

# Sensitivity analysis on production scheduling and draw control strategies for the Carrapateena block cave

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## ABSTRACT

The paper provides a holistic approach for assessment of proposed production schedules and draw controls strategies at the Carrapateena block cave 1 (BC1) through analysis of Key Performance Indicators (KPI's). It highlights the use of first principles approach along with simulations and statistical analysis to identify the KPI's for the planned Carrapateena BC1. Simulation is referred in this paper as Personal computer Block cave (PCBC) production scheduling process. Literature review and benchmarking was performed to create a comprehensive list of KPI's relevant for production scheduling and draw control. Simulation was performed for varied mining constraints to understand the mine performance through mine physical outputs such as tons and grades profile, drawpoint shut-off height of draw, draw rates profile for the footprint. Sensitivity analysis is then performed on selected parameters to understand their impact on mine performance. Factors such as minimum draw rates, production rate curves, drawbell length, and draw cone dimensions were varied and their impact on production schedule for the planned block cave were calculated. The planned Carrapateena BC1 will be established in a high stress environment at a depth of 1.5km (approx.) with a steady state production target of 12mtpa.

## 1 INTRODUCTION

Block caving (BC) as a mining method has evolved from its initial application to mine smaller and weaker orebodies in iron ore and copper mines of Michigan and Arizona, USA, in the late nineteenth century to its current application to mine larger and competent orebodies in copper, diamonds and other base metal mines of Australia, Chile, South Africa, Indonesia etc. (Brown, 2007; Hartman and Mutmanský, 2002). BC has evolved into a highly mechanized and productive mining method, comparable to large scale open pit operations.

### 1.1 Nature of material flow

A key factor in variability and uncertainty in production scheduling is the ability to predict the nature of material flow. Ore recovery and dilution has been a concern with caving operations due to the constant mixing of the ore and waste rock during the loading process (Janelid and Kvapil, 1966; Gustafsson, 1998;

Laubscher, 1994). In BC, material is loaded from the draw points as the cave propagates upwards and outwards from the point of initiation (Laubscher, 2000).

The findings of physical models and marker trials have helped explain the nature of material flow for caving operations. The initial theory of gravity flow described material movement as an ellipsoid of motion for isolated draw from a single draw point (Kvapil, 1965; Janelid and Kvapil, 1966; Kvapil, 1982) in Sub-level caving (SLC) operations. However, the results from various marker trials performed 2000-2019 suggest material flow in SLC is chaotic and non-uniform (Stazhevskii, 1996; Power, 2004; Brunton, 2009; Wimmer et al., 2015; Nordqvist and Wimmer, 2016).

Similar to SLC mines, the material flow in block caving operations was described for individual drawpoints as drawzones with overlap between the individual drawpoints for interactive draw (individual flow zones may or may not interact

actively and material movement can be induced by stress driven yield) (Laubscher, 1994; Laubscher, 2000; Brown, 2007). Although limited literature has been published around marker trials in BC, the results indicate a chaotic and non-uniform material flow similar to the nature of material flow observed in Sub-level caving (SLC) (Brunton et al., 2016; Garcés et al., 2016).

Different cave flow modelling techniques have been developed and applied at various mines to simulate this material flow and predict the resultant tons and grades profile along with other parameters to understand the mine performance (Nedderman, 1995; Sharrock et al., 2004; Selldén & Pierce, 2004; Diering, 2007; Castro et al., 2009; Pierce 2010; Beck et al. 2011). These kinematic and cellular automata-based modelling techniques have been helpful in predicting cave front and material flow boundaries but lack the ability to incorporate randomness of flow as the models are based on predefined rules. These models do not use near continuous drawpoint monitoring systems (lack of relevant technology for low grade Copper and gold deposits) to calibrate the models for a specific mine, using average mill grade instead. Hence, mine planners need to address a stochastic problem using a deterministic method if assertion is given to the results from marker trial from sublevel caving and block caving operations. Sensitivity analysis helps in capturing the variability and uncertainty associated with caving operations using deterministic methods to quantify a stochastic problem statement.

### 1.2 Draw control strategy

A draw control strategy for a caving operation is used to influence this complex loading process and regulates the amount of material to be loaded from individual draw points. An optimal draw control strategy aims:

- to achieve the dual (and contradictory) objective of maximizing ore recovery and minimizing dilution (Gustafsson, 1998; Laubscher, 1994; Power, 2004; Brunton, 2009; Shekhar, 2020)

