GOLDER

Planning for the next land use: Sustainable agricultural use after the closure of a 100-year-old diamond mine

SUSTREM VIRTUAL CONFERENCE 2021

GOLDER AFRICA WATER TEAM

November 2021

Planning for the next land use: Sustainable agricultural use after the closure of a 100-year-old diamond mine

INTRODUCTION

- Golder has been involved in developing a SPR model to evaluate the proposed post mining land use for a diamond mine in the Free State Province of South Africa.
- The anticipated next land use for the wider mine site area is commercial agriculture. The mining area and other Voorspoed properties will be used for profitable extensive sheep and cattle farming, with limited cropping on existing cultivated lands. This land use coincides with the general land use in the boarder study area.
- The mine comprises a 250 m deep open pit and three large waste residue facilities. These mining related features represent possible sources of contamination to the receiving environment.
- The proposed rehabilitation measures involve application of growing medium and vegetation of the waste residue facilities and fencing-off the open pit area.
    - The rehabilitation plan was developed from piece-meal projects undertaken by multiple consultants over the closure preparation phases of the project. In completing the Rehabilitation and EMPR gaps in understanding of the S-P-R were identified.
    - Golder was appointed to evaluated the rehabilitation plans and draw a better understanding of the S-P-R for the site. This work focused largely on characterization of water and soils.

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BEST PRACTICE GUIDELINES

Closure of Mine Residue Deposits (A2 – Mine Residue Deposits)

- Minimisation of long-term post-closure water quality impacts
- Long-term stabilisation of the MRD
- Minimising the environmental impacts of the MRD
- Creating an acceptable aesthetics closure scenario
- Determining the post-closure maintenance requirements.

Redco (2019) proposed cover designs for the Voorspoed MRDs. These comprise a combination of rock, soil and vegetation.

Golder study aims to evaluate these covers in the context of the BPGs related to minimising environmental impact.

1. • Estimate potential infiltration
2. • Characterise expected seepage quality
3. • Estimate expected impact on receiving aquifers and receptors

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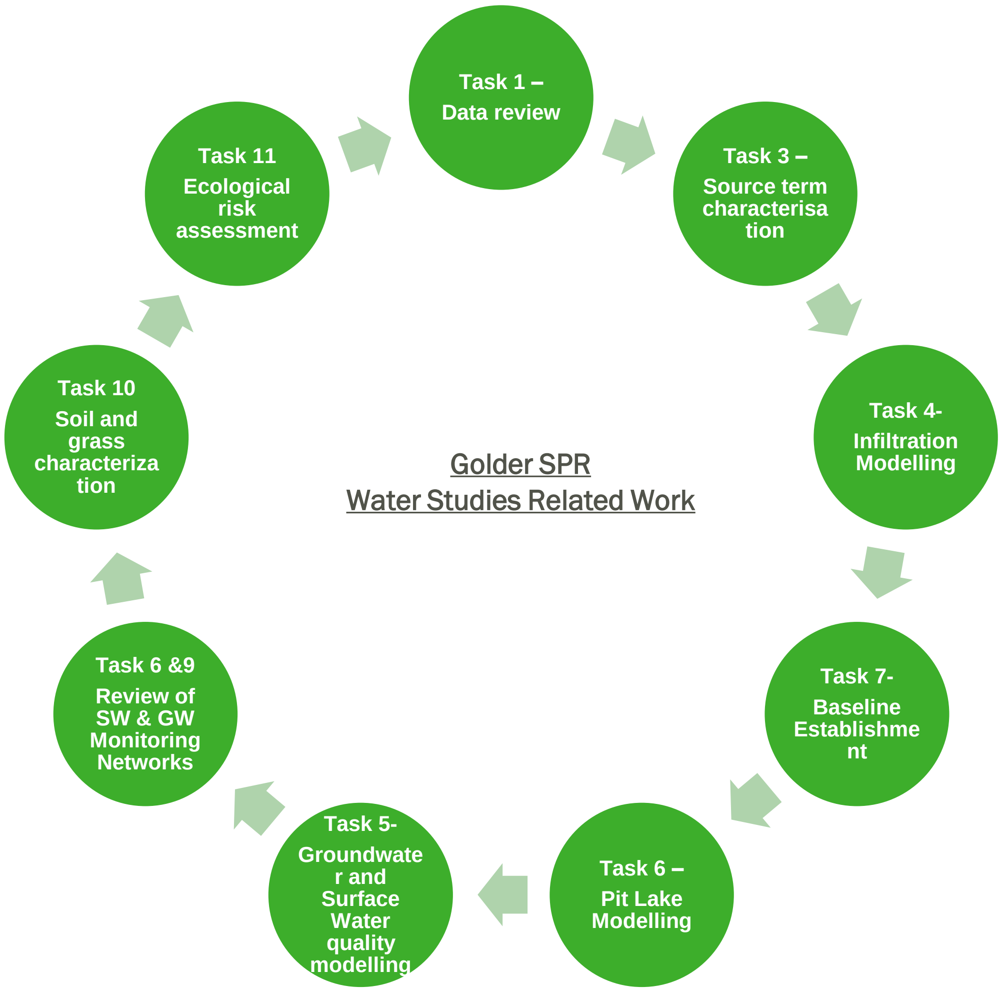
INTEGRATED PROJECT REQUIRING A TEAM OF SPECIALISTS



