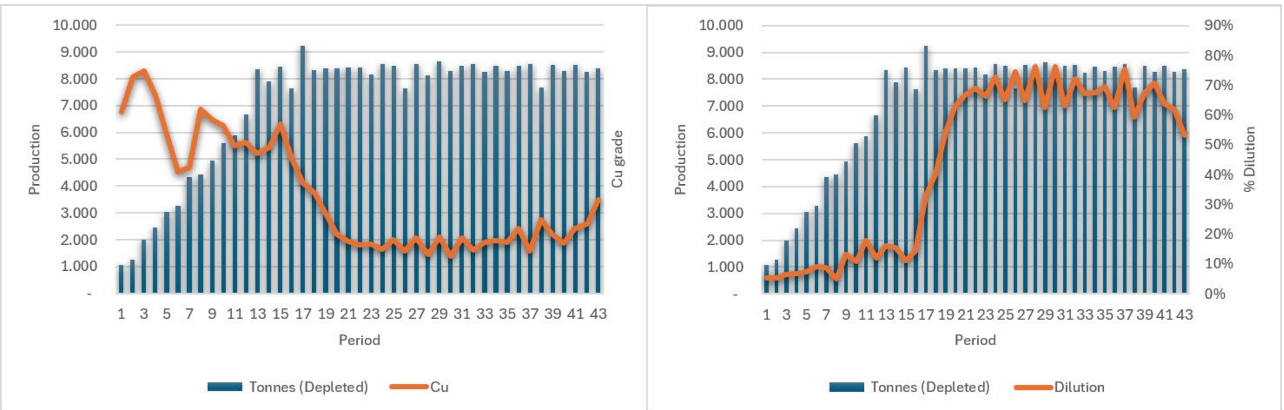


Figure 9 Results of new draw strategy run in terms of tonnage, copper grade and dilution

Table 3 Recovery and dilution outcomes for 3 draw strategies

Scenario	Extraction	Recovery	Dilution	Interpretation
Conservative	Level 1 and 2 30% extraction; Level 3 shut-off grade	77–79%	39%	Tonnage extracted 128% compared with in situ rings Lower dilution; leaving high grade due to irregular orebody and low extraction from Levels 1 and 2
New draw strategy	Level 1 = 40% and Level 2 = 80% extraction; Level 3 shut-off grade	87%	51%	Highest ore recovery, but dilution requires strict draw control

Two dilution-entry mechanisms were identified as particularly important for the small and irregular T4 footprint. First, boundary-driven horizontal and vertical mixing, meaning gravity-driven migration of weak or fine material along ore-waste contacts, can dominate early dilution where drawpoints are closer to irregular contacts. Second, multi-lift interaction becomes controlling when deeper extraction is used to recover ore remaining on upper levels.

Marker mixing concepts explicitly represent this through spatial linkages between slices, reinforcing that deep extraction strategies must be evaluated as dilution strategies as well as recovery strategies (Khodayari & Diering 2022).

5 Discussion

The results support the interpretation of extraction as a flow-driving mechanism rather than only a production target. Once the flow regime shifts towards a dilution-dominated state, the system response becomes increasingly difficult to control, particularly in geometrically constrained orebodies. For T4-scale conditions, 3 practical implications follow:

1. Geometry fit is essential. The T4 layout constrains drilling width to the orebody contour and uses tight ring spacing within a chessboard drift arrangement (Vojinović et al. 2025). Poor geometric conformity would increase the ore-waste contact surface and accelerate boundary-driven dilution.
2. Draw control is the primary economic control variable. Once a drawpoint is over-extracted and dilution enters the flow zone, the effect cannot be fully corrected later. Figure 10 shows this contrast qualitatively for 2 draw strategies modelled: warmer colours indicate higher remaining copper grades, cooler colours indicate lower remaining copper grades and black areas represent dilution.
3. Dilution monitoring must be implemented in the operational process. Vojinović et al. (2025) describe geological sampling and loader-based monitoring as part of T4 dilution control. In a small SLC footprint, these checks are critical because small changes in draw logic can produce changes in material mixing.

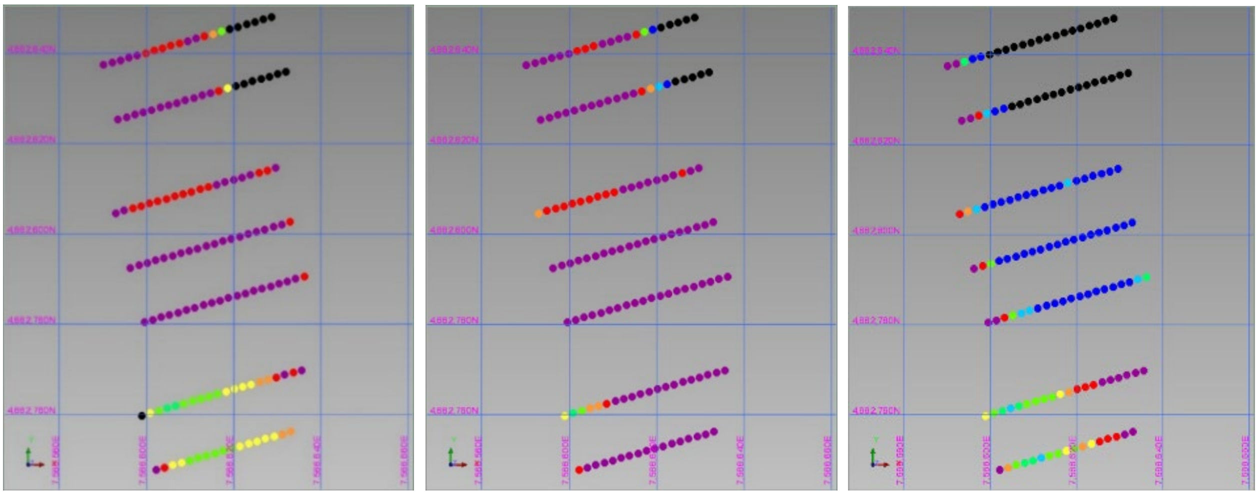
The new draw strategy represents a shift towards more aggressive extraction. It improves recovery, but it also moves the system towards a dilution-dominated regime. This trade-off defines the operational space that draw control must manage.