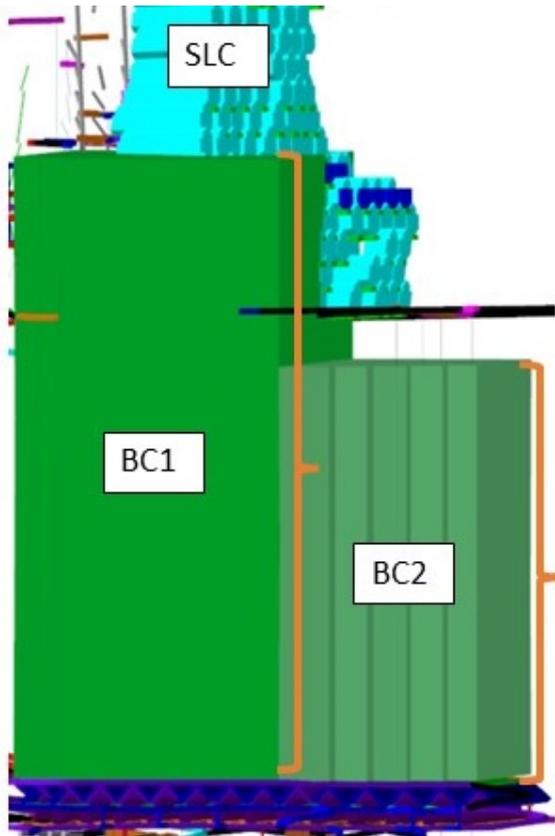
- to avoid geotechnical challenges such as damaging load concentrations on critical infrastructure (Extraction drives, perimeter drives etc.), air blast, mud rush risks etc. (Laubscher, 2000; Brown, 2007; Cuello & Newcombe, 2018).

### 1.3 Key performance indicators

Peterson (2006) states that key performance indicators (KPIs) are numbers designed to succinctly convey as much information as possible. Good KPI's are well defined, well presented, create expectations, and most importantly drive actions (Peterson, 2006). Hence, KPI's relevant to cave flow modelling and draw control strategies in BC are numbers which when changed effect ore recovery, dilution, mine physicals (tons and grade profile), or predicted geotechnical stability (Caveability, air gap risk, mud rush risk). These numbers can be input assumptions, mining constraints or simulation results which when changed drives action in the mine plan or operational procedures.

## 2 CARRAPATEENA MINE

The Carrapateena mine is an operating Sublevel caving (SLC) mine located 160 Km north of Port Augusta in South Australia. The mine produces primary copper concentrate along with gold and silver. The ore body lies under approx. 500m of sedimentary top cover and is nearly vertical, with an average width of 250m (approx.) and length of 200m (approx.) in the SLC footprint. SLC operations will continue down to a depth of 1000m (approx.) with a current production rate of 4.7 MTPA (approx.), ramping up to 7 MTPA (approx.).

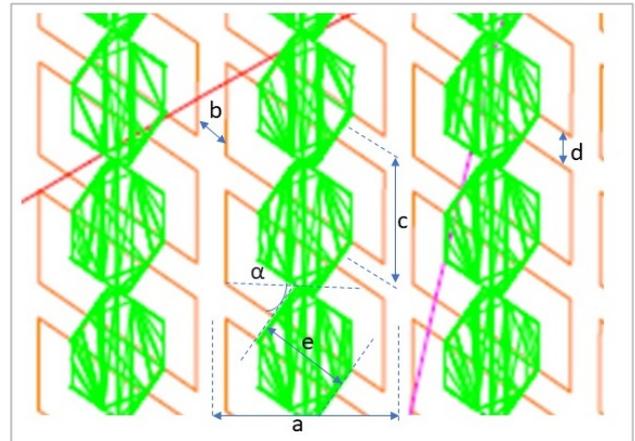


**Figure 1 Overview of block cave 1 location.**

The mine plans to establish a BC footprint at a depth of 1,500m from the surface, to mine the deeper part of the ore body (Figure 1). The planned production rate at steady state will be 12 MTPA for Carrapateena Block cave 1 (BC1). The key mine design parameters relevant to this paper are mentioned in Table 1 and labeled and shown in Figure 2.

**Table 1 Mine design parameters for Carrapateena BC1**

Label	Design Parameter	Value
	Footprint Layout	El teniente
a	Extraction drive (EXD) spacing	32 m
b	Extraction drive width	5 m
c	Drawpoint drive (DPD) spacing	22 m
d	Drawpoint drive width	5 m
$\alpha$	Drawpoint drive angle	34
e	Drawbell length	12 m



**Figure 2 Extraction level design geometry.**

### 3 METHODOLOGY

Exploratory research was performed to understand and enumerate the different KPI's. Descriptive research approach of literature review and baseline mapping of past and current operating BC was conducted. It included published conference proceedings, journals, books, Doctoral thesis, research reports, internal reports, technical manuals, web documents, mail conversations, personal communications, and meeting memos. Thereafter, cave flow modelling and simulation software Geovia's Personal Computer Block Cave (PCBC) was used to perform sensitivity analysis on selected parameters. The results on the sensitivity analysis provide an understanding of the variation in mine performance for Carrapateena BC1.

### 4 KPI'S FOR DRAW CONTROL IN BC

KPI's for draw control in BC has been divided here into input and output. Input KPI's are input indicators such as input assumptions, constraints or parameters which effect the production schedule and draw control strategy. Output KPI's are output indicators which measure the mine performance for a draw controls strategy though estimated mine physicals outputs such as tons and grades profile, drawpoint shut-off height of draw, draw rates profile for the footprint and financial metrics (cashflow, Net present value (NPV), Internal rate of return (IRR) and Present value return (PVR)). Table 2 enlists the input KPI's, and Table 3 enlists the output KPI's for draw control in BC based on

literature review and baseline mapping. The values used for these input KPI's and the calculated outputs should ideally be benchmarked against global caving standards and then calibrated for the unique mining and geotechnical conditions present at the operation.