Specialist team comprising

- Geochemists
- Hydrogeologists
- Hydrologists
- Soil scientists
- Contaminated land specialists

- The Golder team who prepared the integrated study presented here involved over 12 team members.

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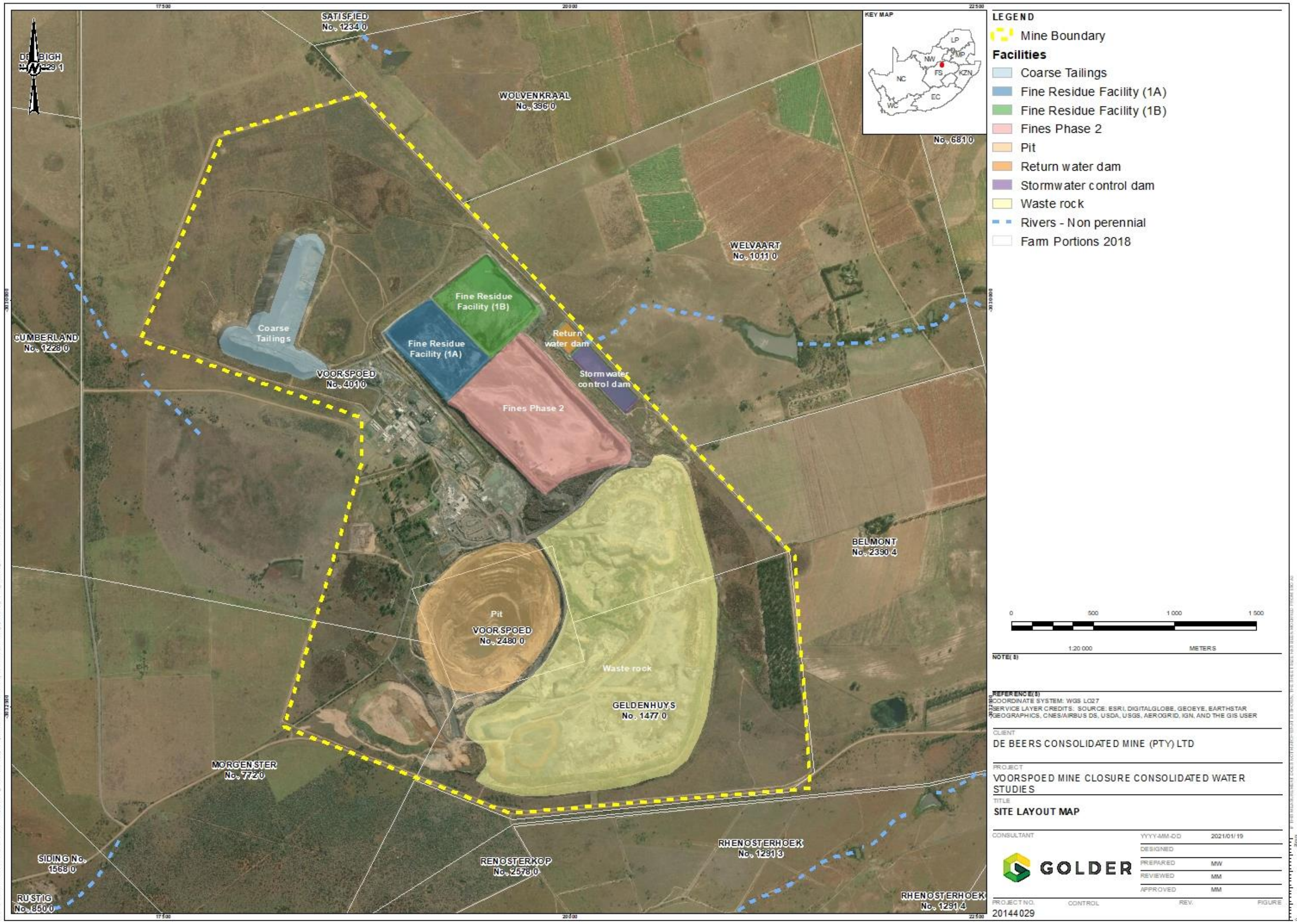
VOORSPOED MINE LAYOUT