Vojinović et al. (2025) indicate that dilution control for T4 relies on geological sampling and loader-based monitoring, particularly where lithological contrasts and variable bulk density are present. This aligns with broader SLC practice, in which draw monitoring and material routing are used as operational indicators of draw quality (Campbell 2022; Quinteiro & Nordqvist 2022).

The modelling approach used in this study is empirical and template-mixing-based. It is appropriate for comparative scenario analysis, but it does not replace site-calibrated flow modelling or full production reconciliation.

Only the flat-front extraction concept was assessed in this study. Alternative front shapes, such as chevron extraction, were not simulated and should be evaluated separately before being adopted for design. Based on the scenarios considered here, a flat-front approach with controlled draw deviation between adjacent rings reduces local overdraw and helps delay early dilution entry. In irregular ore-boundary areas, controlled losses may be preferable to aggressive deep extraction unless the processing system can accommodate higher dilution without compromising economics.

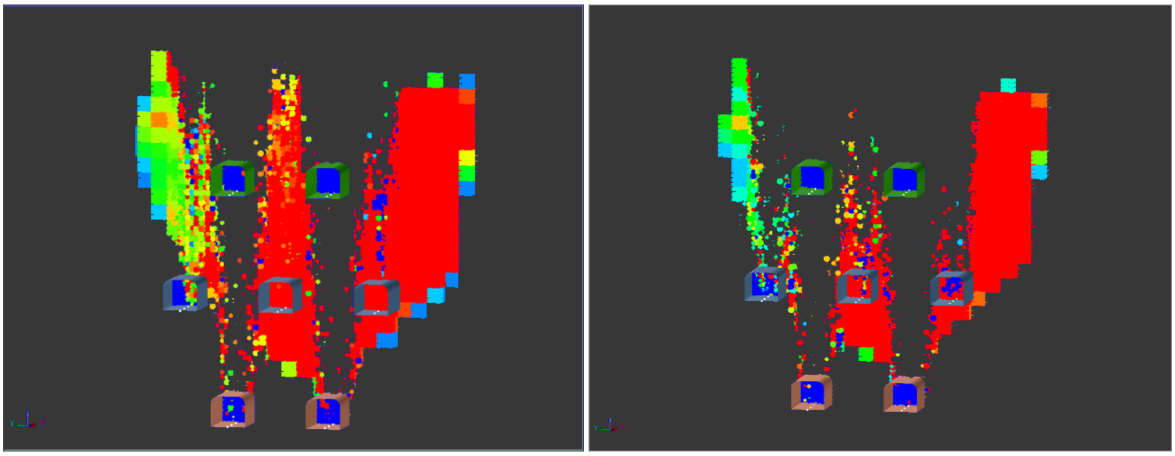
Figure 10 provides a comprehensive overview of the extraction results per ring through an offset view, displaying 3 levels simultaneously from top to bottom. This option is useful for comparing the copper grade allocated in the in situ ring (a), the copper grade mined (b), and the remaining copper grade (c) to analyse the draw strategy used.



(a) (b) (c)

Figure 10 Production schedule offset view: (a) Ring in situ copper grade; (b) Ring mined copper grade; (c) ring remaining copper grade. Colour legend: blue/cyan = lower copper grade; green/yellow = intermediate copper grade; orange/red = higher copper grade; grey/black = not used in simulation

The remaining copper is shown in Figure 11. It is evident that the new draw strategy facilitates the extraction of more ore. This supports the central design interpretation that the draw strategy influences the production response, while the extraction percentage serves as a key factor governing flow behaviour. Additionally, a new iteration could be conducted by adding another tunnel at the lower level to recover the ore located on the left side of Figure 9b.



(a) (b)

Figure 11 Draw strategy comparison: (a) Initial draw strategy; (b) Optimised draw strategy. Colour legend: blue/green = low copper grade; red = high copper grade

6 Conclusion

This study demonstrates that sublevel caving (SLC) can be applied to small-scale and geometrically irregular orebodies when the method is designed as a controlled gravity-flow system. For the T4 orebody, the critical design variable is draw strategy. Increased extraction, particularly at deeper levels, improves recovery but promotes multi-level interaction and accelerates boundary-driven dilution. The modelled new draw strategy achieved the highest recovery among the assessed cases, but it also produced the highest dilution. Successful application therefore depends on strict draw control, careful management of level interaction, clear shut-off criteria and acceptance of controlled ore losses where necessary to delay dilution ingress. In small SLC systems, controlling extraction is equivalent to controlling the flow system itself.

Acknowledgement

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