**Table 2 Input KPI's for Draw control in BC**

Input KPI	Significance for cave flow and draw control strategy
Mine design	Mine design parameters such as EXD and DPD spacing, Drawbell dimension, UC dimension affect the materials ability to flow to the draw point and effect ore recovery, dilution and mine stability. For example, reduced spacing promotes favorable flow conditions while increased spacing provides better pillar stability. Furthermore, larger pillars can also inhibit stability due to poor interaction between drawpoints leading to pillar loading/cave loading.
Draw cone setup	The shape, size, and orientation of the assumed draw cones in BC have an impact on the mine physicals. For example, a narrower draw cone will have a different overlap with its nearby drawpoints then a wider cone which effects the mixing assumptions and finally the estimated grade profiles and ore reserves. Estimated fragmentation is a key input influencing the draw cone setup.
Minimum Height of Draw (HOD)	This parameter controls the minimum amount of material that should be drawn from a drawpoint. The minimum HOD is used to control the tons drawn irrespective of the shut-off grade so even if an individual drawpoint is uneconomical, material can be drawn to fulfill other objectives such as mine stability.
Maximum HOD	This parameter controls the maximum amount of material that can be drawn from a drawpoint. This means that even if the material drawn is above economic grade, the drawpoint is estimated to be closed for other reasons such as safety reasons of mud rush risk potential.
Minimum draw rates	A minimum draw rate constraint is used to avoid drawbell freezing after blast due to lack of mobilization, avoid cave loading on the major apex and reduce potential for any mud rush due to accumulation of excessive finer and wet material.
Cave shapes	This parameter provides the assumed/actual shape the cave will grow/has grown and bounds the slice file column and allows for rilling of material in the column. Information around cave shapes is based on structural and geotechnical modelling. This is an iterative process where an initial draw control strategy provides data for creating cave shapes which is then utilized for a revised draw control strategy.
Mixing assumptions	A total of 16 different mixing parameters are assumed by the mixing algorithm which have been discussed in detail in Diering (2007).
Production rate curve (PRC)	Production rate curves provide the maximum allowable tons to be drawn per period from a drawpoint as a function of extraction ratio. This is a safety constraint needed to promote uniform cave growth, maintain enough muckpile above drawpoints and to manage the airgap. As the cave grows and the drawpoint matures the allowable tons increase and reach maximum level at steady state. The definition of steady state can vary for different mining conditions.
Undercutting strategy	The undercutting strategy encompasses the various rules which are followed during the undercutting process including the approach (Advance/Post/Hybrid), lead-lag rules, drawbell-undercut lag, cave front angle, cave front length etc. These parameters when changed effect the draw control and mine performance.
Ramp-up constraints	Ramp up constraints are driven by mining and operational constraints which control the production ramp-up beyond that calculated by drawpoint opening rate and PRC. Ramp-up constraints can be used to reflect benchmarking and represent operating constraints not specified in PCBC calculations. For example, roadway

	constraints may limit the production from an Extraction drive unless the permanent roadways have been constructed.
Cave growth strategy	Different cave growth strategies can be employed such as uniform draw which mines similar tons from all drawpoints, proportional draw (draw proportional to remaining tons in draw column), high grading etc. These strategies affect the draw control and mine performance.
Shut-off grade	Shut-off grade determines in ideal conditions when a drawpoint should be closed as any more tons drawn will not be economical for a given set of cost, revenue, and recovery assumptions. This is commonly expressed in terms of grades or Net Smelter Return (NSR) (\$). This KPI reflects ore geology, mine economics and processing conditions
Mining constraints	Different mining constraints are applicable for caving operations which must be addressed during production scheduling and draw control. This includes LHD productivity, secondary breakage, rehabilitation assumptions, level maintenance, extraction drive availability and productivity, ventilation constraints. These set of constraints are unique to each operation and must be addressed.

