Appendix X

Assessment of Closure Conditions and Water Management Options for the Wafi-Golpu Block Cave and Subsidence Zone

DISCLAIMER

This disclaimer applies to and governs the disclosure and use of this Environmental Impact Statement ("EIS"), and by reading, using or relying on any part(s) of the EIS you accept this disclaimer in full.

This Environmental Impact Statement, including the Executive Summary, and all chapters of and attachments and appendices to it and all drawings, plans, models, designs, specifications, reports, photographs, surveys, calculations and other data and information in any format contained and/or referenced in it, is together with this disclaimer referred to as the "**EIS**".

Purpose of EIS

The EIS has been prepared by, for and on behalf of Wafi Mining Limited and Newcrest PNG 2 Limited (together the "**WGJV Participants**"), being the participants in the Wafi-Golpu Joint Venture ("**WGJV**") and the registered holders of exploration licences EL 440 and EL1105, for the sole purpose of an application (the "**Permit Application**") by them for environmental approval under the Environment Act 2000 (the "**Act**") for the proposed construction, operation and (ultimately) closure of an underground copper-gold mine and associated ore processing, concentrate transport and handling, power generation, water and tailings management, and related support facilities and services (the "**Project**") in Morobe Province, Independent State of Papua New Guinea. The EIS was prepared with input from consultants engaged by the WGJV Participants and/or their related bodies corporate ("**Consultants**").

The Permit Application is to be lodged with the Conservation and Environment Protection Authority ("**CEPA**"), Independent State of Papua New Guinea.

Ownership and Copyright

The EIS is the sole property of the WGJV Participants, who reserve and assert all proprietary and copyright ©2018 interests.

Reliance and Use

The EIS is intended and will be made available to CEPA, for review by CEPA and other applicable agencies of the Government of the Independent State of Papua New Guinea ("**Authorised Agencies**"), for the purpose of considering and assessing the Permit Application in accordance with the Act ("**Authorised Purpose**"), and for no other purpose whatsoever.

The EIS shall not be used or relied upon for any purpose other than the Authorised Purpose, unless express written approval is given in advance by the WGJV Participants.

Except for the Authorised Purpose, the EIS, in whole or in part, must not be reproduced, unless express written approval is given in advance by the WGJV Participants.

This disclaimer must accompany every copy of the EIS.

The EIS is meant to be read as a whole, and any part of it should not be read or relied upon out of context.

Limits on investigation and information

The EIS is based in part on information not within the control of either the WGJV Participants or the Consultants. While the WGJV Participants and Consultants believe that the information contained in the EIS should be reliable under the conditions and subject to the limitations set forth in the EIS, they do not guarantee the accuracy of that information.

No Representations or Warranties

While the WGJV Participants, their Related Bodies Corporate and Consultants believe that the information (including any opinions, forecasts or projections) contained in the EIS should be reliable under the conditions and subject to the limitations set out therein, and provide such information in good faith, they make no warranty, guarantee or promise, express or implied, that any of the information will be correct, accurate, complete or up to date, nor that such information will remain unchanged after the date of issue of the EIS to CEPA, nor that any forecasts or projections will be realised. Actual outcomes may vary materially and adversely from projected outcomes.

The use of the EIS shall be at the user's sole risk absolutely and in all respects. Without limitation to the foregoing, and to the maximum extent permitted by applicable law, the WGJV Participants, their Related Bodies Corporate and Consultants:

- do not accept any responsibility, and disclaim all liability whatsoever, for any loss, cost, expense or damage (howsoever arising, including in contract, tort (including negligence) and for breach of statutory duty) that any person or entity may suffer or incur caused by or resulting from any use of or reliance on the EIS or the information contained therein, or any inaccuracies, misstatements, misrepresentations, errors or omissions in its content, or on any other document or information supplied by the WGJV Participants to any Authorised Agency at any time in connection with the Authorised Agency's review of the EIS; and
- expressly disclaim any liability for any consequential, special, contingent or penal damages whatsoever.

The basis of the Consultants' engagement is that the Consultants' liability, whether under the law of contract, tort, statute, equity or otherwise, is limited as set out in the terms of their engagement with the WGJV Participants and/or their related bodies corporate.

Disclosure for Authorised Purpose

The WGJV Participants acknowledge and agree that, for the Authorised Purpose, the EIS may be:

- copied, reproduced and reprinted;
- published or disclosed in whole or in part, including being made available to the general public in accordance with section 55 of the Act. All publications and disclosures are subject to this disclaimer.

Development of Project subject to Approvals, Further Studies and Market and Operating Conditions

Any future development of the Project is subject to further studies, completion of statutory processes, receipt of all necessary or desirable Papua New Guinea Government and WGJV Participant approvals, and market and operating conditions.

Engineering design and other studies are continuing and aspects of the proposed Project design and timetable may change.

NEWCREST MINING LIMITED DISCLAIMER

Newcrest Mining Limited ("**Newcrest**") is the ultimate holding company of Newcrest PNG 2 Limited and any reference below to "Newcrest" or the "Company" includes both Newcrest Mining Limited and Newcrest PNG 2 Limited.

Forward Looking Statements

The EIS includes forward looking statements. Forward looking statements can generally be identified by the use of words such as "may", "will", "expect", "intend", "plan", "estimate", "anticipate", "continue", "outlook" and "guidance", or other similar words and may include, without limitation, statements regarding plans, strategies and objectives of management, anticipated production or construction commencement dates and expected costs or production outputs. The Company continues to distinguish between outlook and guidance. Guidance statements relate to the current financial year. Outlook statements relate to years subsequent to the current financial year.

Forward looking statements inherently involve known and unknown risks, uncertainties and other factors that may cause the Company's actual results, performance and achievements to differ materially from statements in this EIS. Relevant factors may include, but are not limited to, changes in commodity prices, foreign exchange fluctuations and general economic conditions, increased costs and demand for production inputs, the speculative nature of exploration and project development, including the risks of obtaining necessary licences and permits and diminishing quantities or grades of reserves, political and social risks, changes to the regulatory framework within which the Company operates or may in the future operate, environmental conditions including extreme weather conditions, recruitment and retention of personnel, industrial relations issues and litigation.

Forward looking statements are based on the Company's good faith assumptions as to the financial, market, regulatory and other relevant environments that will exist and affect the Company's business and operations in the future.

The Company does not give any assurance that the assumptions will prove to be correct. There may be other factors that could cause actual results or events not to be as anticipated, and many events are beyond the reasonable control of the Company. Readers are cautioned not to place undue reliance on forward looking statements. Forward looking statements in the EIS speak only at the date of issue. Except as required by applicable laws or regulations, the Company does not undertake any obligation to publicly update or revise any of the forward looking statements or to advise of any change in assumptions on which any such statement is based.

Non-IFRS Financial Information

Newcrest results are reported under International Financial Reporting Standards (IFRS) including EBIT and EBITDA. The EIS also includes non-IFRS information including Underlying profit (profit after tax before significant items attributable to owners of the parent company), All-In Sustaining Cost (determined in accordance with the World Gold Council Guidance Note on Non-GAAP Metrics released June 2013), AISC Margin (realised gold price less AISC per ounce sold (where expressed as USD), or realised gold price less AISC per ounce sold divided by realised gold price (where expressed as a %), Interest Coverage Ratio (EBITDA/Interest payable for the relevant period), Free cash flow (cash flow from operating activities less cash flow related to investing activities), EBITDA margin (EBITDA expressed as a percentage of revenue) and EBIT margin (EBIT expressed as a percentage of revenue). These measures are used internally by Management to assess the performance of the business and make decisions on the allocation of resources and are included in the EIS to provide greater understanding of the underlying performance of Newcrest's operations. The non-IFRS information has not been subject to audit or review by Newcrest's external auditor and should be used in addition to IFRS information.

Ore Reserves and Mineral Resources Reporting Requirements

As an Australian Company with securities listed on the Australian Securities Exchange (ASX), Newcrest is subject to Australian disclosure requirements and standards, including the requirements of the Corporations Act 2001 and the ASX. Investors should note that it is a requirement of the ASX listing rules that the reporting of Ore Reserves and Mineral Resources in Australia comply with the 2012 Edition of the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (the JORC Code) and that Newcrest's Ore Reserve and Mineral Resource estimates comply with the JORC Code.

Competent Person's Statement

The information in the EIS that relates to Golpu Ore Reserves is based on information compiled by the Competent Person, Mr Pasqualino Manca, who is a member of The Australasian Institute of Mining and Metallurgy. Mr Pasqualino Manca, is a full-time employee of Newcrest Mining Limited or its relevant subsidiaries, holds options and/or shares in Newcrest Mining Limited and is entitled to participate in Newcrest's executive equity long term incentive plan, details of which are included in Newcrest's 2017 Remuneration Report. Ore Reserve growth is one of the performance measures under recent long term incentive plans. Mr Pasqualino Manca has sufficient experience which is relevant to the styles of mineralisation and type of deposit under consideration and to the activity which he is undertaking to qualify as a Competent Person as defined in the JORC Code 2012. Mr Pasqualino Manca consents to the inclusion of material of the matters based on his information in the form and context in which it appears.

HARMONY GOLD MINING COMPANY LIMITED DISCLAIMER

Harmony Gold Mining Company Limited ("**Harmony**") is the ultimate holding company of Wafi Mining Limited and any reference below to "Harmony" or the "Company" includes both Harmony Gold Mining Company Limited and Wafi Mining Limited.

Forward Looking Statements

These materials contain forward-looking statements within the meaning of the safe harbor provided by Section 21E of the Securities Exchange Act of 1934, as amended, and Section 27A of the Securities Act of 1933, as amended, with respect to our financial condition, results of operations, business strategies, operating efficiencies, competitive positions, growth opportunities for existing services, plans and objectives of management, markets for stock and other matters. These include all statements other than statements of historical fact, including, without limitation, any statements preceded by, followed by, or that include the words "targets", "believes", "expects", "aims", "intends", "will", "may", "anticipates", "would", "should", "could", "estimates", "forecast", "predict", "continue" or similar expressions or the negative thereof.

These forward-looking statements, including, among others, those relating to our future business prospects, revenues and income, wherever they may occur in this EIS and the exhibits to this EIS, are essentially estimates reflecting the best judgment of our senior management and involve a number of risks and uncertainties that could cause actual results to differ materially from those suggested by the forward-looking statements. As a consequence, these forward-looking statements should be considered in light of various important factors, including those set forth in these materials. Important factors that could cause actual results to differ materially from estimates or projections contained in the forward-looking statements include, without limitation: overall economic and business conditions in South Africa, Papua New Guinea, Australia and elsewhere, estimates of future earnings, and the sensitivity of earnings to the gold and other metals prices, estimates of future gold and other metals production and sales, estimates of future cash costs, estimates of future cash flows, and the sensitivity of cash flows to the gold and other metals prices, statements regarding future debt repayments, estimates of future capital expenditures, the success of our business strategy, development activities and other initiatives, estimates of reserves statements regarding future exploration results and the replacement of reserves, the ability to achieve anticipated efficiencies and other cost savings in connection with past and future acquisitions, fluctuations in the market price of gold, the occurrence of hazards associated with underground and surface gold mining, the occurrence of labour disruptions, power cost increases as well as power stoppages, fluctuations and usage constraints, supply chain shortages and increases in the prices of production imports, availability, terms and deployment of capital, changes in government regulation, particularly mining rights and environmental regulation, fluctuations in exchange rates, the adequacy of the Group's insurance coverage and socio-economic or political instability in South Africa and Papua New Guinea and other countries in which we operate.

For a more detailed discussion of such risks and other factors (such as availability of credit or other sources of financing), see the Company's latest Integrated Annual Report and Form 20-F which is on file with the Securities and Exchange Commission, as well as the Company's other Securities and Exchange Commission filings. The Company undertakes no obligation to update publicly or release any revisions to these forward-looking statements to reflect events or circumstances after the date of this EIS or to reflect the occurrence of unanticipated events, except as required by law.

Competent Person's Statement

The Wafi-Golpu Joint Venture is an unincorporated joint venture between a wholly-owned subsidiary of Harmony Gold Mining Company Limited and a wholly-owned subsidiary of Newcrest Mining Limited.

The information in the EIS that relates to Golpu Ore Reserves is based on information compiled by the Competent Person, Mr Pasqualino Manca, who is a member of The Australasian Institute of Mining and Metallurgy. Mr Pasqualino Manca, is a full-time employee of Newcrest Mining Limited or its relevant subsidiaries, holds options and/ or shares in Newcrest Mining Limited and is entitled to participate in Newcrest's executive equity long term incentive plan, details of which are included in Newcrest's 2017 Remuneration Report. Ore Reserve growth is one of the performance measures under recent long term incentive plans. Mr Pasqualino Manca has sufficient experience which is relevant to the styles of mineralisation and type of deposit under consideration and to the activity which he is undertaking to qualify as a Competent Person as defined in the JORC Code 2012. Mr Pasqualino Manca consents to the inclusion of material of the matters based on his information in the form and context in which it appears.

PITEAU ASSOCIATES SOUTH AFRICA
GEOTECHNICAL AND
HYDROGEOLOGICAL CONSULTANTS

25 RUDD ROAD, ILLOVO, JOHANNESBURG,
GAUTENG, SOUTH AFRICA

www.piteau.com

PASA file: 3932TM01v6

30th May 2018

TECHNICAL MEMORANDUM

Wafi Golpu Australia Services Pty Ltd
Level 2, 189 Coronation Drive
Milton, QLD 4064
Australia

Attention: Mr. Aymeric Beaulavon
Aymeric.Beaulavon@wafigolpujv.com

From: Martin Williams, Group Geochemistry Advisor
mwilliams@piteau.com

SUBJECT: ASSESSMENT OF CLOSURE CONDITIONS AND WATER MANAGEMENT OPTIONS FOR THE WAFI-GOLPU BLOCK CAVE AND SUBSIDENCE ZONE: REVISION IV

1 INTRODUCTION

This technical memorandum constitutes a fourth revision of a document originally dated 12th January 2018 (ref. 3932TM01v1), prepared by Piteau Associates on behalf of Wafi-Golpu Australia Services Pty Ltd (WGAS) subsequent to the receipt of review comments from WGAS, Coffey and the WGJV Owners Team. It outlines a preliminary assessment of the hydrological, hydrogeological and water quality regime which will develop following the closure of the proposed Wafi-Golpu mine in Papua New Guinea. Mining is to be undertaken through the development of block-caves which will be accessed by the Watut twin declines entering the orebody from the WNW, plus a secondary access at Nambonga. The cave zone will ultimately propagate to the surface, producing a subsidence zone which will partially fill with water post-closure.

Pre-mining groundwater levels lie above the elevation of anticipated cave development. Flooding of the caves will therefore be inevitable following the cessation of active dewatering. Key considerations for both the environmental permitting process and the design of a robust closure plan for the project thus include the prediction of:

- (i) The rate at which mine inundation will occur following the completion of mining,
- (ii) The final elevation of any permanent water body in the caves and/or subsidence zone, and the extent to which potentially acid forming rock will be permanently submerged or, conversely, left exposed above the water level,
- (iii) Potential pathways for discharge to the wider surface water and groundwater system, and
- (iv) The chemical quality of water which will occupy and/or discharge from the cave zone and any overlying subsidence zone lake.

Numerical models for prediction of the groundwater flow regime and the surface water balance of the Golpu project throughout its development and operations phases have previously been constructed by Piteau for the purposes of supporting the design of an appropriate mine dewatering system for inclusion in the 2017/18 Golpu Feasibility Study Update (FSU). This memorandum outlines the modification of these models to predict the dynamics of the groundwater and surface water system in the Golpu block caves and subsidence zone following closure.