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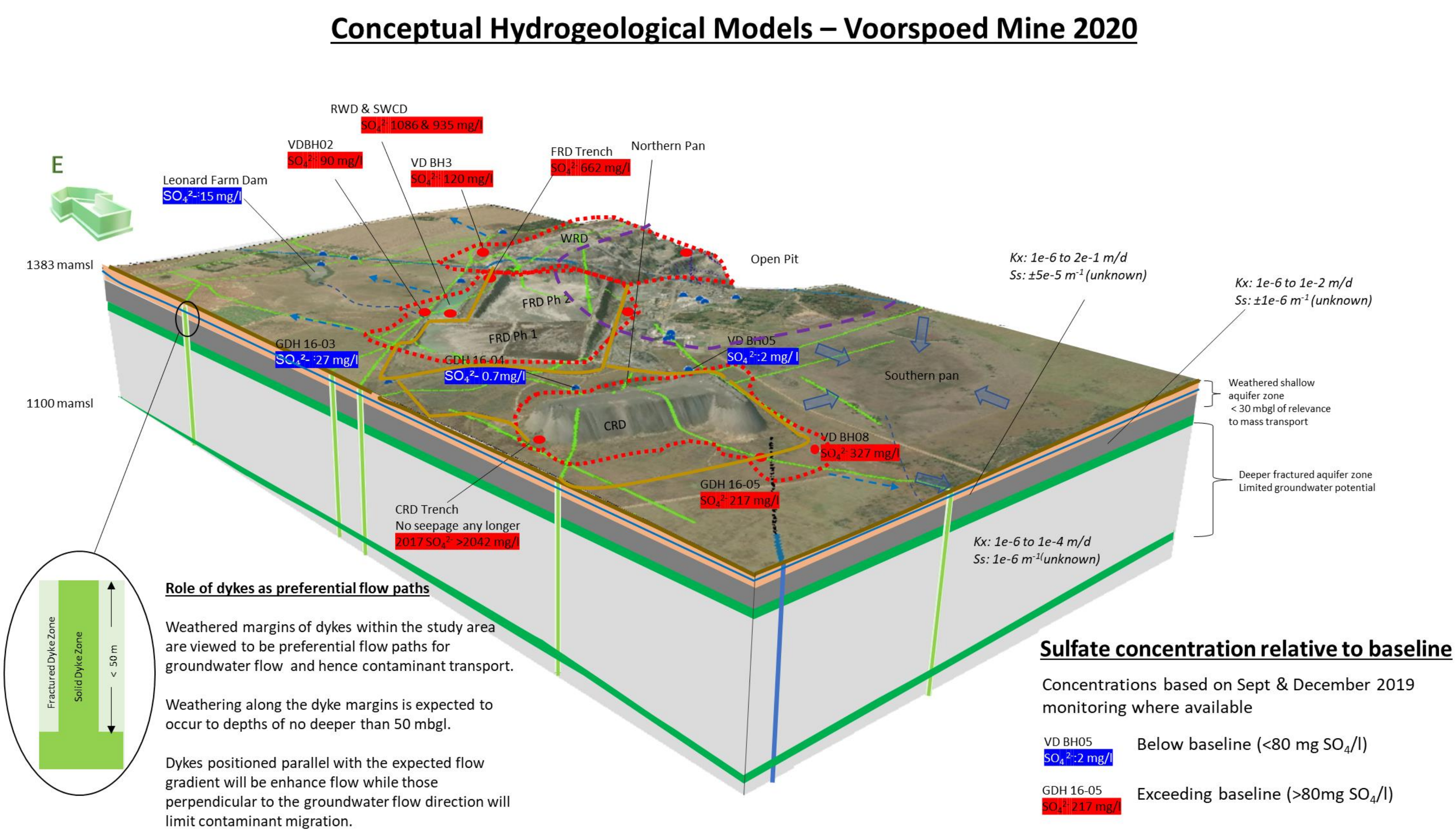
CONCEPTUAL MODEL – VOORSPOED MINE 2020