**Table 3 Output KPI's for Draw control in BC**

Output KPI	Significance for cave flow and draw control strategy
Tons & Metal	The tons and metal profile for a given set of input KPI's discussed above is estimated over different time intervals (yearly, quarterly, monthly etc.).
Draw tons distribution	The distribution of the planned tons over the footprint can be estimated and visualized for the Life of Mine plan (LOMP). Different mines can have different distributions based on specific mining conditions.
Draw metal distribution	The distribution of the planned metal over the footprint can be estimated and visualized. Due to variability in ore grade this distribution can vary from tons distribution. This KPI's help in highlighting the critical drawpoints which must be kept open for a profitable and sustainable mining operation.
Intermittent & Final HOD	The progressive estimated HOD as material is draw from individual drawpoints together with geotechnical modelling provides an understanding of the cave growth.
Intermittent & Final grade/NSR	The estimated grade/NSR profile for individual draw points provide an understanding about the grade/metal performance of different parts of the footprint through the LOMP.
Closing reason	This KPI shows if the drawpoint is planned to be closed due to declining grade, geotechnical constraints, or other operational constraints.
Draw rate	Draw rates provides the estimated tons/drawpoint/day through the LOMP. This KPI is used to check the compliance of the draw control to various input KPI's for a sustainable draw control strategy.
Dilution/Material entry curves	The entry of dilution/material from outside the in-situ drawpoint column is estimated and presented for LOMP. This KPI is affected by input Mixing assumptions such as mixing horizon etc.
Drawpoint availability	The availability of drawpoint for loading operation depends on hang-ups, wet muck, excessive fines, oversize, brow stability, geotechnical stability, tunnel deformation, rehabilitation etc. This can be estimated based on historical data, benchmarking, or through fragmentation and numerical modelling.
Financial metrics	Based on cost, revenue and recovery assumptions along with estimated tons and grades profile financial metrics such as cashflow, NPV, IRR & PVR can be calculated and monitored for assessment of different draw control strategy.

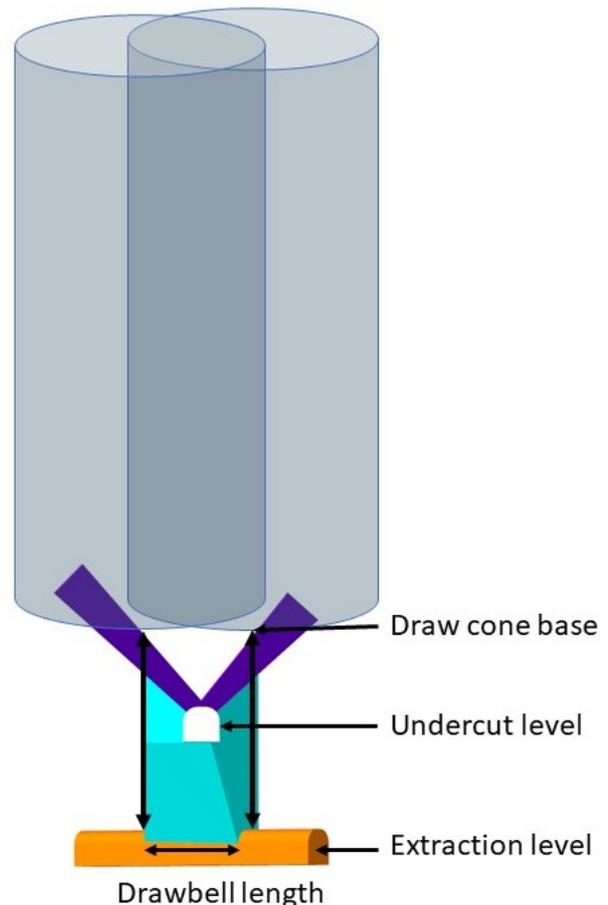
## 5 SENSITIVITY ANALYSIS

The input KPI's described above can be varied depending on mine design, input assumptions and operational conditions which will affect the draw control strategy for a caving operation. Hence, mine planners must perform sensitivity analysis on these KPI's to understand the variability in production profile, recovery and draw control. Two such sensitivity analysis has been showcased to highlight the importance of these input KPI's on cave flow and draw control.

### 5.1 Drawbell length and Draw cone

Based on uniform material flow and interactive draw theory (Janelid & Kvapil, 1966; Laubscher, 1994), the Isolated draw zone (IDZ) diameter for Carrapateena BC1 is between 9 to 11.5m which is dictated by rockmass class, fracture spacing, rock size range and loading width. Based on the sandbox-model tests described in Laubscher (1994) drawpoint spacing can be placed at 1.5 times the IDZ which means theoretical drawbell lengths of up to 17.25m can be explored. However, three main drawbell lengths tested in this paper are 10, 12 and 15m. The assumptions on block cave design parameters based on sandbox-models, especially after marker trial results of SLC operations around material flow showing contradictor results highlights the limitation of this approach to choose mine design parameters.

A draw cone in PCBC defines a volume of rock, which can potentially be extracted from a drawpoint (Diering, 2007). The shape and dimension of this cone can be varied in cave flow modelling software's. Literature review shows draw cone radius can vary from 6.3m to 15m depending on mine design, fragmentation, and cave material properties (Diering, 2007; Laubscher, 2000; Sahupala et al., 2010; Brunton et al., 2016; Garcés et al., 2016). A sensitivity analysis of the draw cone dimension was performed by assuming a cylindrical shape with base at two-third the height of the undercut to simplify the analysis and understand the isolated effect of dimension on recovery (Figure 3). Draw cone radius was varied from 8m to 17m.