2 CONCEPTUALIZATION OF POST-CLOSURE CONDITIONS

2.1 Mine hydrology

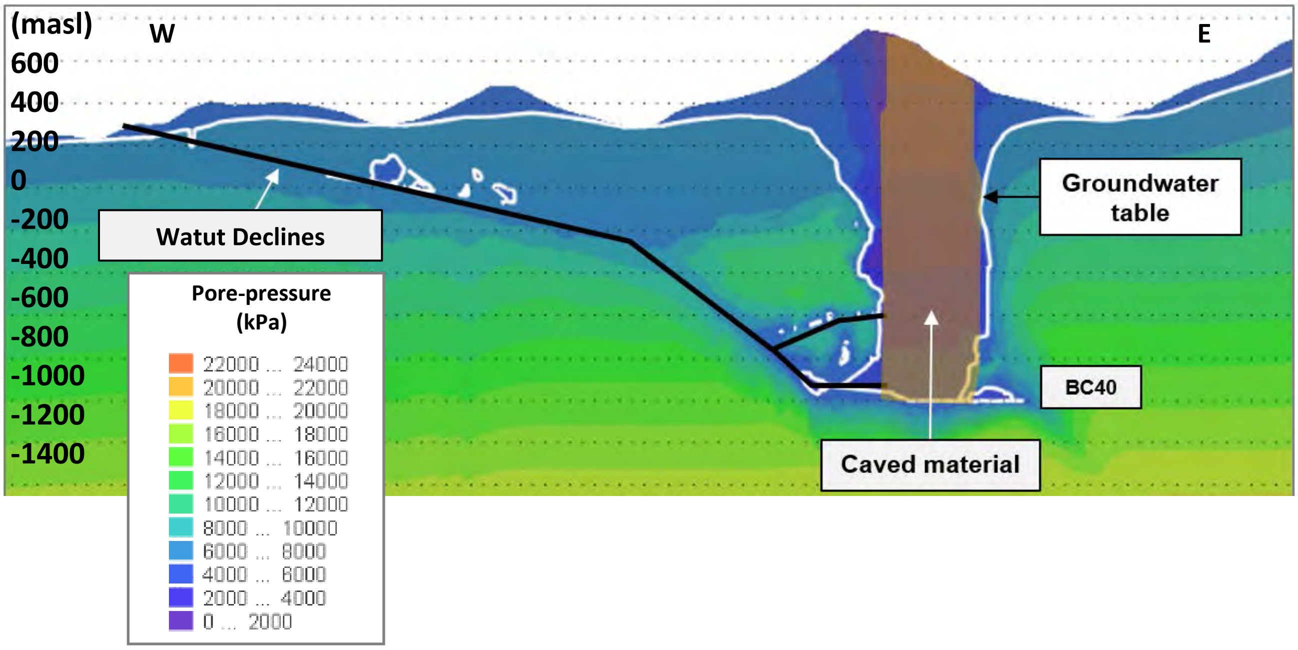
The mine plan incorporated into the Golpu 2017/18 FSU contemplates the termination of mining in 2056. Over the preceding three decades, continual dewatering from sumps within the block caves and/or via abstraction from peripheral wells will induce localized depression of the phreatic surface (to below the caving level). Model simulations of the effect of dewatering through mine life (Piteau, 2017) suggest that a steep cone of depression will form with a maximum lateral extent of no more than 1500 m, as illustrated in Figure 1. Groundwater draw-down will also occur along the axes of the Watut twin declines and the Nambonga decline, both of which will effectively act as drains.

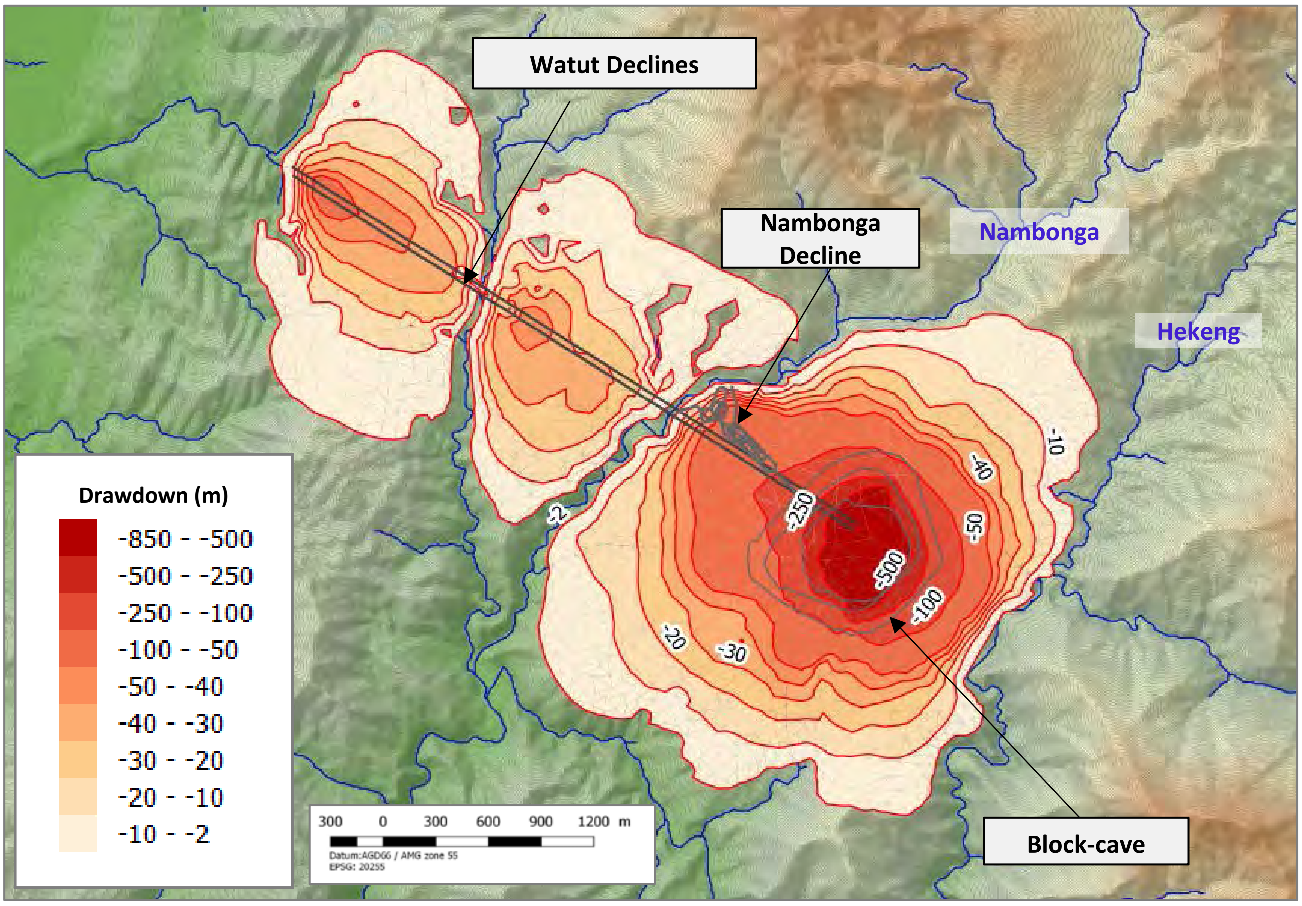
The surface expression of the block cave zone at closure is anticipated to comprise a subsidence zone created by the gravitational slumping of unsupported rock. The subsidence zone has been estimated through geotechnical model simulations as likely to be of the order of 900 m in diameter with a base elevation at around 250 masl. The rock mass underlying the subsidence zone will be highly fragmented and of greater porosity and permeability than the existing in-situ rock.

The final block caves are predicted to possess a total void space of the order of 278 Mm^3, not including development voids. This will, however, largely be occupied by rock from the collapse zone and the residual space which may ultimately be occupied by water is estimated on the basis of geotechnical modelling to range from between 55 to 97 Mm^3. Inundation of the void space will commence immediately following the termination of dewatering at a rate dictated (for passive conditions) by (a) local recharge through the subsidence zone (plus the transmissive units of the host rock to the ore-zone), (b) the hydraulic gradient associated with the cone of depression and (c) the hydraulic properties of the rock mass, in particular the fill within the subsidence zone.

Progressively rising water levels in the cave zone will be accompanied by inundation of the mine workings and declines. Without intervention, this would result in perpetual decant at both the Watut and Nambonga portal elevations. To avert this, the present concept for closure involves hydraulic sealing at the two portals. In consequence, groundwater elevations may be expected to continue to rise until such point as the natural pre-mining phreatic surface is established, or to a finite point at which discharge from the system is in equilibrium with recharge. This may occur, for example, through the rejuvenation of springs.

Given that the natural groundwater elevation in the vicinity of the Golpu orebody is considerably higher than the anticipated base-level of the zone of subsidence at closure, it is expected that a significant water body will form in the subsidence zone following inundation of the underlying block caves. The upper elevation of the subsidence zone lip is estimated as likely to lie at around 450 masl. This has been defined simply as the lowest topographic point where the modelled subsidence zone intersects current topography, as per the digital elevation model (DEM) for the project. The maximum depth of a future subsidence zone lake would therefore be around 200 m depth (see Figure 2), assuming that a condition of recharge-discharge equilibrium is not attained prior to lake reaching the 450 masl elevation. Should this level be reached, any additional



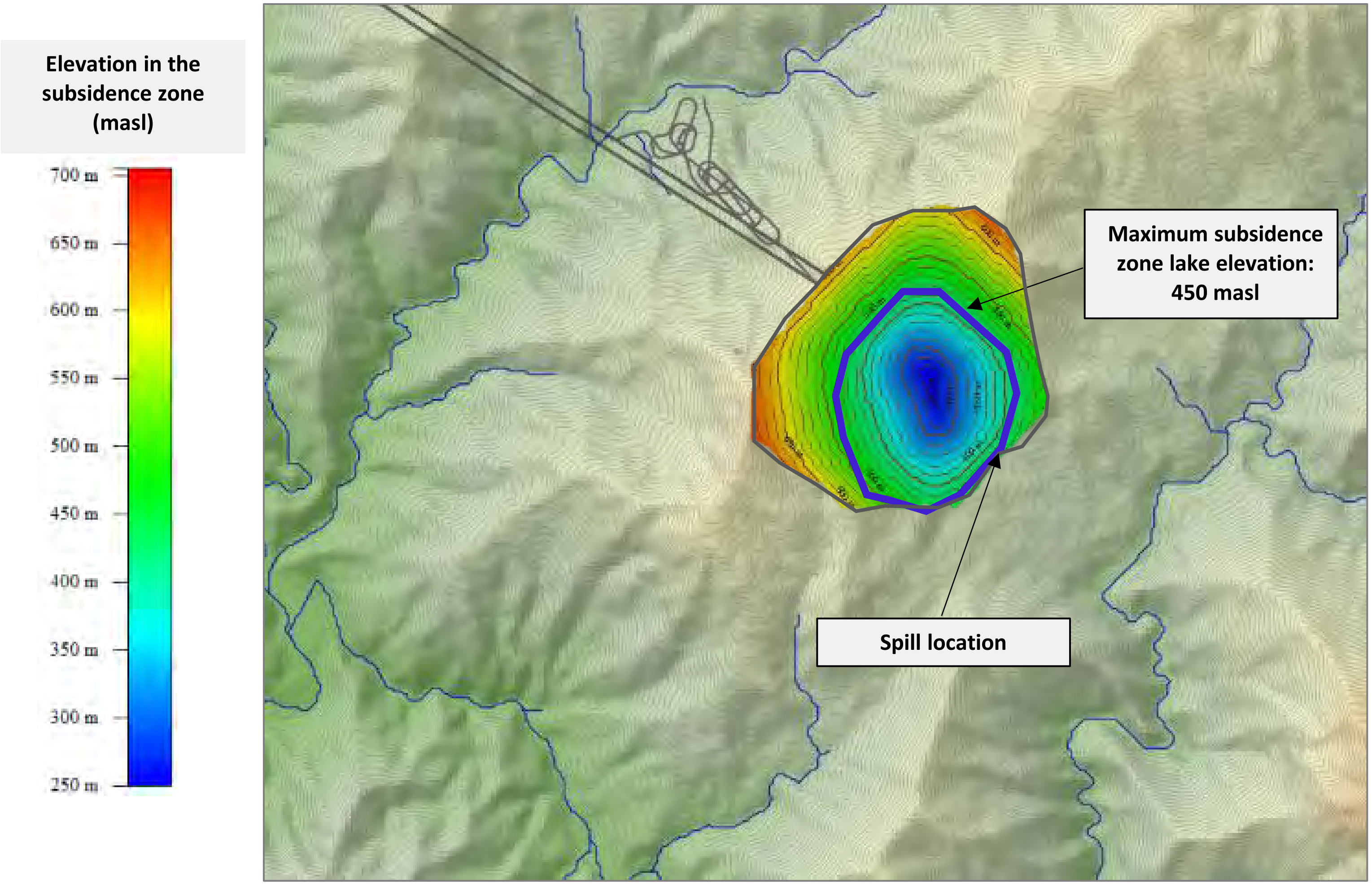


Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

Intial drawdown for the closure model

By	FB	Date	Jan 2018
Approved	AR	Fig	01



Maximum subsidence zone lake elevation: 450 masl

Spill location

Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

Subsidence zone and maximum subsidence zone lake extent

By	FB	Date	Jan 2018
Approved	AR	Fig	02

input to the lake water balance in excess of losses through seepage or evaporation will discharge as spillage to the natural surface drainage system.

2.2 Water quality

From a water quality perspective, the component of inflow to the block caves associated with infiltration from the overlying subsidence zone may be particularly significant. The rock zone which extends from the upper limit of cave development to the surface is characterized by high-sulphidation type epithermal mineralization. Enrichment of this zone is evident with respect to a suite of hypogene sulphates and sulphides with strong acid-forming propensity. Natural buffering capacity of the primary host lithologies has been largely eliminated by argillic to advanced argillic alteration and silica flooding. The proportion of water ingress via this pathway may thus strongly influence the pH and solute chemistry of the emergent groundwater in the cave voids.

In addition to inflow through infiltration from the overlying subsidence zone inundation of the block cave will occur through groundwater flow through the district host-rock sequence in accordance with the inward hydraulic gradient towards the caves. This water will progressively flush sulphide oxidation products into the emergent water body. The chemistry of water in the mine void will to a substantial extent be dependent on the time-frame over which complete flooding occurs, and hence the period over which exposed sulphide in the cave walls and caved material will continue to generate acidity, SO_4 and metals through oxidation.

3 APPROACH TO NUMERICAL MODELLING OF POST-CLOSURE CONDITIONS

The conceptualization described in Section 2 (above) of cave inundation and lake development following closure at Golpu has been applied as a foundation for numerical model predictions of post-closure inundation rates, final steady state discharge and water quality. Predictions of the physical hydrodynamics of the system have been generated for two alternative management scenarios:

1) Scenario 1: This comprises the ‘base case’ scenario in which no active intervention is applied to natural rates of inundation of the cave zone.

2) Scenario 2: This contemplates the induction of accelerated flooding of the cave zone through pumping of water from a fluvial source at a nominal rate of 500 L/s until such time as inundation reaches the base of the subsidence zone (at around 250 masl). The rate of 500 L/s used in this scenario was proposed by WGAS, as this corresponds to the installed capacity of the water abstraction system envisaged for mine operations. Continued use of this installed capacity would therefore minimize any requirement for additional pumping infrastructure.

3) Within the specific context of water quality evolution, a third condition was also modelled involving accelerated flooding of the cave zone as per hydro-dynamic Scenario 2 (above) but with concurrent addition of a hydrated lime slurry, administered to maintain a nominal pH of 7.

For purposes of simulation of the dynamics of groundwater inflow to the cave zone under the above scenarios, a groundwater model previously developed in FEFLOW for simulation of operational mine inflows, dewatering system performance and rates of drawdown throughout mine life was used to simulate the rates of inflow which would be anticipated in response to the inward hydraulic gradient towards the cave void on closure, and during the progressive recovery of the cone of depression to a final steady-state condition. In parallel with the groundwater simulations performed in FEFLOW, the previously developed surface water balance model for Golpu constructed in GoldSim (Piteau, 2017) was applied to conduct physical water balance simulations over a corresponding time-period for the subsidence zone lake.

Modelling of the quality of water during and following inundation of the block cave and overlying subsidence zone was performed essentially through extrapolation of results of kinetic tests performed by WGAS using representative samples of major wall rock lithotypes from the Golpu deposit. Leachates from such tests were variably used to assign chemical signatures to the major components of the cave and lake water balances, which were subsequently mixed in appropriate proportions in a simple thermodynamic model (constructed using PHREEQC) for the cave, and a probabilistic water balance and chemical mass balance (constructed in GoldSim) for the overlying lake.

4 PHYSICAL MODEL CONSTRUCTION

4.1 Groundwater flow model

The FEFLOW model previously developed by Piteau (2017) to simulate the progressive drawdown of water levels in the vicinity of the mine throughout operations was used to predict the post-closure rebound of groundwater to an elevation approximating the base of the subsidence zone. Thereafter, the inundation of the subsidence zone by an open water body was simulated using a surface water balance approach (using GoldSim). To establish a starting condition for assessment of post-closure inundation dynamics, the operational FEFLOW model was used to predict the hydraulic-head distribution in the area of drawdown on termination of active dewatering. The spatial distribution of rock hydraulic properties (hydraulic conductivity, specific yield) was maintained to replicate precisely that defined for the last stress-period of the life-of-mine (LOM) model. Most boundary conditions were also maintained through the transition from the operations to closure, with the following exceptions:

- Seepage nodes representing the Watut Declines, the Nambonga Decline and all other inter-connecting tunnels were deactivated in FEFLOW to permit the simulation of passive recovery of groundwater levels.
- The value used to represent recharge over the subsidence zone was set to 25 L/s, as calculated from the GoldSim model. This recharge value is considered in the post-closure groundwater model to comprise (i) a 10% component arising from direct rainfall, assumed to flow preferentially through the cave zone to the upper extraction level (with a mean travel time of two days assigned to simulate large-scale surface fractures which produce preferential pathways), and (ii) a 90% component of direct rainfall which is assumed to be subject to behavior as defined by an AWBM runoff model (thus influenced by evaporation and soil moisture storage). There is no run-on catchment reporting to the subsidence zone as the subsidence zone effectively daylights at the top of Mount Golpu.
- Drainable porosity values were entered into the model to represent the cave rock fill. These were set across a range of 20% to 35%, thus producing an envelope of effective storage or void space values.
- For Scenarios 2 and 3, a pumping well was configured into the model to produce an artificial cave inflow rate of 500 L/s.

It should be noted that the void space of the remainder of the underground workings has not been considered since the current FeFlow model does not include these areas as voids, and there are a significant number of unknowns such as the location of seals and the final layout of tunnels.

4.2 Surface water balance

4.2.1 Overview

The development of a lake within the subsidence zone was simulated using GoldSim. Since runoff and direct evaporation are interdependent on the surface area and elevation of the pit lake, the model is highly dynamic. GoldSim was considered an appropriate model tool due to its ability to simulate such highly dynamic systems. Inputs derived for the WGJV site-wide water and mass balance model as reported by Piteau (2017) were used to represent rainfall, evaporation and catchment runoff reporting to the subsidence zone, while outputs from the FEFLOW numerical groundwater model were used to represent the rate of groundwater rise into the subsidence zone as an integral component of the GoldSim lake water balance. The geometry of the subsidence zone was defined in the model based on WGJV file *BC40_crater_cut_AMG66_6-10-17.dxf.*

4.2.2 Meteorological Inputs

The stochastic precipitation generator developed previously for use in the WGJV site-wide water and mass balance model (Piteau, 2017) was transposed for use in the post-closure subsidence zone lake development model. The generator uses a second-order Markov chain derived from the WGEN model of the United States Department of Agriculture (1984). It includes a Boolean probability distribution to predict the occurrence of rain on a particular day, and probabilistic distribution to express the amount of rain on any given day. Both are generated using a Monte Carlo simulation. Wafi Camp daily total precipitation data from the 26-year record (1990 to 2015) were used to populate and calibrate the precipitation generator.

There are no daily evaporation data recorded at the WGJV site. Composite Bulolo and Erap records of monthly mean evaporation were therefore used in the closure model, as defined in *Hydrology Assessment for the Golpu Project* (Highlands Hydrology, October 2015). These data are summarized in Table 1.

Table 1: GoldSim pan evaporation dataset (from Highlands Hydrology, 2015)

Month	Mean pan evaporation (mm/d)
January	6.13
February	6.12
March	5.84
April	5.63
May	5.23
June	4.57
July	4.90
August	5.23
September	5.57
October	6.06
November	6.80
December	6.35

4.2.3 Hydrological Inputs

The Australian Water Balance Model (AWBM) was used to calculate catchment runoff reporting to the subsidence zone. Results from the AWBM were then applied to calibrate curve numbers in the GoldSim model. The AWBM module within the Australian eWater Rainfall Runoff Library (RRL) software package was used to calibrate a runoff model for the Bavaga River at Bavaga Village (2015 to 2017) as part of the site-wide water and mass balance model development. The AWBM was calibrated to replicate the flow duration curve while maintaining typical responses to rainfall events. Further information can be found in *Wafi Golpu Site-wide Water and Mass Balance Model* (Piteau, October 2017). The calibrated values (Table 2) are used as inputs to a GoldSim version of the AWBM within the subsidence zone lake development model.

Table 2: Calibrated AWBM inputs for the Bavaga River at Bavaga Village

Parameter	Value		Parameter	Value		Parameter	Value
A1	0.32		C1	5 mm		BFI	0.42
A2	0.20		C2	200 mm		K_{surf}	0.97
A3	0.48		C3	700 mm		K_{base}	0.65

4.2.4 Groundwater Inputs

Groundwater flow to and from the subsidence zone lake was defined using the FEFLOW numerical groundwater model. The magnitude of flow is essentially dependent upon the head differential between the lake and surrounding groundwater. This relationship, as included in the GoldSim model, is summarised in Table 3.

Table 3: Relationship between lake elevation and net groundwater inflow

Lake Elevation (mRL)	Net groundwater Inflow (L/s)
250	18.6
300	15.9
350	12.7
400	8.5
450	3.8

4.2.5 Lake development algorithm

To simulate the development of a lake, a water balance algorithm was developed for the subsidence zone within GoldSim. The model is configured to run on a daily time-step. At each step, the model calculates

1. Inflows to the subsidence zone as a function of:
   - runoff and interflow from the upgradient catchment and subsidence zone walls – defined using the AWBM
   - direct rainfall onto open water in the subsidence zone– assumed runoff coefficient of 1
   - groundwater inflow – derived from the FEFLOW numerical groundwater model.
2. Outflows from the subsidence zone, comprising:
   - evaporation from the upgradient catchment – incorporated into the AWBM
   - evaporation from open water in the subsidence zone – using pan evaporation with a factor of 0.7
   - seepage to groundwater – incorporated into the net groundwater inflow.

3. The volume of water in storage in the subsidence zone at the end of the time-step using the inflows, outflows and volume of water in storage from the previous step. If the volume in storage exceeds the capacity (spill point at 450 mRL), any excess water is assumed to be discharged to the environment and the volume set to the maximum capacity.
4. The surface area (for direct precipitation and evaporation calculations) and elevation of water in the subsidence zone using the volume-area-elevation relationship derived from the final subsidence zone geometry file.

Flows from the springs are not incorporated into the surface water balance as they are incorporated as losses from the groundwater system

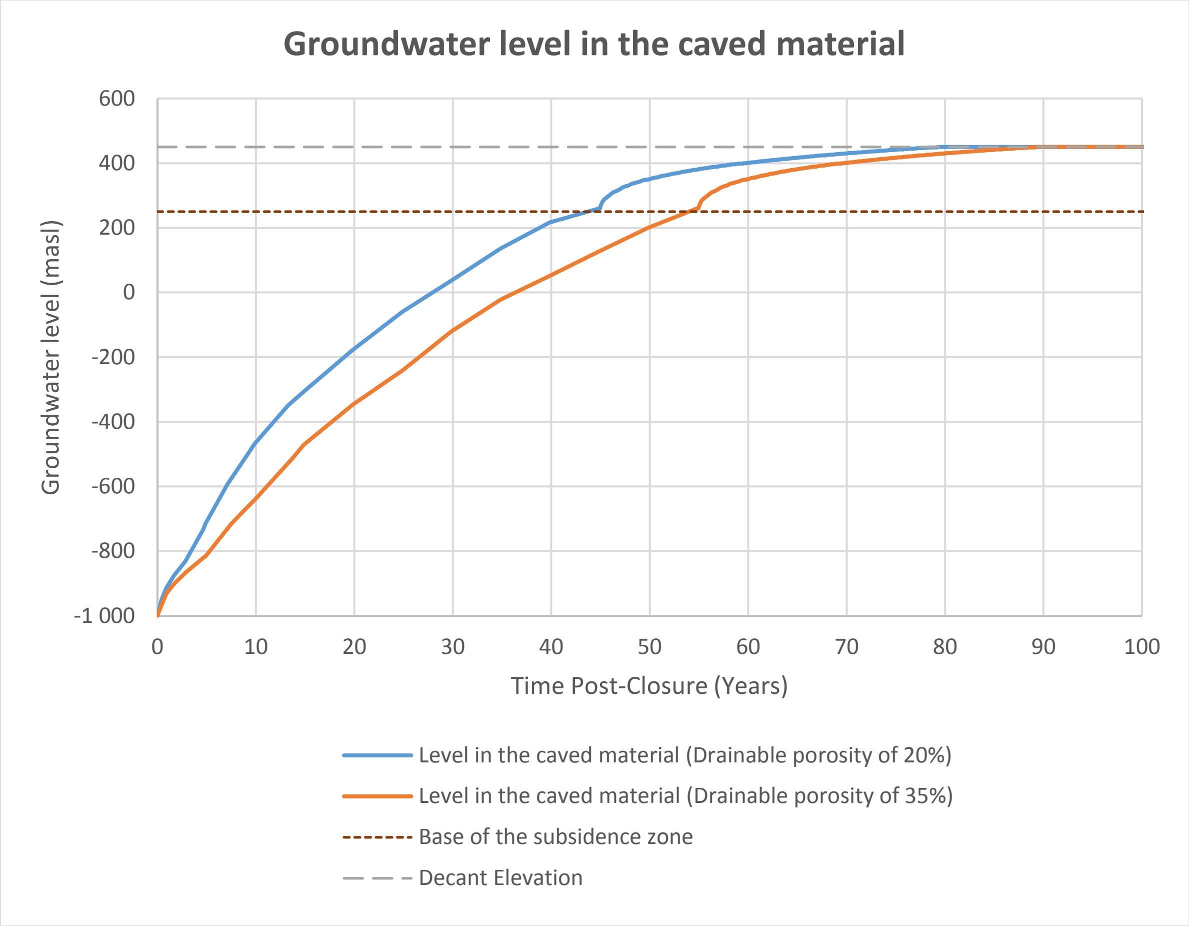
5 PHYSICAL MODEL RESULTS

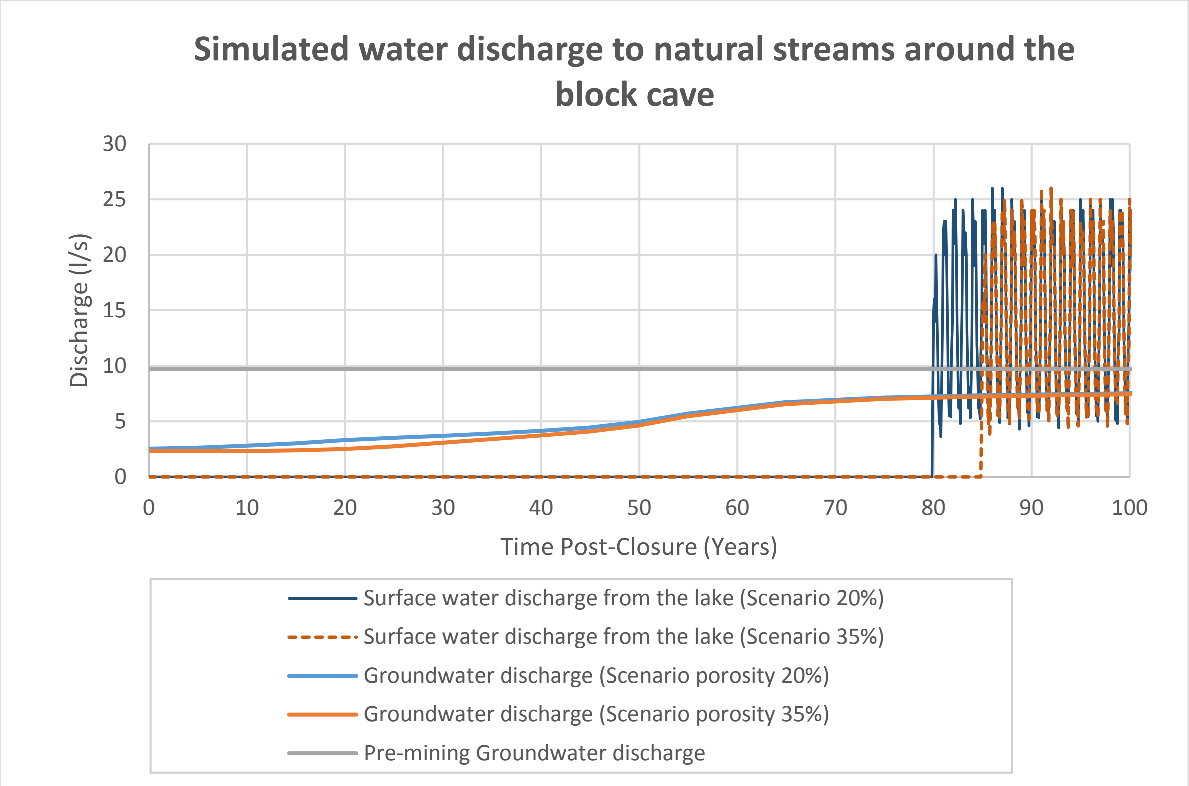
5.1 Scenario 1

Model predictions for Scenario 1, in which the block cave is assumed to be inundated passively, are displayed in Figure 3. This Figure shows the rate of rise of the groundwater level in the caved material, and subsequently the groundwater level as the subsidence subsidence zone (a), and the discharge of water as baseflow to natural streams around the block cave (b). Discharge to streams includes both baseflow from groundwater, flow from springs where applicable and surface water flows from the subsidence subsidence zone once water starts to discharge from the lake. The rate of inundation of the cave zone is shown for the bounding limits of the drainable porosity (20 to 35%) included in the model. Figure 3, showing the rate of groundwater elevation rise following closure, indicates that the cave zone is projected to flood to the base of the subsidence zone (at around 250 masl) over a period ranging from 45 years assuming a rock-fill drainable porosity of 20%, to 55 years at 35% drainable porosity. Subsequently, water is predicted to accumulate in the subsidence zone, for which the trends shown in Figure 3 are derived from predictions generated using the GoldSim surface water balance model. These suggest that over a period of around 35 years following complete cave inundation, the lake level will rise to the presumed topographic spill point at around 450 masl. On reaching this time-step, steady state decant will occur from the lake at rates of between 10 and 25 L/s (see Figure 3). It should be noted that the precision with which the elevation of the spill point can be predicted is inherently uncertain, as seepage through the rim at lower elevations may prospectively occur given the highly fragmented nature of the rock mass.

The results of FEFLOW simulations of inundation rates for the block cave zone following mine closure correspond closely with analytical calculations performed independently using an average inflow of 70 L/s (or 2.21×10^6 m^3/y) and a volume of between 5.55×10^7 m^3 (for a rock-fill drainable porosity of 20%) and 9.72×10^7 m^3 (for a rock-fill drainable porosity of 35%). Such calculations indicate that the period over which complete cave flooding would occur ranges from 25 to 44 years. The analytical calculations may be regarded as relatively conservative (i.e. tending towards over-estimation of the inundation rate), as they assume steady-state inflow of water to the cave. In reality, the inflow rate will decrease over time as the inward hydraulic gradient towards the cave is progressively reduced.