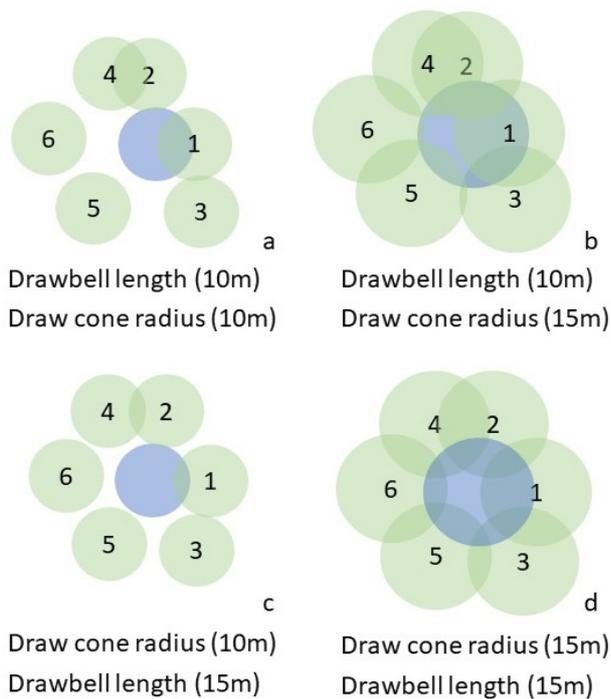


**Figure 3 Draw cone setup.**

The three mine design KPI's closely related to draw cone dimensions are extraction drive spacing, drawpoint drive spacing and drawbell length. The first two KPI's are fixed here and Drawbell length was varied. Drawbell length is dependent on cave load on extraction drives, interactive draw, pillar stability, equipment lengths, Drill & Blast constraints, rill angle of cave material (Laubscher, 2000; Brown, 2007; Pierce, 2019).

A longer drawbell length increases the theoretical horizontal opening from which material can flow to the draw point. As drawbell length is increased the interaction between the drawpoints on the same drawbell reduces for the same drawcone radius as shown in Figure 4b & d with the reduction in area with circle 1. The interaction between drawpoints of the adjacent ED increase as shown by circle 5 & 6 in Figure 4b & d. This increased overlap helps in avoiding cave load on the extraction drive, but it also reduces the volume and hence strength of the pillars supporting the Extraction level.

Operational experience suggests that smaller drawbell length provides more space for loaders and other equipment to operate even when the rill angle is less than ideal. However, for a smaller drawbell length for a smaller drawcone the interaction between the draw cones is considerably reduced as shown in Figure 4a & c. Hence, an optimal drawbell length is a compromise between these parameters. Draw cone dimension and drawbell length were varied to quantify the combined effects of varying these two KPI's.



**Figure 4 Effect of drawbell length on draw cone overlap.**

### 5.2 Minimum and maximum draw rates

Minimum and maximum draw rate constraints are applied on the footprint to control the cave growth and protect against potential safety hazards. Maximum draw rates have a focus on protecting against potential safety hazard of air gaps, air blast and uneven cave growth. This constraint is generally derived and estimated through iterative geotechnical and cave flow modelling analysis along with benchmarking against other caving operations. The PRC used for this paper is based on benchmarking data. During simulation, maximum draw rates are applied through Production rate curves (PRC). PRC estimates the maximum tons that can be

drawn from the drawpoint as a function of the column height. Minimum draw rates can be applied using various inbuilt functions. Minimum draw rates can be used for managing cave loads, drawbell freeze, and differential draw. Cave load refers to the stress on the extraction drives due to the overlying caved material (Pierce, 2019). Cave load increases if the material above the Extraction drive is not being mobilized by drawing material through the draw points (Brown, 2007; Pierce, 2019). Drawbell can get frozen if material is not drawn from drawpoint after drawbells are blasted during cave initiation. Mud rush potential elevates if isolated draw is practiced and nearby draw points are not being drawn which could trigger a mud rush potential in the isolated draw point (Brown, 2007). Differential draw due to poor draw control discipline or operational challenges can lead to non-ideal preferential flow and early dilution entry (Garcés et al., 2016). Recent caving operations have defined stage wise minimum and maximum draw rates as risk mitigation to avoid the above challenges (Ooi, 2023). The robustness of the footprint to different minimum and maximum draw rates must be tested through sensitivity analysis.