Rising water levels in the cave will inevitably result in recovery of the cone of depression in the surrounding rock units. This effect in shown by the FEFLOW model results presented in Figure 4. As a consequence, re-activation of springs and the associated discharge of groundwater at the topographic surface will occur. Model projections suggest that this will occur by around 80 years post-closure. Rates of spring discharge are assumed within the model to be a function of hydraulic head development in the overlying subsidence zone lake and the hydraulic conductivity of the rock mass between the cave and the re-activated spring locations. Steady state rates are predicted to be of the order of 7 L/s around the block-cave (see Figure 3).



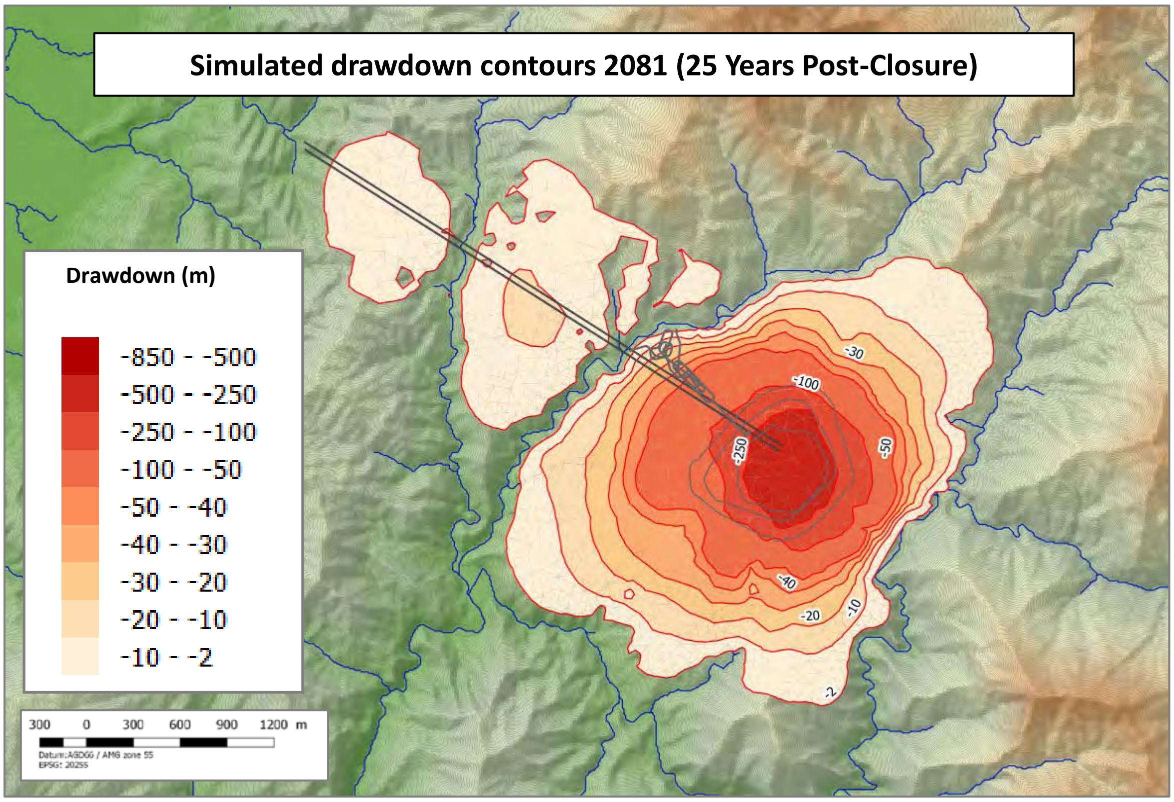


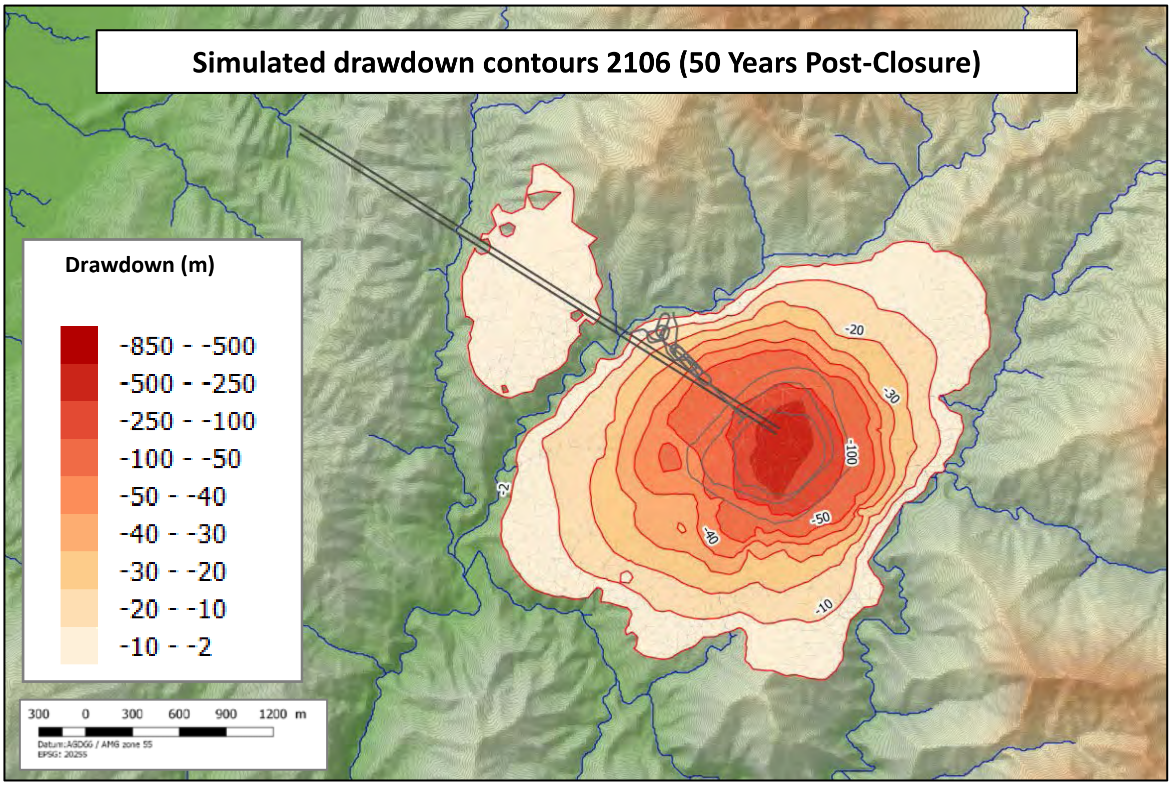
Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

Scenario 01: Simulated water level and discharge to natural streams around the block cave

By	FB	Date	Jan 2018
Approved	AR	Fig	03


Simulated drawdown contours 2081 (25 Years Post-Closure)


Simulated drawdown contours 2106 (50 Years Post-Closure)

Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

Evolution of drawdown contours 25 and 50 years post-closure

By	FB	Date	Jan 2018
Approved	AR	Fig	04

As is implicit from the conceptual model described in Section 2 (above), the groundwater system within the area of influence of the cave zone will, in addition to reactivating spring discharges, ultimately be re-established as a source of baseflow to the surface water drainage network. Thus, while a reduction of groundwater discharge to streams is likely to occur during the active dewatering of the access tunnels and block-caves, a recovery of groundwater discharge is anticipated following closure. This effect has been quantified using the FEFLOW model. Surface areas encompassing specific catchments over, and around, the Watut twin declines, Nambonga decline and the block-caves were determined to evaluate the variation of groundwater contribution over the LOM (see Figure 5). These comprise:

- Catchment 01 - located over the Watut decline footprint and corresponding to the entire Buvu Creek catchment.
- Catchment 02 - corresponding to the Nambonga catchment to the elevation of flow gauge station MWNAMNAM
- Catchment 03 - corresponding to the Hekeng catchment to the elevation of flow gauge station MWHEKYOR.
- Catchment 04 - corresponding to the entire area of contribution to the Wafi river, up to the edge of the model domain. It should be noted that a part of the upper catchment of the Wafi river is located to the east of the project area and is not included in the model domain. Temporal variations of baseflow are consequently predicted by the model only for the sector near the block-cave.

Results of stream baseflow discharge projections are presented in Figure 5 and Table 4. In Catchments 02 and 04 the recovery of the baseflow follows the same rate of recovery observed with respect to groundwater rebound. Most of the groundwater contribution to baseflow is returned to pre-mining conditions after around 80 years. In Catchment 01, the full recovery of baseflow is obtained after approximately 20 years. The recovery is more rapid over the Watut decline because the initial drawdown is smaller than will be the case in the sector of Mount Golpu. In all catchments, natural baseflow discharge rates are predicted to be virtually re-established by 100 years after closure.

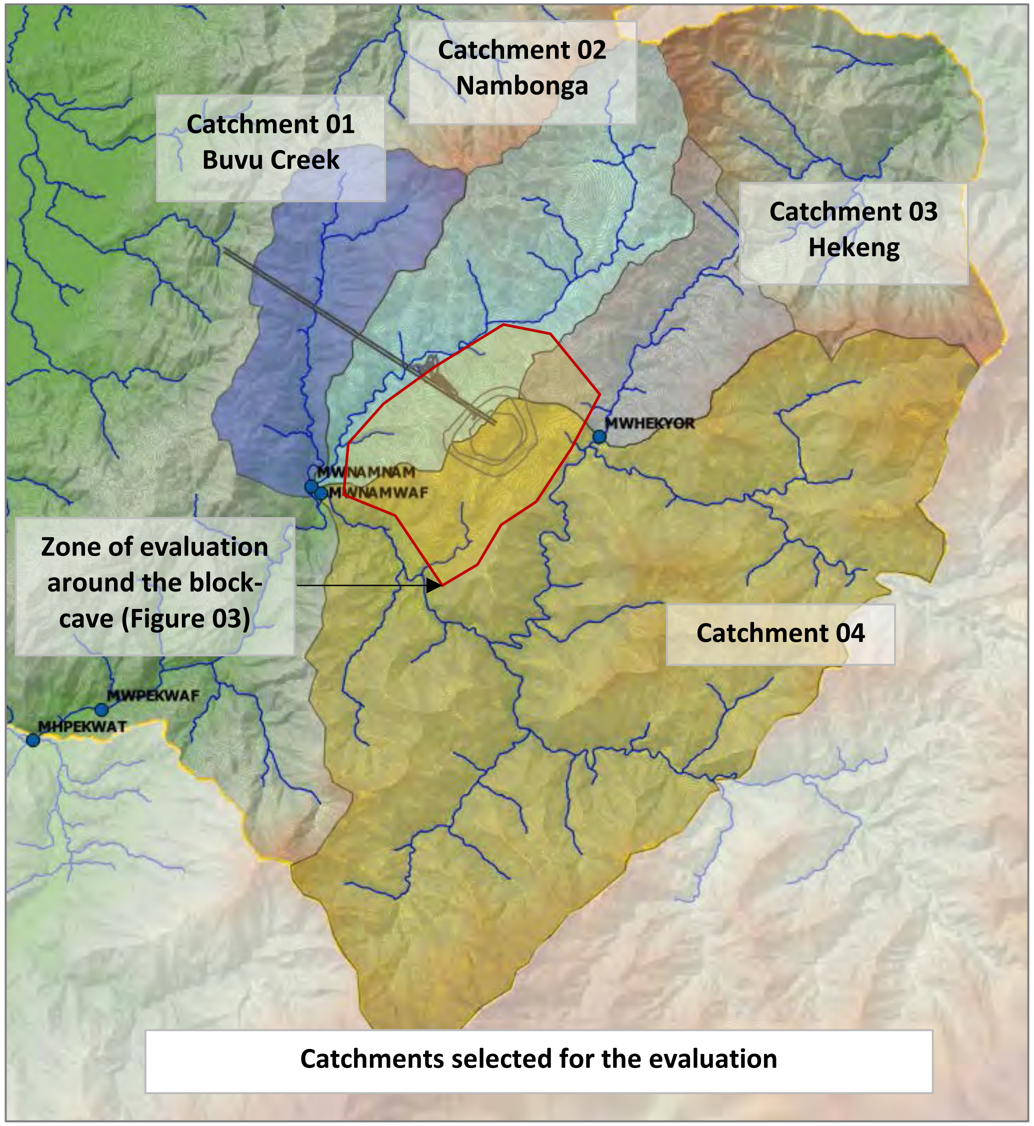
Table 4: Baseflow contribution to surface streams 100 years after closure

	Groundwater Contribution		
Catchment ID	Initial Baseflow (l/s)	Simulated baseflow 100 years after closure (l/s)	Percentage of recovery (%)
1 – Buvu Creek	63	62	99
2 - Nambonga	110	108	98
3 - Hekeng	57	56	99
4 – Wafi River	406	404	99

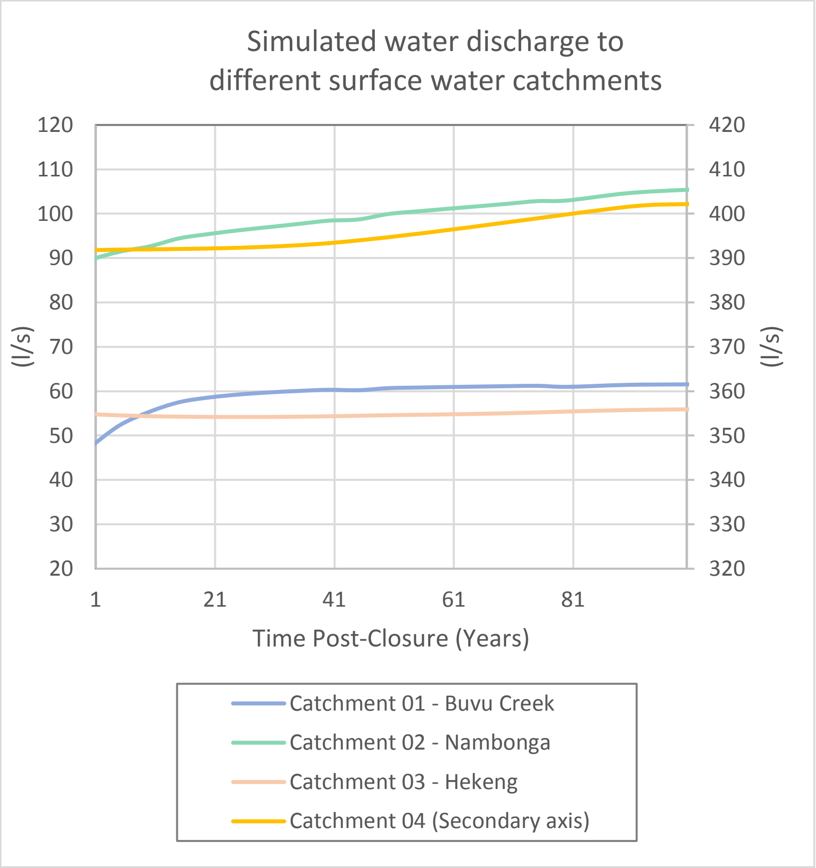
5.2 Scenario 2

FEFLOW model results for Scenario 2, in which artificial enhancement of cave inflows is assumed through pumping at a rate of 500 L/s, are presented in Figure 6. It is assumed that pumping ceases when the water level reaches the base of the subsidence zone. At this stage the entry point for pumped water will be below the water level. It would thus be impractical to continue pumping under pressure. Under Scenario 2, the time-frame over which flooding to the 250 masl elevation will occur is comparatively insensitive to the drainable porosity of the cave rock-fill. Consequently, results for the 20% drainable porosity case only are shown in Figure 6. These indicate a post-closure inundation time of only four years, after which water will start to accumulate in the subsidence zone.

FEFLOW model results for Scenario 3 do not differ from Scenario 2 as the model assumptions and physical hydro-dynamics of the two scenarios are essentially identical.



Catchments selected for the evaluation



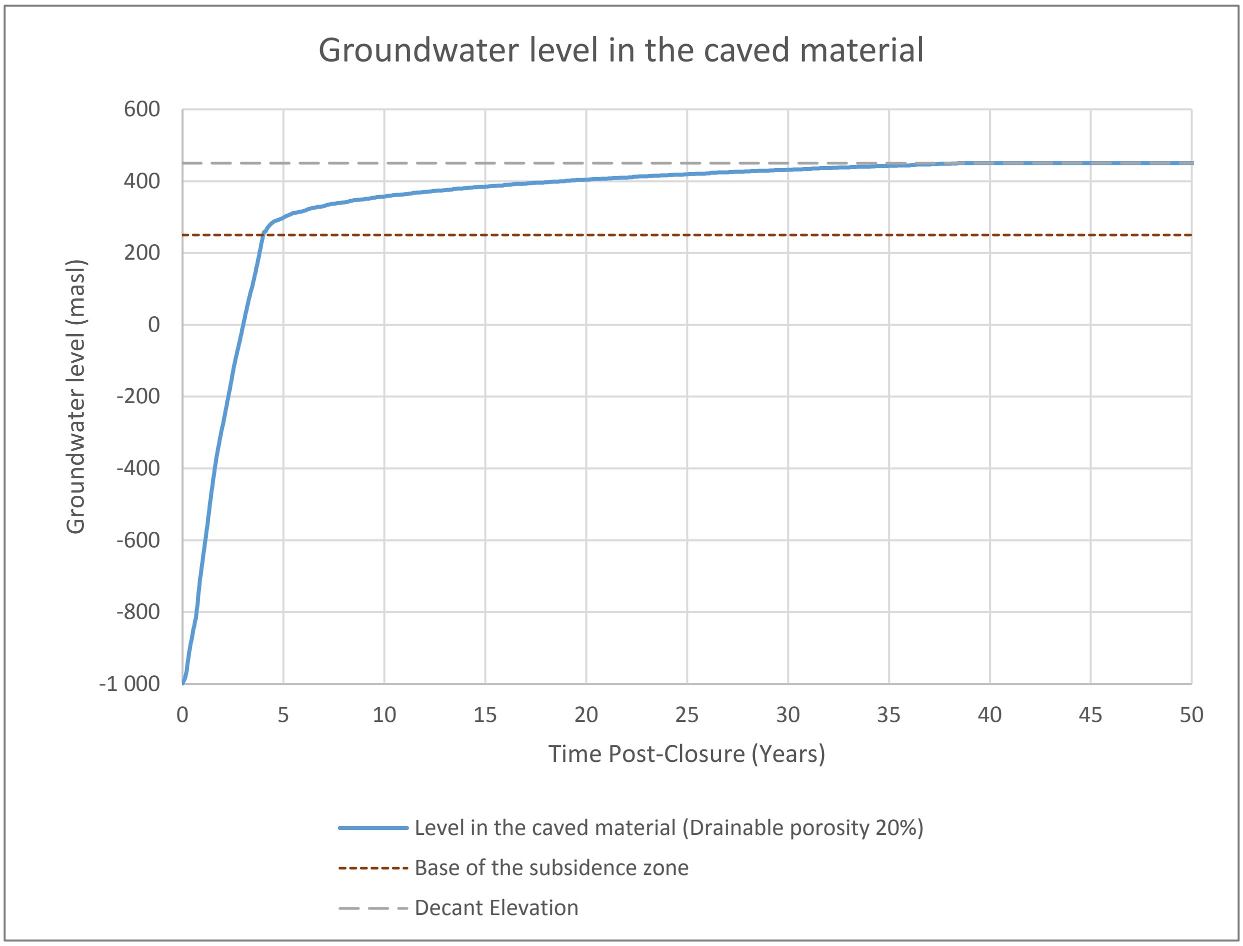
Simulated water discharge to different surface water catchments

Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

Scenario 01: Simulated water discharge to natural streams at the catchment scale

By	FB	Date	Oct 2017
Approved	AR	Fig	05



Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

Scenario 02: Simulated water level in the caved material and subsidence zone

By	FB	Date	Jan 2018
Approved	AR	Fig	06

5.3 Long term equilibrium

While the time-frame over which flooding of the block cave, and the subsequent development of a subsidence zone lake is reduced by several decades for Scenario 2 relative to Scenario 1, long-term equilibrium conditions with respect to recharge and discharge (via the lake spill point and re-activated springs) from the mining zone will be closely analogous for the two scenarios. Under these steady-state conditions, groundwater levels around the subsidence zone are predicted to be such that an inward flow gradient towards the lake will be established to the west, while the gradient will favor flow into the district groundwater system to the east (as shown in Figure 7). Effectively, the cave zone will adopt the status of a through-flow system.

Particle tracking has been performed using the FEFLOW model to assess pathways and fates of groundwater discharge from the inundated mine. Figure 8 shows the maximum extent of mass transport at long-term equilibrium. Particles in groundwater cease to be tracked by FEFLOW when they reach a surface water drainage line. Water conveyed in response to the head within the subsidence zone lake will pass through the groundwater system predominantly on the eastern side of Mount Golpu (Figure 8), ultimately discharging in one or more springs and in the drainage system. Existing spring 'SPR02' lies within the limits of the final subsidence zone and any discharge through its re-activation will report to the subsidence zone lake. Spring SPR03, a sacred spring (Gova) to the east of the subsidence subsidence zone, is located at an elevation higher than that of the final lake elevation (450 masl) and is thus unlikely to be impacted. Spring SPR04 is located at a distance of only around 70 m from the projected limit of the subsidence zone and may prospectively form a major point of discharge. Springs SPR01 and SPR05 are located at a greater distance of the subsidence zone, and the impact on groundwater levels and discharge will be negligible.

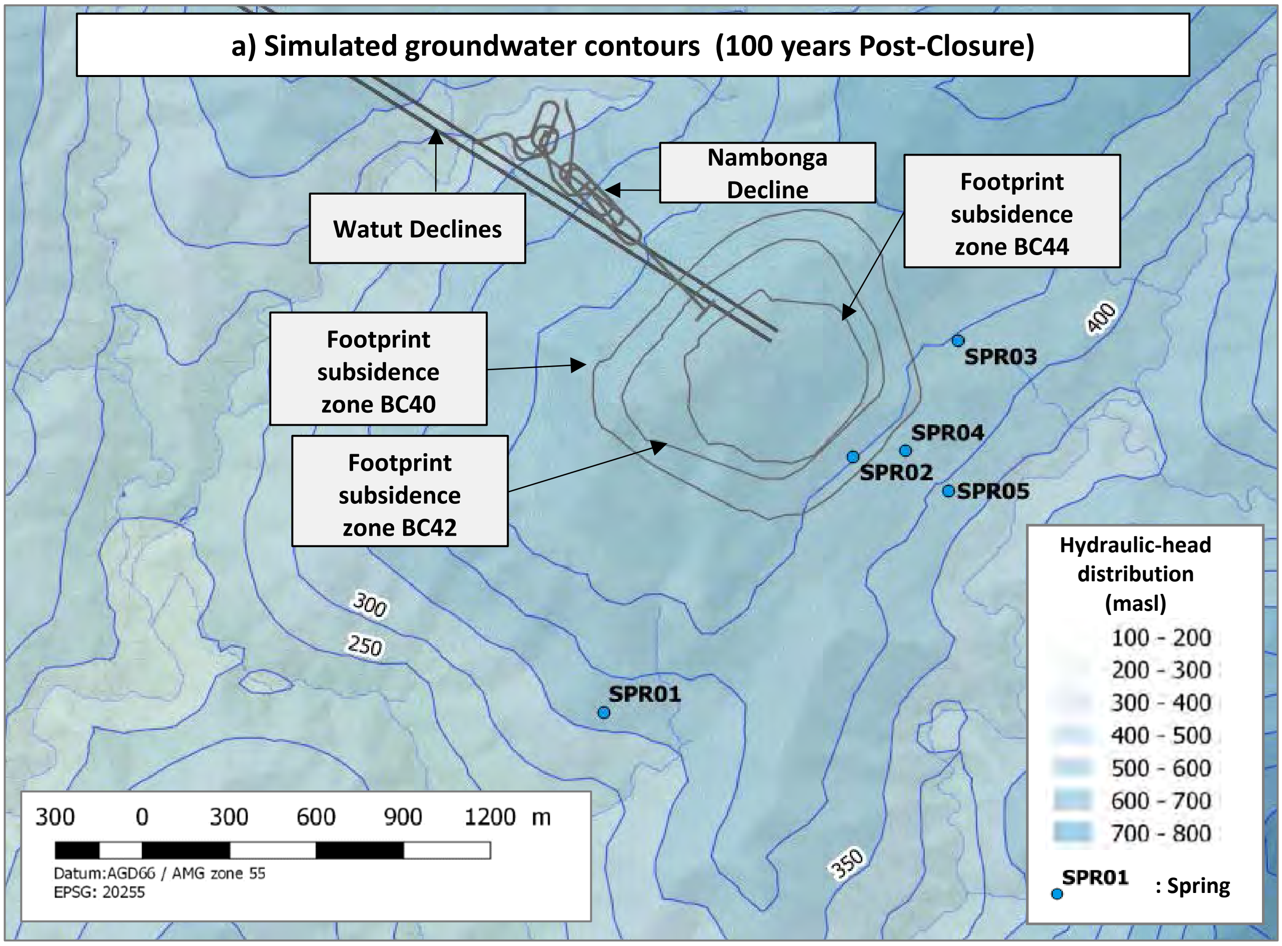
6 WATER QUALITY

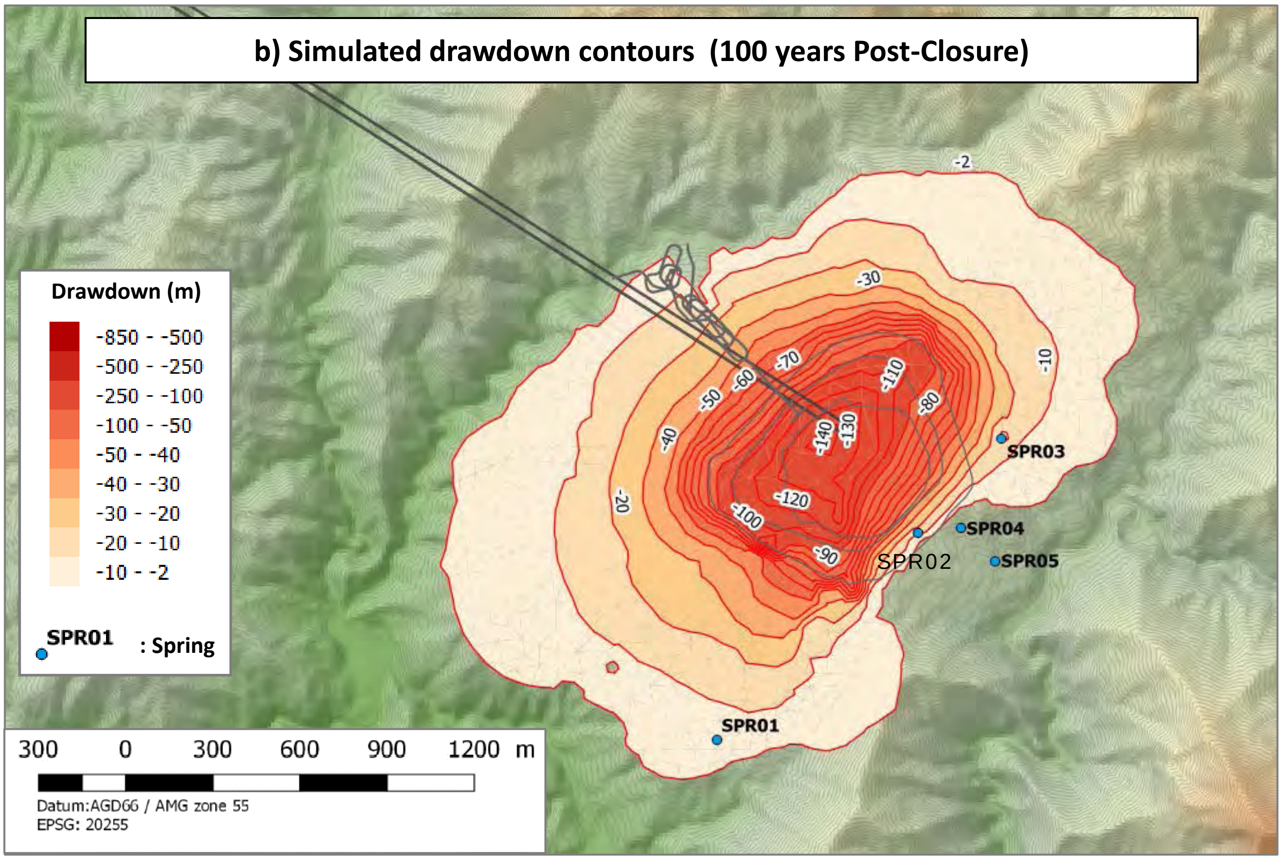
6.1 Overview and conceptualization of water chemistry controls

Water chemistry evolution in the block cave and, ultimately, in the subsidence zone lake will be controlled by a range of variables of which (i) the composition of the reactive rock-fill, (ii) the rate at which is it subject to inundation and (iii) the proportion of rock which is left permanently exposed above the water level under equilibrium conditions (and its geochemical reactivity) are particularly critical. Implicit in the water quality models for all selected scenarios is the premise that the rock-fill in both the cave and subsidence zones will continue to be subject to active oxidation and attendant proton plus metal liberation only until such time as it is permanently submerged. Accelerated flooding of the cave zone, as considered under Scenario 2, would shorten the duration of this active oxidation period and therefore restrict the aggregate mass of protons, SO_4 and metals released into the resurgent water.