## 6 RESULTS AND DISCUSSION

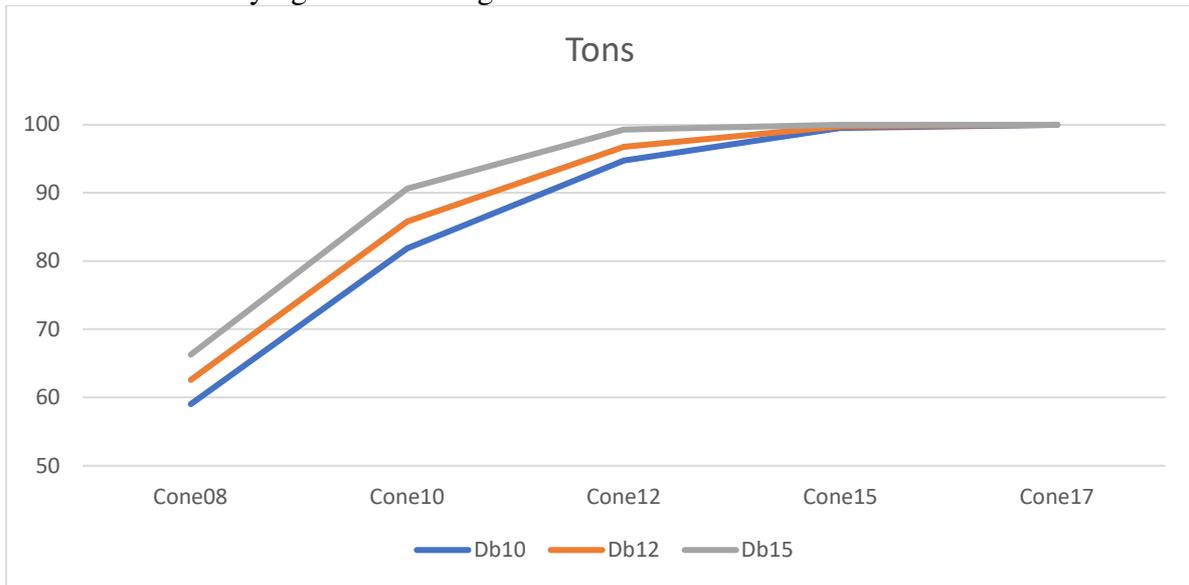
The output KPI's mentioned in section 4 were analyzed and relevant results have been presented here. All simulation results presented were performed on the entire footprint using an even draw strategy that aimed at creating a flatter cave back. This was achieved by using inbuilt function QREMAIN & PAST in PCBC.

### 6.1 Draw cone and Drawbell length

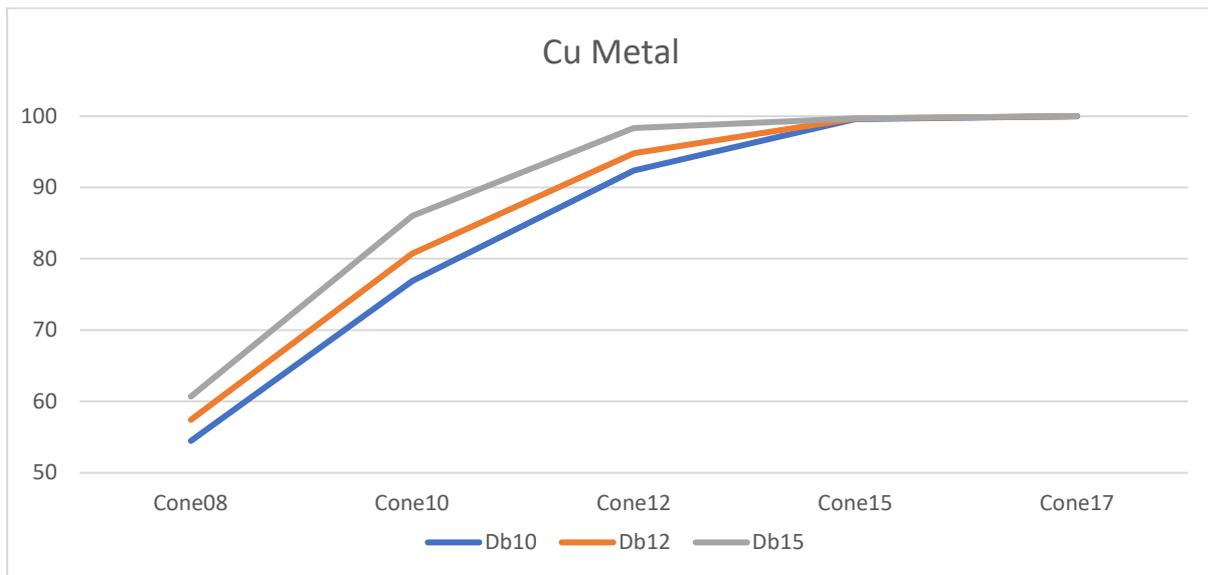
The draw cone radius was varied from 8m to 17m for three drawbell lengths of 10, 12 and 15m. Figure 5 and 6 shows the effect of the KPI's on the total tons mined and the total Cu metal respectively from the footprint on a relative scale to protect confidentiality. The radius of cylindrical draw cone is represented on the x-axis and the estimated total tons mined is represented on the y-axis on a relative scale in Figure 5. Similarly, the estimated total Cu metal mined is represented on the y-axis on a relative

scale in Figure 6. Three separate line plots for drawbell lengths of 10m, 12m and 15m show the combined effect of varying drawbell length and

draw cone dimension on the estimated total tons mined based on simulation results.