For purposes of modelling the evolution of water in the block cave zone and the overlying subsidence zone lake during the period of inundation and under steady state conditions, the following general conceptualization of the system was adopted:

1) On closure, the block cave is conceptualized as representing a column of approximately 278 Mm^3 total capacity. This is assumed to be in-filled with rock from the overlying collapse zone with an effective-porosity of 35%. While this constitutes the most conservative (from a water quality perspective) end-member in the range of effective porosity values inferred from the geo-mechanical modelling of the cave-zone, it is unlikely to result in a water quality which is substantively different from that associated with lower effective porosities.


a) Simulated groundwater contours (100 years Post-Closure)


b) Simulated drawdown contours (100 years Post-Closure)

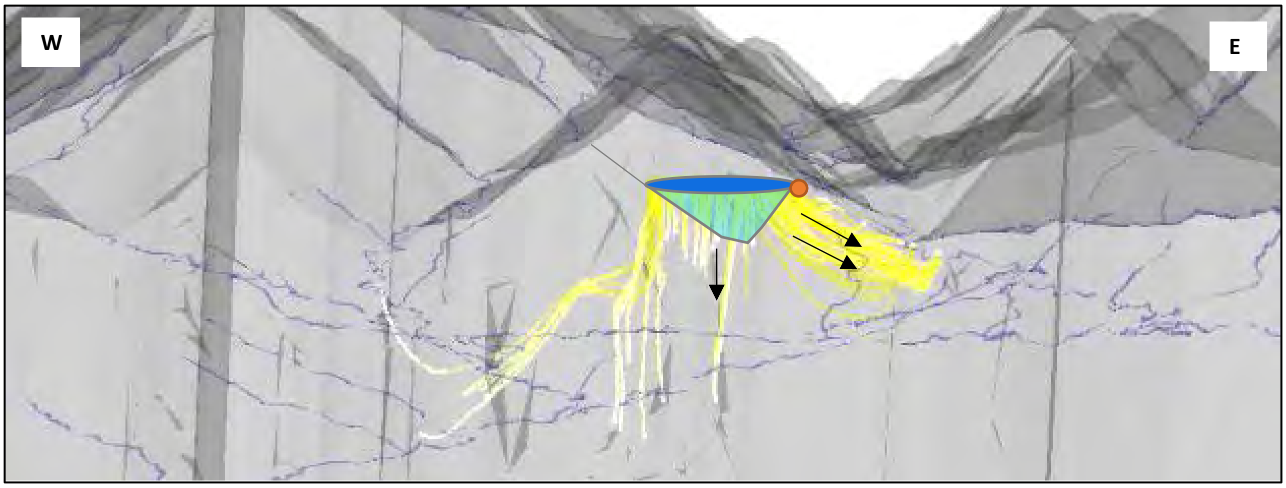
Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

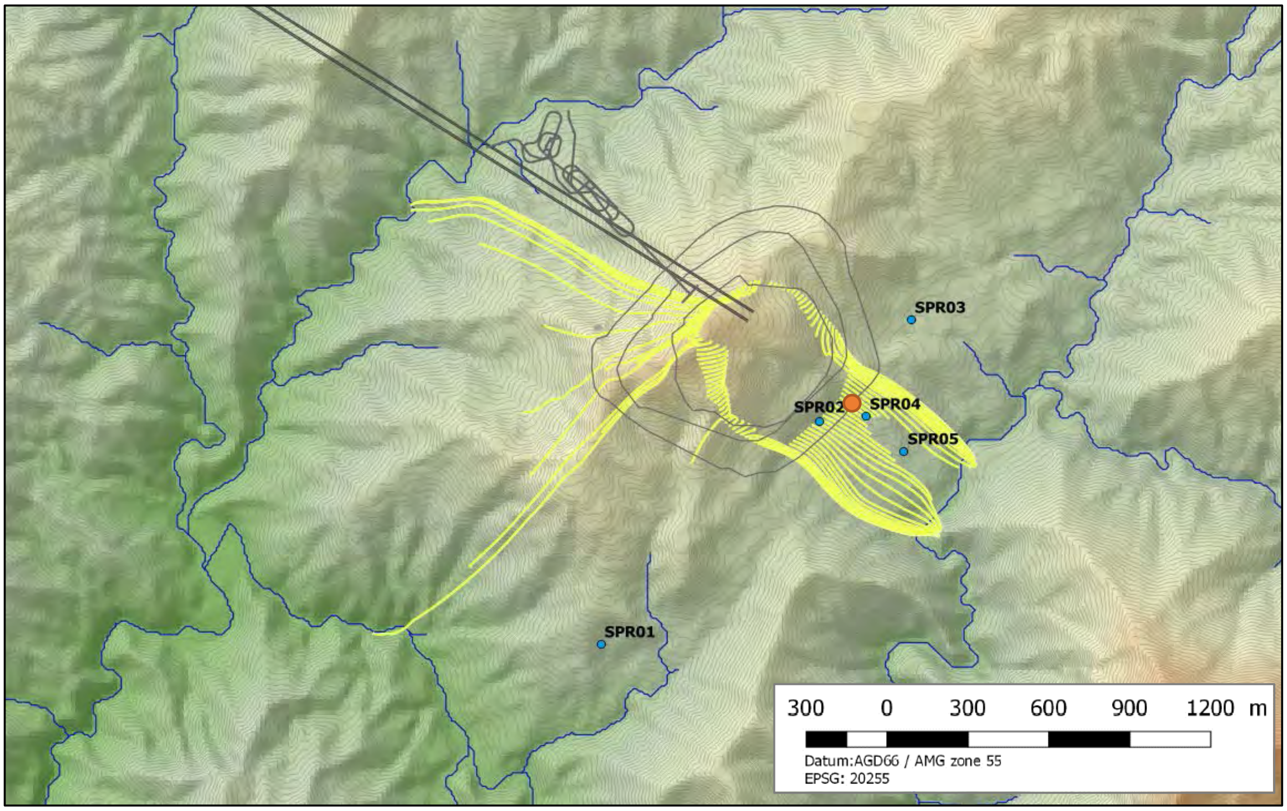
Location of springs on the eastern side of mount Golpu and groundwater levels & drawdown contours 100 years after closure

By	FB	Date	Jan 2018
Approved	AR	Fig	07

Cross-section view



Plan view



● : Spill point

SPR01 : Spring

Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

Particle-tracking from the subsidence zone lake

By	FB	Date	Jan 2018
Approved	AR	Fig	08

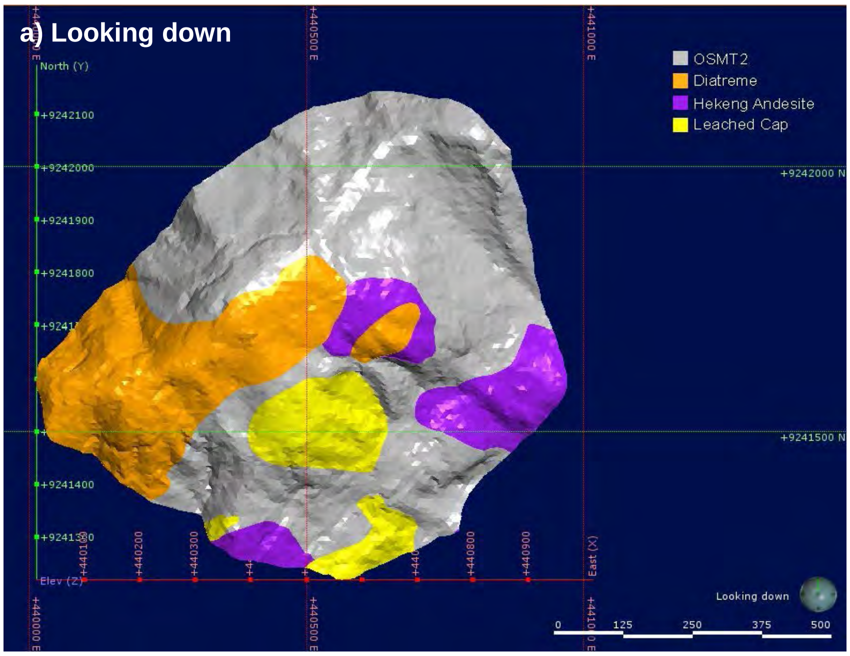
2) The voids within the rock fill (97 Mm3) are envisaged to be progressively filled with water at an inflow rate corresponding to that predicted by the FEFLOW model for the cave zone. The subsidence zone will then be subject to inundation at rates as predicted by GoldSim (see Section 5, above).
3) Ingress of water to the cave will occur through inflow from the district groundwater system plus infiltration through the subsidence subsidence zone. Because the latter of these flows will drain through the entire column of rock-fill, it is liable to dominate the chemical loading to the emergent groundwater in the cave system.
4) Over-time, the rock-fill will become inundated from the base upward. With each increment of groundwater elevation, flushing of oxidation products from the rock mass will occur. However, following the inundation of rock by rising water, further oxidation and thus liberation of additional chemical mass load will be precluded.
5) Ultimately, a condition will be reached in which the entire column is inundated. This condition will, on the basis of FEFLOW model projections outlined in Section 5 (above), be reached at around 55 years post-closure for Scenario 1 and around 4 years post-closure for Scenarios 2 and 3. The chemical quality of water which occupies the fully flooded cave zone will differ to some degree in accordance with the rate of flooding and hence the period of active oxidation of the rock fill prior to flooding. Consequently, a superior chemistry may be anticipated under Scenario 2 than would be the case under Scenario 1. Following the attainment of steady-state conditions of full inundation of the cave zone, water quality under both Scenarios 1 and 2 is anticipated to progressively improve at a rate determined by the residence/replacement time of water within the rock fill.
6) Lake development in the subsidence subsidence zone will commence only following full flooding of the cave zone to the 250 masl elevation. The chemistry of the lake water can be conceptualized as the direct function of the mixing ratios of the major components of the physical water balance. These comprise direct precipitation, runoff and/or infiltration though the unconsolidated rock mass in the subsidence zone catchment area, and resurgent groundwater. The last of these components is predicted by the water balance (see below) to decline progressively during lake filling and is minor under steady-state conditions. Consequently, long-term lake chemistry and discharge is expected to vary little between scenarios.

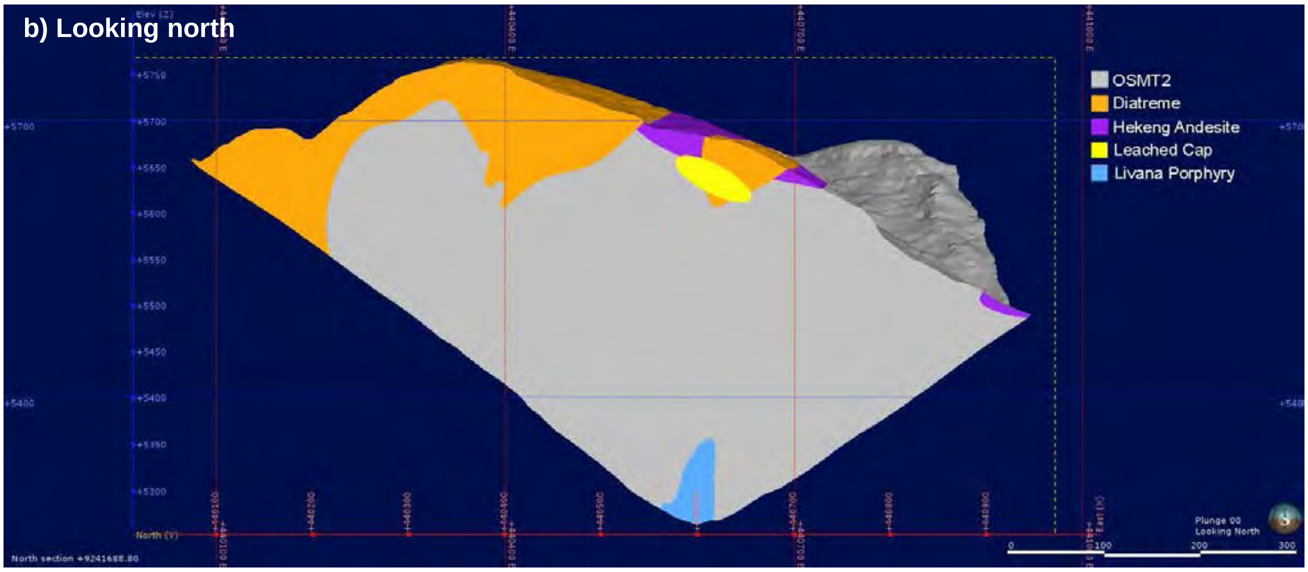
6.2 Modelling approach

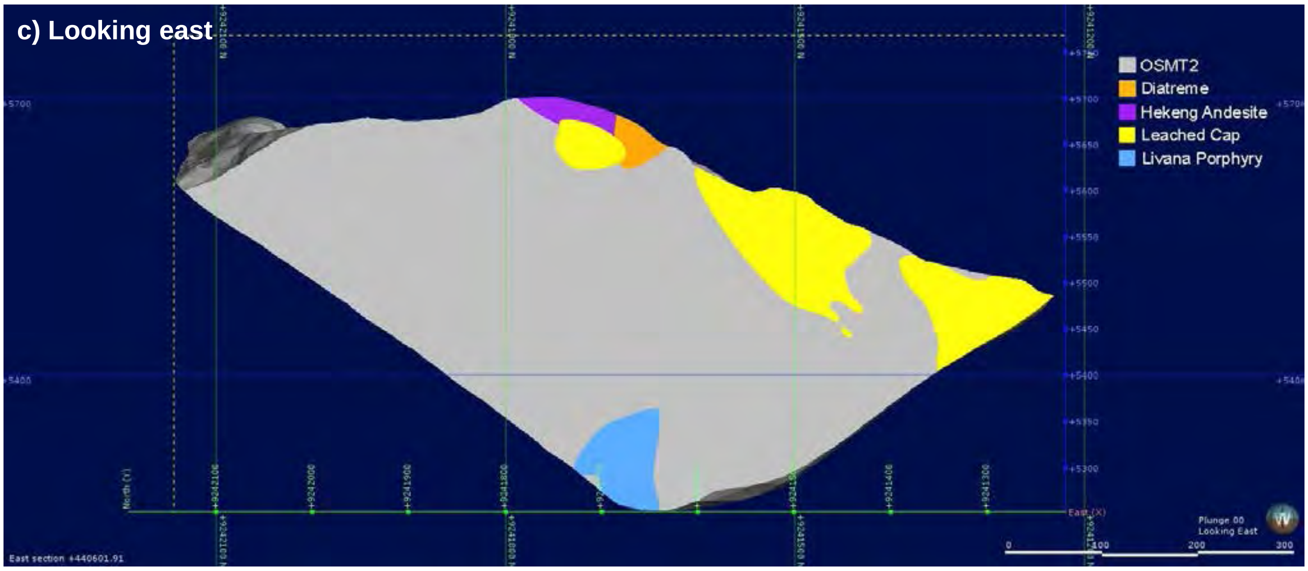
6.2.1 Block cave water quality

Numerical modelling of water chemistry evolution in the block cave zone and, by extension, that which will accumulate in the subsidence zone lake, discharge as lake decant or feed re-activated springs, has been attempted at only a preliminary resolution. Ideally, such modelling should be founded on detailed information relating to the proportional contribution of all lithology-alteration-mineralization (LAM) assemblages in the cave-fill rock mass. A fragmentation analysis for the rock should ideally also be applied in the numerical model to depict the reactive surface area of rock within each LAM unit liable to interact with resurgent water during cave and subsidence zone inundation. In the absence of detailed information relating to the LAM composition of the cave rock-fill or its particle size distribution, a simplified model for the block cave was constructed in which:

1) Rock fill in the cave was assumed to comprise a homogeneous mixture of the principal lithotypes which directly overlie the projected cave shape. This mixture was estimated through importation of the final cave-shape and the BC40 subsidence zone (which is the largest subsidence zone present at closure) geometry into the 3D geological modelling software Leapfrog, in which this information was super-imposed onto the Golpu geological block model, as exemplified in Figures 9 and 10 for lithology and alteration respectively. The major contributors to the collapse material will comprise diatreme, andesite, leach cap and metasediment units. Due to the