**Figure 5 Draw cone and drawbell length sensitivity on total tons mined.**



**Figure 6 Draw cone and drawbell length sensitivity on total Cu metal.**

In figure 5, as the draw cone radius increases the total tons mined increases first rapidly and then plateaus at 15m. In PCBC, a wider draw cone will provide better recovery results. Based on the simulation setup, the plateau is due to the fixed mine design KPI's extraction drive spacing (32m) & drawpoint drive spacing (22m) which together with an increased draw cone radius led to a reasonable overlap between the draw cones in simulation. Observation during limited marker trial data published highlights that the draw cone grow initially from a narrow draw

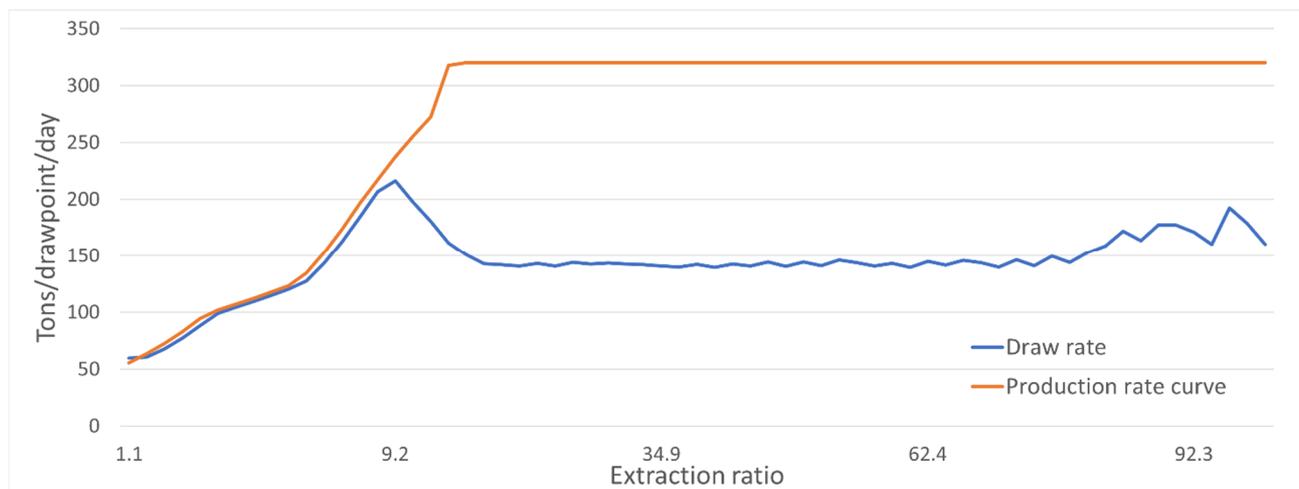
cone to a wider draw cone with time as more material is loaded from the drawpoint (Sahupala et al., 2010; Brunton et al., 2016; Garcés et al., 2016). The current analysis is limited with having static draw cones during the complete life of mine, hence sensitivity analysis is used to understand the variability in total tons and Cu metal profile and the impact of draw cone dimension and drawbell length. Based on simulation results and analysis, a longer drawbell length will provide better recovery and will assist in improving recovery for conditions

that may cause narrower draw cone to be developed. It must be understood that in the simulation as the drawbell lengths and draw cone radius are being increased, more material has a higher probability to be extracted from different drawpoints which in turn led to improved recovery figures. However, these simulation results provide an indication and can't accurately estimate recovery. In reality, recovery is dependent on the actual overlap of material being drawn which can vary depending on geotechnical, operating and mining conditions. If a narrower area is mobilized during draw, the recovery will be low hence calibration of cave flow models during operations is key to understand and estimate recovery. The final decision on drawbell length must be taken by balancing the mine recovery against operability and geotechnical stability.