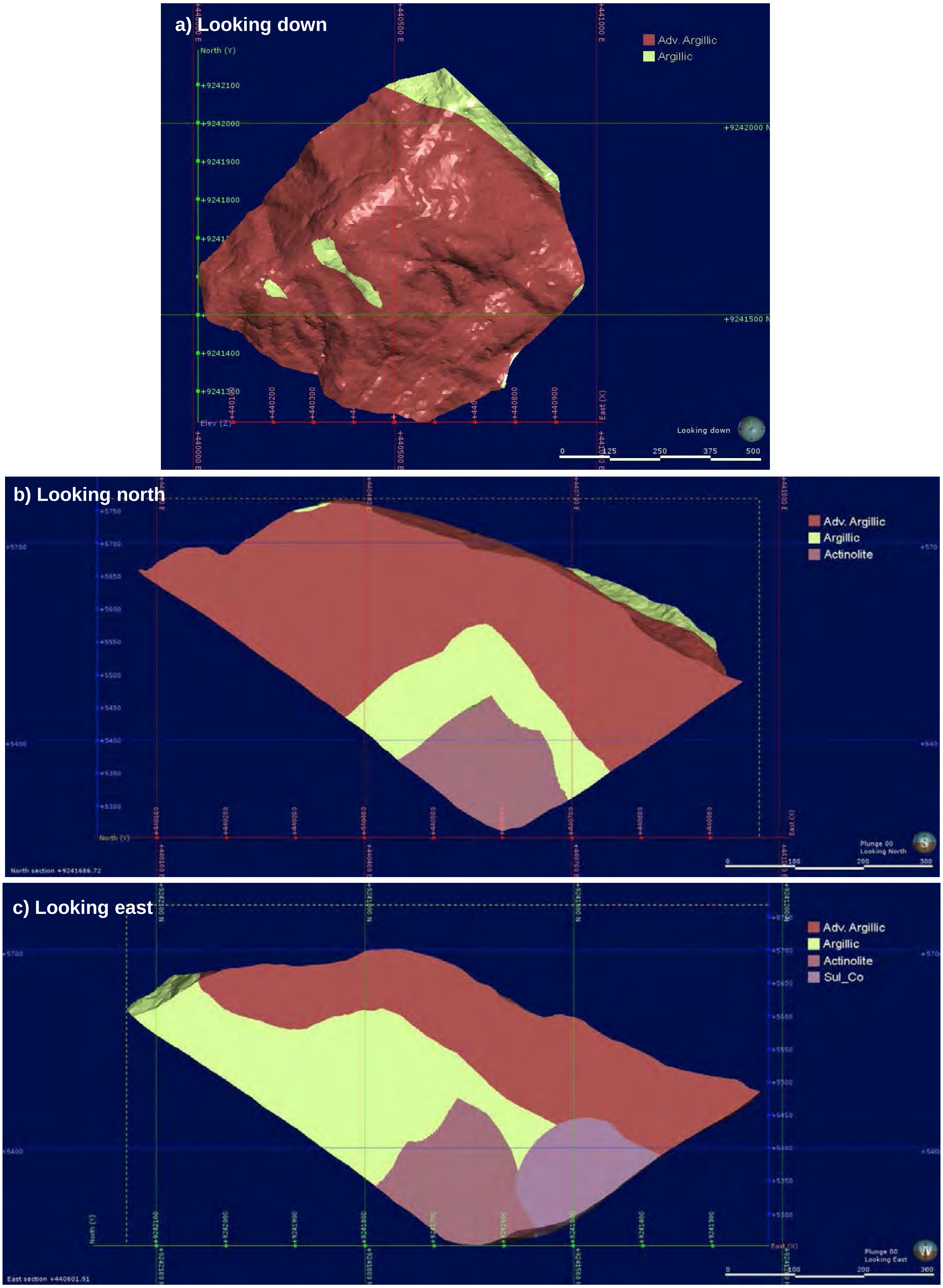


Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

Lithological units intersected by BC40 subsidence zone

By	FB	Date	Jan 2018
Approved	AR	Fig	09



Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

Alteration zones intersected by BC40 subsidence zone

By	FB	Date	Jan 2018
Approved	AR	Fig	10

relatively high elevation of the collapse material within the mineralized system, much is projected to be within the argillic to advanced argillic zone of epithermal overprinting.

2) While a significant proportion of the rock-fill is liable to be derived from above the zone of oxidation, in terms of lithology and alteration, reasonable comparability exists with the rock composites utilized by WGJV for laboratory scale column tests initiated in 2015, results of which have been described in detail by WSP in their technical memorandum titled "56072TM05v0.3 - Review of Geochemistry Investigation – Morobe Wafi Golpu Project, dated 10 October 2016 and Piteau (2017). Multiple WGJV columns were developed using a single rock composite, with differentiation between columns relating strictly to the mode of irrigation as follows:

   - Column 1 – irrigation using alternation of wet and dry cycles
   - Column 2 – irrigation via continuous feed
   - Column 3 – irrigation by continuous feed with batch re-cycling of solution
   - Column 4 – flooding with continual feed and batch re-cycling.

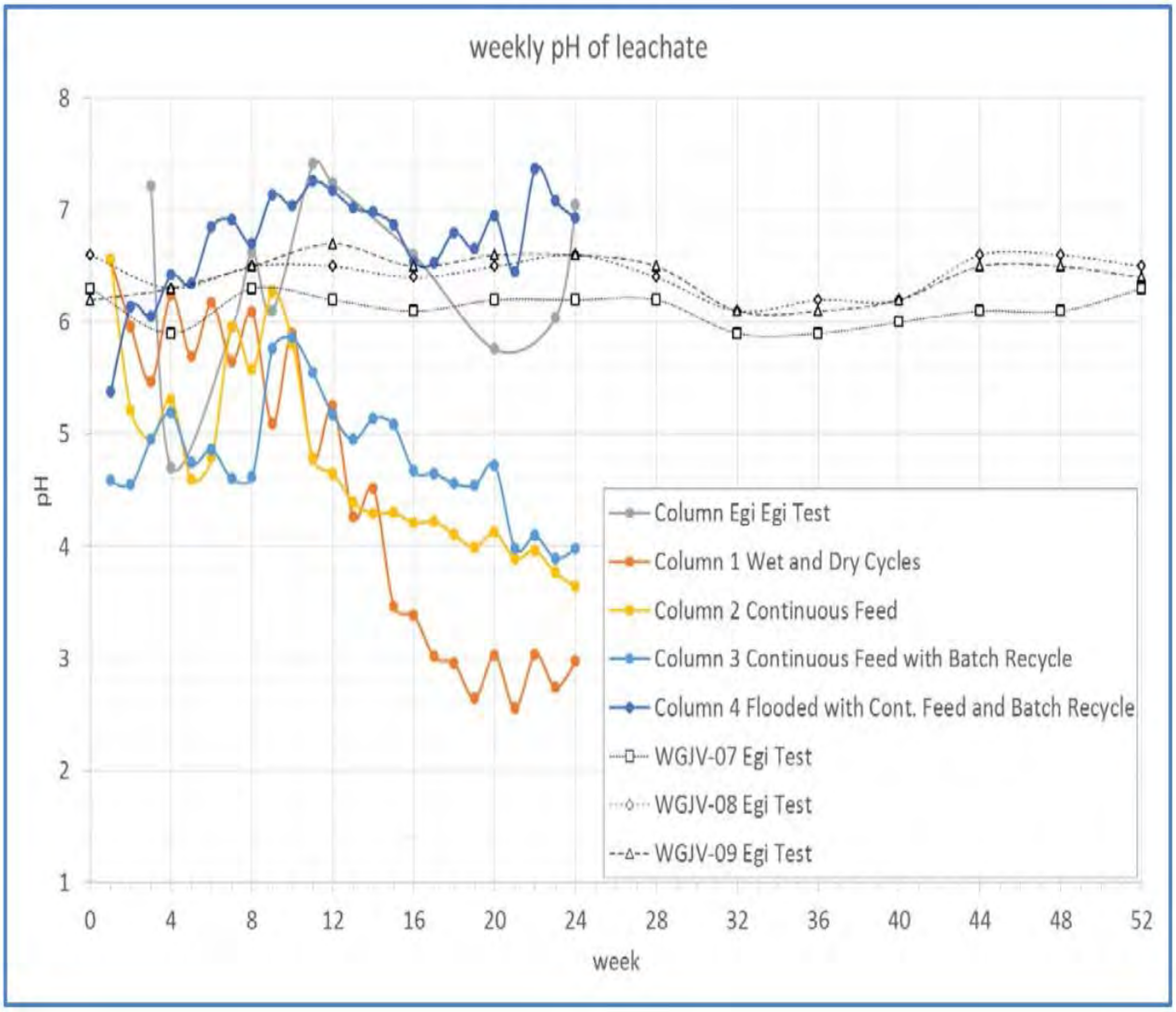
   The weekly trends for leachate pH in the test columns are shown in Figure 11.

   For purposes of model construction, Column 2 of the WGJV column test series was selected to mimic the condition which may be anticipated during the initial stages of inundation of the cave rock-fill, at which time most inflowing water will pass through a column of unsaturated rock. Over time, an increasing thickness of the rock fill will become permanently saturated from the base upward. This sector of the cave zone is assumed for modelling purposes to be best represented by WGJV test Column 4.

3) Construction of a geochemical mass balance for the block cave during each of a succession of post-closure filling steps was undertaken by integration of the geochemical mass loadings anticipated to be liberated per unit time for each of the unsaturated and saturated components of the rock column into a volume of water predicted for each time-step based on FEFLOW model output (Section 5). Mass loadings were determined from WGJV columns 2 and 4 in units of mg/kg/week, as summarized in Table 5. These were then extrapolated to units of tons per year for the entire 181 Mm^3 rock mass. The loadings were integrated into the volume of water predicted to enter the cave over model time-steps each of 5 years. Under Scenario 1, for all but the first time-step of the model the volume of the antecedent water calculated for the preceding time-step was also mixed into the chemical mass balance calculations. For Scenario 2 this was unnecessary as complete flooding is predicted by the FEFLOW model to occur within a single 5 year time-step. Table 6 provides a summary of the gross inflow rates applied in the model for Scenario 1, as predicted from the FEFLOW model for which results are described in Section 5 (above).

4) For Scenario 3, a single time-step model was executed as per Scenario 2, but with alkalinity added to the 500 L/s artificial flow introduction to the cave zone to replicate administration of hydrated lime at sufficient molarity to attain a pH end-point of nominally 7.0. Water quality at the completion of the time-step was then determined based on equilibration of the mass loading mobilized from the rock mass to a pH 7.0 condition.

5) Due to the potentially super-saturated nature of the solution chemistries predicted for each time-step on the basis of (3) above, equilibration of solutions was performed in PHREEQC. This applied thermodynamic equilibrium conditions as defined by the MINTEQ4 database. An important consideration in this stage of the



Wafi-Golpu, 3D Groundwater

PITEAU ASSOCIATES
GEOTECHNICAL AND WATER MANAGEMENT CONSULTANTS

pH Trends in WGJV test columns

By	FB	Date	Jan 2018
Approved	AR	Fig	11

modelling process is the assignment of an appropriate redox potential. Calculations of the time-period over which water entering the cave under natural groundwater inflow conditions will remain within the rock-fill voids suggest that residence times under steady-state conditions will be of the order of 495 years. This, coupled with the depth of the cave zone below surface, prompted the adoption of an assumption that anoxic conditions will be sustained. A nominal Eh of -100 mV was therefore adopted. This is significant with respect to the model outputs as precipitation of Fe and associated sorption of trace metals is effectively precluded irrespective of the pH evolution trend predicted by the model.

Table 5: Mass loading rates for WGJV columns 2 and 4

Parameter	Unit	Column 2	Column 4
	pH units	3.9	5.74
Acidity as $CaCO_3$	mg/kg/wk	11	0.8
SO_4	mg/kg/wk	48	32
Cl	mg/kg/wk	-0.5	0.1
Al	mg/kg/wk	0.7	0
As	mg/kg/wk	0.00008	0.00003
Ca	mg/kg/wk	12	12
Mg	mg/kg/wk	1.9	1.2
Na	mg/kg/wk	0.1	0.2
K	mg/kg/wk	1	0.8
Cd	mg/kg/wk	0.0002	0.0001
Cr	mg/kg/wk	0.00008	0.00003
Co	mg/kg/wk	0.007	0.002
Cu	mg/kg/wk	1.5	0.001
Fe	mg/kg/wk	0.06	0.002
Mn	mg/kg/wk	0.6	0.3
Zn	mg/kg/wk	1.5	0.4

Table 6: Estimated inflow and outflow rates to and from the block cave zone per 5 year time-step during inundation (Scenario 1)

Internal Transfer to the cave rock fill		
Time (Years)	Rate In (L/s)	Rate Out (L/s)
0	71.9	0.0
5	73.1	19.2
10	63.3	16.8
15	55.9	16.5
20	52.8	15.5
25	42.3	18.1
30	30.3	17.0
35	27.9	17.5
40	23.5	15.8
45	21.5	16.3
50	7.6	6.2
55	10.2	7.5

6.2.2 Subsidence zone lake water quality

Modelling of the chemistry of the water body which will develop within the Golpu subsidence zone is particularly problematic due to uncertainties regarding the physical limnology of the lake (particularly the likelihood of permanent chemo-stratification), the surface condition of the catchment area (for example the rate of natural rehabilitation of the surface) and the geochemistry of any permanently un-inundated rock above the 450 masl lake spill point. Additionally, the depth to which aerobic conditions may be established in the lake, and hence the potential for $Fe(OH)_3$ precipitation, are uncertain. These variables may influence both the chemistry of the lake itself and that of long-term discharge via the spill point.

A preliminary model was constructed which assumed a fully mixed lake. This is a conservative assumption given the substantial prospect of density stratification. For each of a series of time-steps between year 0 of lake development and the onset of steady-state discharge via the spill point, a mixing algorithm was used to predict lake chemistry as a function of the proportion of incoming water associated with (a) groundwater ingress, (b) catchment runoff, (c) direct precipitation and (c) the antecedent lake water inventory. Mixing ratios for all time-steps were extracted from GoldSim and assumed 50th percentile conditions within the climatically-driven probabilistic range, as summarized in Table 7. Following each mixing step, the lake chemistry was equilibrated in PHREEQC to account for pH induced precipitation of metals. The assignment of chemistries to each component of the water balance was undertaken in the following manner:

a) Catchment runoff and infiltration was assigned a chemistry based on WGJV test column 2, mass loading per unit time data for which are provided in Table 5 (above). This constitutes a significant amendment from previous versions of the Golpu subsidence zone lake water quality model reported by Piteau (January 2018) in which a pre-mining baseline chemical loading was assigned to catchment runoff. The change of conceptualization reflects assertions made by Coffey that engineered rehabilitation of the subsidence zone is unlikely to be achievable, and that consequently the catchment loading to the lake would reflect the substantial mass of PAG rock within the subsidence zone above the 450 masl elevation.

b) Direct precipitation onto the lake surface was assigned a zero solute load and a pH of 5.8. This is a typical pH for rainfall in tropical environments and essentially assumes equilibrium with atmospheric CO2 at 25oC.
c) Groundwater inflow was assumed to possess a chemistry as modelled for the final time-step of the cave inundation simulation for each of Scenarios 1 through 3 (see Section 6.3, below).

Table 7: 50th percentile estimates of water balance contributions to the Golpu subsidence zone lake over the period from year 1 of lake development to steady-state discharge via a spill point.

Lake development year	Precipitation	Catchment runoff/infiltration	Groundwater	Total Inflow	Accumulated volume
	L/s	L/s	L/s	L/s	Mm^3
1	1.7	4.8	17	23	0.028
5	8.3	5.3	12	26	0.34
10	12	3.7	9.9	25	0.6
15	15	3	8.3	26	0.97
20	18	2.1	6.8	27	1.2
30	20	1.3	5.6	27	1.6
35	22	0.54	4.6	27	1.9
40	23	0.00019	3.8	27	2.2
45	23	0.00015	3.8	27	2.5

6.3 Results

6.3.1 Scenario 1 block cave water chemistry

Table 8 summarizes the results of model simulations of the chemistry of water in the block cave under conditions of ‘natural flooding’ (Scenario 1) from closure year 0 through to a time-step at which the cave is fully inundated to the base of the subsidence zone at around 250 masl. Results are shown for selected parameters only, but are sufficient to provide clear insight into the evolution trends predicted. The cave water quality is predicted to be poor, with an initial pH condition of less than 3 accompanied by a TDS in excess of 10,000 mg/l and strongly elevated concentrations of Al, Fe, Mn, Cu and Zn. In practical terms, the water quality predicted for the final time-steps of the filling period are of greatest relevance as at this time re-activation of springs at surface may occur. Model projections for year 55 under Scenario 1 suggest that the water will remain acidic (around pH 4), with concentrations of SO_4 at around 1700 mg/l and Fe, Mn, Cu and Al at concentrations of >100, >20, >50 and >25 mg/l respectively. While the predictions for certain solutes are contingent on the assumption of a perpetually low Eh regime such a condition is virtually inevitable for any flooded block cave setting. At low redox potential, the model indicates that both Fe and Mn are predominantly stabilized in divalent states and are thus highly soluble. Inhibition of the precipitation of hydrous Fe or Mn oxides with progressively increasing pH during cave flooding exerts a compounding effect on the solubility of Cu, Zn and other metals due to the lack of any potential for surface sorption to precipitated oxides.

Table 8: Scenario 1 simulation of cave-zone water quality during progressive inundation to the base of the subsidence zone

Parameter	Unit	Year							
		0	5	10	15	25	35	45	55
Net inflow (L/s)		71.9	53.9	46.5	39.4	24.2	10.4	5.2	2.7
pH	SU	2.4	3.1	3.3	3.5	3.9	4.0	4.1	4.1
Alkalinity as $CaCO_3$	mg/L	0	0	0	0	0	0	0	0
SO_4	mg/L	7365	4628	3817	3168	2276	1972	1815	1743
Cl	mg/L	15.1	10.6	8.2	7.6	6.9	6.1	5.9	5.7
Al	mg/L	107	68	56	46	33	29	14	25
As	mg/L	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Ca	mg/L	965	621	519	497	460	421	415	399
Mg	mg/L	121	76	67	54	49	41	37	34
Na	mg/L	12	11	9	8	8	7	7	7
K	mg/L	72	59	51	47	44	40	36	34
Cd	mg/L	0.01	0.008	0.007	0.006	0.004	0.004	0.003	0.002
Cr	mg/L	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001
Co	mg/L	0.09	0.07	0.02	0.008	0.007	0.006	0.005	0.004
Cu	mg/L	230	146	119	99	71	62	57	54
Fe	mg/L	705	447	366	304	218	189	174	167
Mn	mg/L	92	58	48	40	28	25	23	22
Zn	mg/L	197	128	107	77	65	51	44	41

6.3.2 Scenario 2 block cave water chemistry

Modelling of Scenario 2 was performed to represent a condition in which water from the Watut River is introduced to the cave zone at a constant rate of 500 L/s through the period of inundation until the 250 masl elevation is reached. Thereafter, lake development is assumed to commence at a rate controlled exclusively by the natural water balance, as shown in Figure 6. Due to the rapid time period over which full flooding of the block cave is predicted by the FEFLOW model to occur, the geochemical model for Scenario 2 was conceptualized as effectively involving a single flush of near-neutral, low TDS water through a rock column with a total volume (excluding void space) of approximately 181 Mm^3. For conservatism, the alkalinity of the Watut River water source was assumed in the preliminary model for which results are presented in this memorandum to be low (50 mg/L), with a constant feed pH of 6.5. A further important assumption of the Scenario 2 model set-up involved the introduction of artificial recharge at the draw point elevation, rather than at the upper elevation of the cave (as would occur in the event of infiltration through the subsidence zone). This exerts a major beneficial influence on water quality during the initial period of water accumulation (depicted by the 'year 0' results shown in Table 9) as flushing of the rock column occurs only by progressive inundation from the base-up, rather than by diffuse seepage from the 250 masl elevation downward through the entire rock column.

Results of the Scenario 2 water quality model are presented in Table 9. At the year 0 time-step, water chemistry within the cave is inevitably closely analogous to that under Scenario 1, with modest comparative improvement of metal concentrations essentially a function of a slightly increased pH. By the time of complete flooding of the cave at year 5, the pH of the water is predicted to remain strongly acidic. Consequently, SO_4 and metal concentrations, although lower than those predicted for Scenario 1, remain extremely high.

Table 9: Scenario 2 simulation of cave-zone water quality during inundation to the base of the subsidence zone

Parameter	Unit	Year	
		0	5
Net inflow (L/s)		500	550
pH	SU	2.7	3.3
Alkalinity as $CaCO_3$	mg/L	0	0
SO_4	mg/L	7220	1620
Cl	mg/L	11.1	7.4
Al	mg/L	95	9
As	mg/L	0.002	0.001
Ca	mg/L	840	322
Mg	mg/L	122	20
Na	mg/L	14.9	6.2
K	mg/L	77	14
Cd	mg/L	0.001	0.001
Cr	mg/L	0.002	0.002
Co	mg/L	0.004	0.001
Cu	mg/L	210	31
Fe	mg/L	426	118
Mn	mg/L	90	52
Zn	mg/L	185	37

6.3.3 Scenario 3 block cave water chemistry

Scenario 3 was modelled to represent an intervention involving hydrated lime ($Ca(OH)_2$) addition to the artificial recharge flow previously described under Scenario 2 for a duration corresponding to that required for flooding of the block cave to the 250 masl elevation. The rationale for this intervention is provided by the conceptualization of the system described in Section 2 (above), in which active sulphide oxidation and the associated production of a protons, sulphate and metals is assumed to take place only within the unsaturated sector of the collapsed rock column in the cave. Neutralization of the acidity during active flooding may thus offer a sustained benefit following full inundation due to the strictly limited potential for additional acid production under steady-state conditions.

Model execution for Scenario 3 involved the replication of the Scenario 2 model, with an adjusted solution chemistry applied to the Watut River recharge term. A stoichiometric balance was defined between the mass of H_2SO_4 predicted to be liberated from the rock column within the cave zone during the five year period of flooding and the lime mass required for neutralization to pH 7. During rock inundation, a total H_2SO_4 yield of around 4000 tons is predicted. This equates to an average dose of around 3 g/L of $Ca(OH)_2$ in the artificial recharge stream. This calculation assumes 100% lime purity, complete lime-consumption in the neutralization of acidity. Acidity generates from ferric hydroxide precipitation was ignored in the stoichiometric balance, however, this is likely to be minor given the assumed low Eh of the inundated cave and hence the tendency for Fe to remain in solute in ferrous state.

Table 10 provides a summary of PHREEQC predictions of dissolved SO_4 and metal concentrations in the block cave waters at the year 5 time-step under Scenario 3. Thereafter, the chemistry of water in the cave is anticipated to evolve in a manner controlled by the rate of mixing and/or replacement of the initial void volume of water within the rock mass by groundwater inflow. Model results which demonstrate this effect at the 50 and 100 year post-closure time-steps are also shown in Table 10.

Table 10: Scenario 3 simulation of cave-zone pH, sulphate and dissolved metal concentrations during block cave inundation to the base of the subsidence zone, and at 50 and 100 year time-steps post-closure. Lime addition is assumed for the first five years only

Parameter	Unit	Year 5	Year 50	Year 100
Net inflow (L/s)		550	NA	NA
pH	SU	6.9	6.2	5.6
Alkalinity as $CaCO_3$	mg/L	187	149	131
SO_4	mg/L	1740	1330	1220
Cl	mg/L	14.7	12.3	11.2
Al	mg/L	1.1	2.2	2.1
As	mg/L	0.001	0.001	0.001
Ca	mg/L	560	490	465
Mg	mg/L	110	81	80
Na	mg/L	14.3	16.1	15.7
K	mg/L	61	32	31
Cd	mg/L	0.001	0.001	0.001
Cr	mg/L	0.001	0.001	0.001
Co	mg/L	0.001	0.001	0.001
Cu	mg/L	0.6	0.9	0.8
Fe	mg/L	71	61	54
Mn	mg/L	44	29	21
Zn	mg/L	2.7	3.5	3.4

If evaluated strictly on the basis of dissolved SO_4 and metal concentrations, model results for Scenario 3 indicate that liming of the Watut River recharge stream could induce improved water quality following initial flooding of the cave zone, plus sustained improvement relative to Scenarios 1 and 2 over a post-closure period which would extend to the time-step at which spring rejuvenation and stream baseflow recovery is predicted by FEFLOW to occur. The major beneficial effects of liming, in addition to the inevitable increase of pH, are predicted to involve those metals which are not subject to high solubility at low redox potential, notably Cu and Al. This tendency would also apply to most other first row transition elements with the exceptions of Fe and Mn. Important caveats to this 'beneficial' influence of lime addition relate to the fact that the geochemical model assumes (i) full mixing and hence heterogeneity of block cave water quality and (ii) effective sedimentation, with no subsequent redissolution, of precipitated gypsum and metals in response to lime amendment.

6.3.4 Steady-state conditions

Following full inundation of the block cave, the rate of mass transfer of water within the void space will be broadly equated to the rate of recharge. This is estimated following the recovery of groundwater levels to their equilibrium condition to be no more than 10 L/s. The average discharge rate from the cave though a combination of resurgence into the overlying lake water body and lateral flow through the cave zone is of the order of 1% of the total void space per annum if calculated on an average basis for the first 100 years following flooding to the 250 masl elevation. The implication of this is a long residence time for water in the cave and thus relatively unvariable water quality over time-scales of decades and possibly centuries.

6.3.2 Lake chemistry

Modelling of subsidence zone lake water chemistry evolution was undertaken using a chemical mass balance constructed in GoldSim, into which solubility constraints founded on PHREEQC model simulations were included to account for any saturation-precipitation controls on metal solubility that are likely to occur. The model was run over a time period of 50 years commencing with the first year of onset of lake development (around year 50 post-closure in Scenario 1 and year 5 in post-closure scenarios 2 and 3). The final stages of the model simulation therefore capture a period in which, on the basis of the physical water balance, steady-state discharge from the spill point is projected to occur. Assuming conditions of complete mixing, the chemical evolution of the lake under all scenarios reflects a trend over time of progressively increasing dominance of catchment runoff and direct precipitation onto the lake relative to resurgent groundwater.

Table 11 provides a summary of water quality model results for all scenarios. The major trends predicted for each case are as follows:

- Under Scenarios 1 and 2, the lake water body is predicted to remain acidic throughout the 50-year period of model execution. In both cases, pH increases modestly from a starting condition of close to 4 to a level of above 5 by year 30. Adjustments of pH over the subsequent 20 years are predicted to be minor.
- From the onset of lake development, Scenario 2 is predicted to display slightly lower SO_4 concentrations and metals than Scenario 1. This is attributable to the relatively large component of the lake water balance which is associated with discharge from the cave zone during early lake filling. As the proportional significance of this component relative to direct lake surface precipitation decreases over time, the differential metal concentrations predicted for the two scenarios become smaller. Steady-state water quality at the time of onset of discharge via the lake spill point is predicted to be broadly analogous for Scenarios 1 and 2.
- Concentrations of Fe are predicted to decline abruptly during early lake development under scenarios 1 and 2 in response to a solubility limit induced by a combination of rising pH and redox potential. By year 25, Fe levels are predicted to be reduced to only a few mg/l in both cases. A similar trend is evident with respect to Mn following the increase during lake filling of pH to around 4.5, and with respect to Al at above pH 5.
- Scenario 3 is distinguished from scenarios 1 and 2 in that the predicted pH at the commencement of lake development is significantly higher (6.2). This reflects the effect of lime amended water emanating from the

underlying block cave zone. Over time, the significance of this inflow as a contribution to the overall lake water balance declines, resulting in a projected reduction of lake pH to 5.5 by the onset of discharge via the lake spill point.

Table 11: Model simulation of **subsidence zone** lake water quality during progressive filling to the onset of steady-state discharge, assuming prior cave zone inundation in accordance with each of Scenarios 1, 2 and 3.

	Units	Scenario 1			Scenario 2			Scenario 3		
Year		1	10	50	1	10	50	1	10	50
Lake volume	Mm^3	0.028	0.60	3.2	0.028	0.60	3.2	0.028	0.60	3.2
pH	SU	4.2	4.9	5.2	4.4	4.9	5.2	6.2	5.7	5.5
SO_4	mg/L	1419	1015	245	1247	970	245	1120	960	240
Al	mg/L	20.02	16.1	1.8	8.7	6.2	0.9	0.8	1.1	1.6
As	mg/L	0.0009	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Ca	mg/L	329	231	84	310	207	82	442	290	246
Mg	mg/L	30.3	27	23	24	21	18	37.4	29.2	21.8
Cd	mg/L	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Cr	mg/L	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Co	mg/L	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Cu	mg/L	42	7.0	2.2	29	6.2	1.4	0.4	0.2	0.2
Fe	mg/L	109	7.4	6,6	49	6.1	5.8	21.5	3.5	2.9
Mn	mg/L	17.3	13.2	6.4	12.1	9.4	8.8	19.3	12.7	3.2
Zn	mg/L	32.6	11.6	7.1	27.2	8.5	7.3	3.3	3.1	1.7

7 SUMMARY AND CONCLUSIONS

This memorandum provides a preliminary assessment of the post-closure hydrological and associated water quality regime which may be expected to develop following the termination of mining at Golpu. The principal conclusions which may be drawn from the FEFLOW, GoldSim and geochemical modelling simulations performed may be summarized as follows:

1) Under conditions of passive flooding of the Golpu block cave, complete inundation to the base of the overlying subsidence zone is likely to occur over a time period of around 45 to 55 years, depending on matrix porosity. Development of a lake will then commence in the subsidence zone, fed by a combination of resurgent groundwater, catchment runoff and precipitation. This will reach an elevation at which decant to the surface drainage network would occur after a further period of approximately 35 years.

2) Under a scenario in which accelerated flooding of the block cave is induced through the pumping of water from a river source at a constant rate of 500 L/s (denominated Scenario 2), complete inundation to the base of the subsidence zone would occur in a period of around 4 years.
3) Under a passive inundation scenario, the quality of water which will accumulate in the block cave zone will be strongly acidic, with an early flooding pH level of less than 3 rising progressively to around 4 by the end of the cave flooding period. Concentrations of TDS would be of the order of 10,000 mg/L at the onset of flooding and will remain above 3,000 mg/l at the end of the flooding period. Concentrations of metals and SO_4 will be correspondingly high. The practical implication of this is that any discharge via re-activation of springs in the vicinity of the block cave will be acidic and will contain levels of Fe, Mn, Cu, Al and other metals which exceed industry-standard thresholds for mine effluents.
4) Accelerated flooding of the block cave, if applied in in isolation (Scenario 2), is predicted to marginally reduce, but not eliminate, the risks of degradation of re-activated springs and/or of any groundwater system. A fundamental reason for this relates to the fact that while the period of time over which active oxidation of sulphides in the rock mass within the block cave is reduced, the contact water pH will remain low. This constrains any benefit that would otherwise occur in response to metal saturation and precipitation.
5) The application of an accelerated flooding strategy, as per Scenario 2, but with supplementation of the artificial recharge with hydrated lime (denominated Scenario 3) is indicated by model simulations to offer significant benefits with respect to the chemistry of water which will occupy the inundated cave zone. The improvement of water quality, in addition to pH, is most strongly evident with respect to metals which are least prone to remain mobile in their lower valency states, as exemplified by Cu.
6) Prediction of the quality of water which will accumulate in, and ultimately discharge from, the Golpu subsidence zone lake is complex and should ideally be performed in conjunction with a detailed physical limnological assessment. Initial, simplistic modelling simulations performed in GoldSim, with limited incorporation of mineral solubility controls determined using PHREEQC, suggest that for cave-inundation Scenarios 1 and 2, the subsequent lake chemistry evolution trend would be similar. Assuming full mixing, the lake water quality is projected to improve progressively during the period of flooding of the subsidence zone lake in each of these cases. By the time of initial discharge to the surface water drainage network, pH levels of around 5 would be anticipated, with SO_4 levels of no more than a few hundred mg/l and concentrations of Fe, Mn, Cu and Al in the low mg/l range. Under Scenario 3, the pH trend predicted for the period of lake development is effectively reversed, with a level of above 6 likely during the early years of lake formation and declining to around 5.5 by the onset of discharge via the lake spill point. The concentrations of metals are, however, predicted to be lower than those associated with Scenarios 1 and 2.

The results of preliminary modelling undertaken to date provide guidance for further efforts to refine the closure strategy for the Golpu cave and subsidence zone. Detailed analysis of the feasibility of Scenario 3 appears particularly strongly warranted. In any further analysis, some of the major uncertainties inherent to the models outlined in this memorandum require particular attention. These include an assessment of the extent to which the block cave and overlying subsidence zone lake will be prone to permanent chemical stratification as this may substantially influence the quality of discharges to both the district groundwater system and surface spring/drainage network.

Due to the long (several decade) time-frame over which block cave and subsidence zone lake water quality is likely to attain an equilibrium state following closure, substantial provision must be included in the closure plan for performance monitoring. This should ideally include a full water quality audit twice annually during the first few years of closure, and subsequently at approximately once every two years until compliance conditions are met.

With kind regards

Martin Williams
Group Chief Geochemist, Piteau Associates.