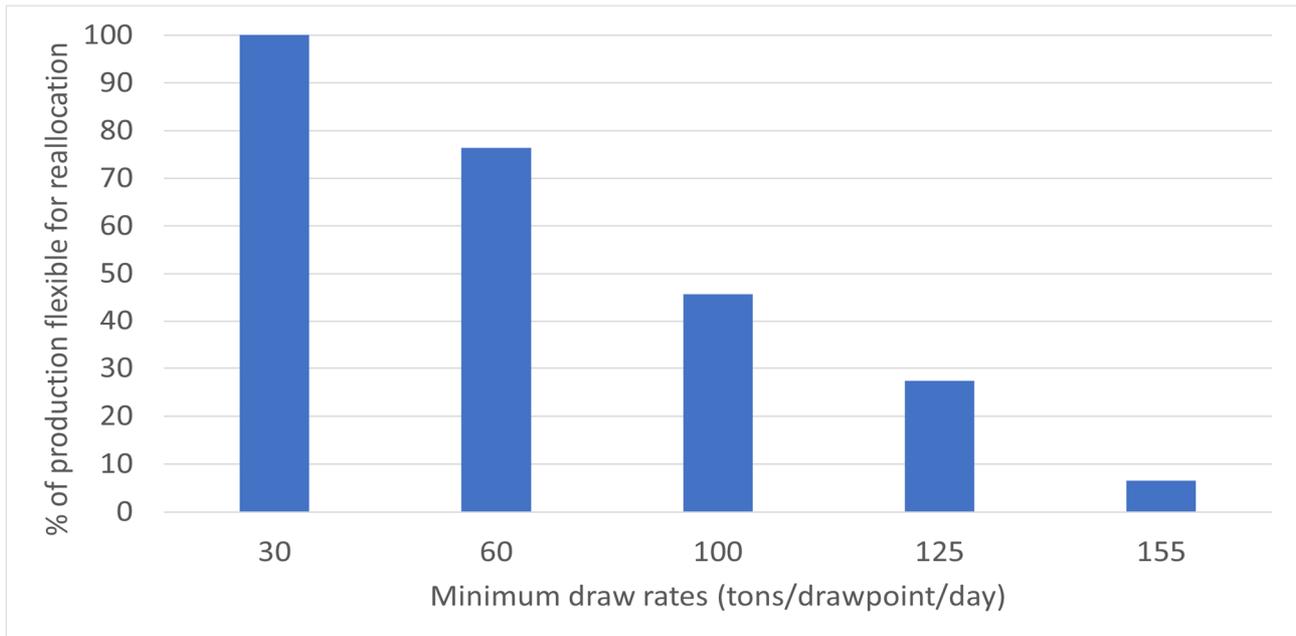
### 6.2 Minimum and maximum draw rates

Maximum and minimum draw rates are generally measured as tons/drawpoints/day. This unit can be applied on different time horizons

(yearly, quarterly, monthly, daily, and shift-wise) in terms of draw control compliance. In this paper, the constraints have been applied on monthly and quarterly time horizons. Maximum draw rates based on benchmarking data were applied to the footprint through PRC. Sanity checks are performed on individual drawpoints to assure that the draw control strategy follows the PRC. Figure 7 shows the draw rate curve for an individual drawpoint alongside the PRC. As seen in Figure 7, the amount of material that can be mined from a drawpoint increases with extraction ratio which is a function of column height. The amount of material that can be drawn eventually reaches a maximum value and stays constant through the rest of LOM for this simulation. The Draw rate curve shows that material is drawn under the limit of the PRC to grow the cave safely and quickly and eventually as steady state is reached, and drawbells continue to be blasted, the draw rate per drawbell goes down. The nature of these draw rate curves are different for different drawpoints but they all pass the sanity check of being under the limit of the assumed PRC.



**Figure 7 Draw rate curve for an individual drawpoint.**



**Figure 8** Production flexibility as a function of minimum draw rates.

Similarly, a minimum draw rate constraint can be applied to the footprint. Figure 8 captures the effect of different minimum draw rates on the footprint by quantifying the percentage of material that can be flexibly drawn from various drawpoints on a relative scale to protect confidentiality. This sensitivity analysis checks the footprint's ability to achieve the steady state production targets across a variety of scenarios. As the minimum draw rate applied increases the draw control strategy gets locked and less flexible. For example, at a minimum draw rate of 100 tons/drawpoint/day approximately 45% of material draw can be allocated if needed over the life of mine to promote specific cave growth strategy, target favorable grade or maintain production in case of non-availability of drawpoints or Extraction drives (due to operational or maintenance reasons). A lower

minimum draw rate provides more flexibility but runs the risk of creating scenarios which can lead to cave loading or other issues discussed in section 5. On the other hand, a high minimum draw rate locks the draw control strategy and leaves little room for flexibility in draw to address cave growth or other operational issues. A staged approach to minimum and maximum draw rates have been taken in recent caving operations and based on the above analysis a similar approach is proposed for draw control at Carrapateena BC to achieve a safe and sustainable BC operation. Table 4 shows the proposed minimum and maximum draw rate limits based on sensitivity analysis, literature review and benchmarking against other caving operations. This is an indicative table and will evolve with time.

**Table 4** Minimum and maximum draw rate constraints (in tons/drawpoint/day)

Stage	Min	Reason	Max	Reason
Swelling removal	30	Avoid drawbell freeze	60	Avoid open cavern
Ramp up (before Critical HR is achieved)	30	Promote cave growth	60	Avoid open cavern
Ramp up (before Undercut completion)	50	Promote cave growth	100	Reduced air gap risk
Before breakthrough to SLC	50	Promote cave growth	200	Uniform cave growth & reduced air gap risk
Steady state	100	Avoid cave loading	320	Good draw control practice

## 7 CONCLUSION

The sensitivity analysis presented highlights the importance of the input KPI's on the mine performance. Due to the inherent variability and uncertainties associated with caving operations, mine planners must perform systematic sensitivity analysis on the input KPI's discussed in the paper and capture the effect of these variations through the output KPI's. The results then inform the life of mine plans and highlight the variability in performance that can be expected depending on the mining, geotechnical and operational conditions. This approach also helps in quantifying the robustness of the draw control strategy to various changes in the mine environment.

## 8 FUTURE WORK

Further sensitivity will be performed to be able to inform the life of mine plans going forward about the uncertainty and variability associated with the mine performance. The results from draw cone dimension and drawbell length analysis will help inform drawbell geometry and future marker trial work for the Carrapateena BC and eventually the results will be used to calibrate future cave flow simulations.

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