Current conditions – pre-final land use



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CONCEPTUAL MODEL – VOORSPOED MINE 2020

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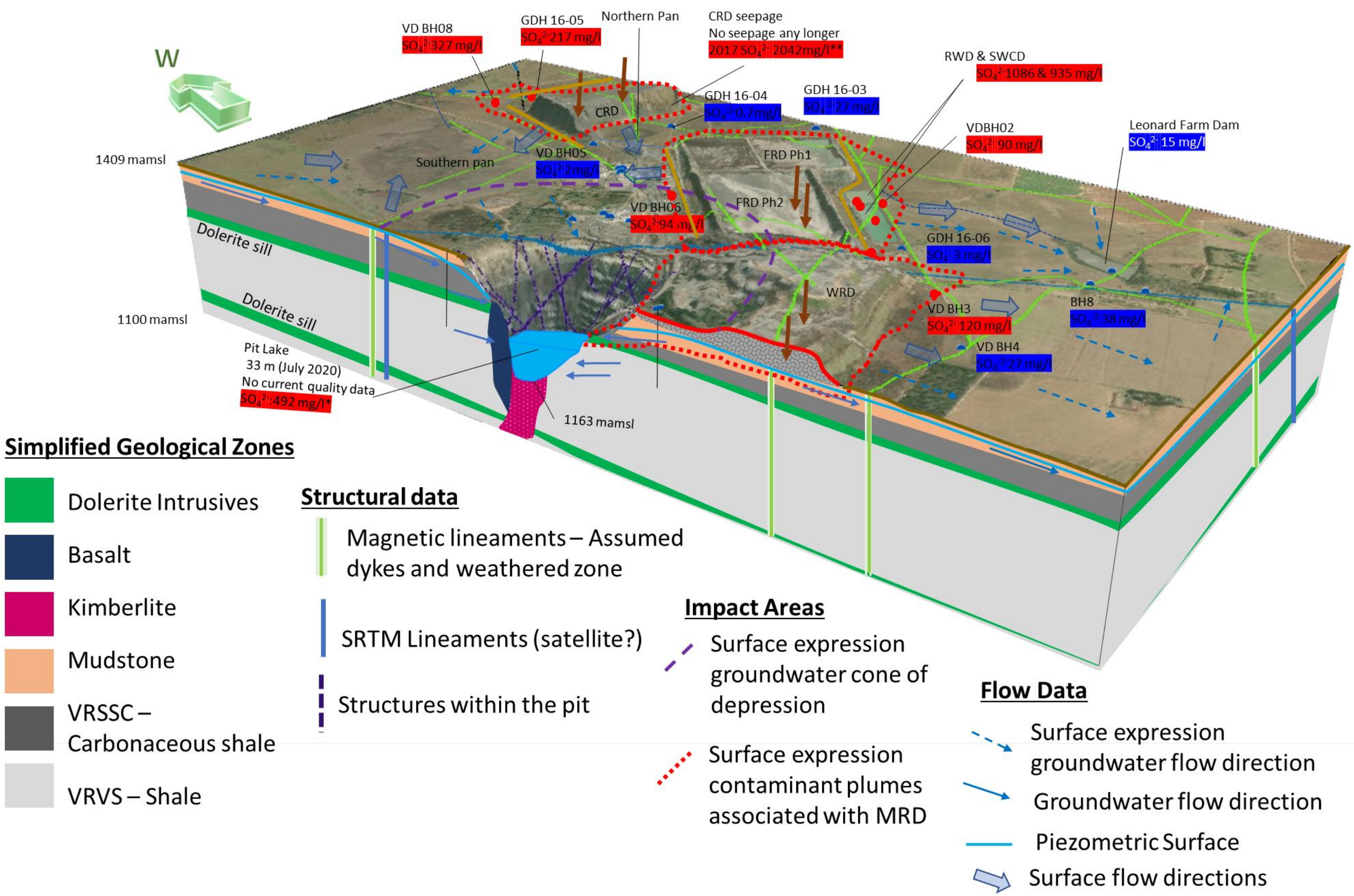

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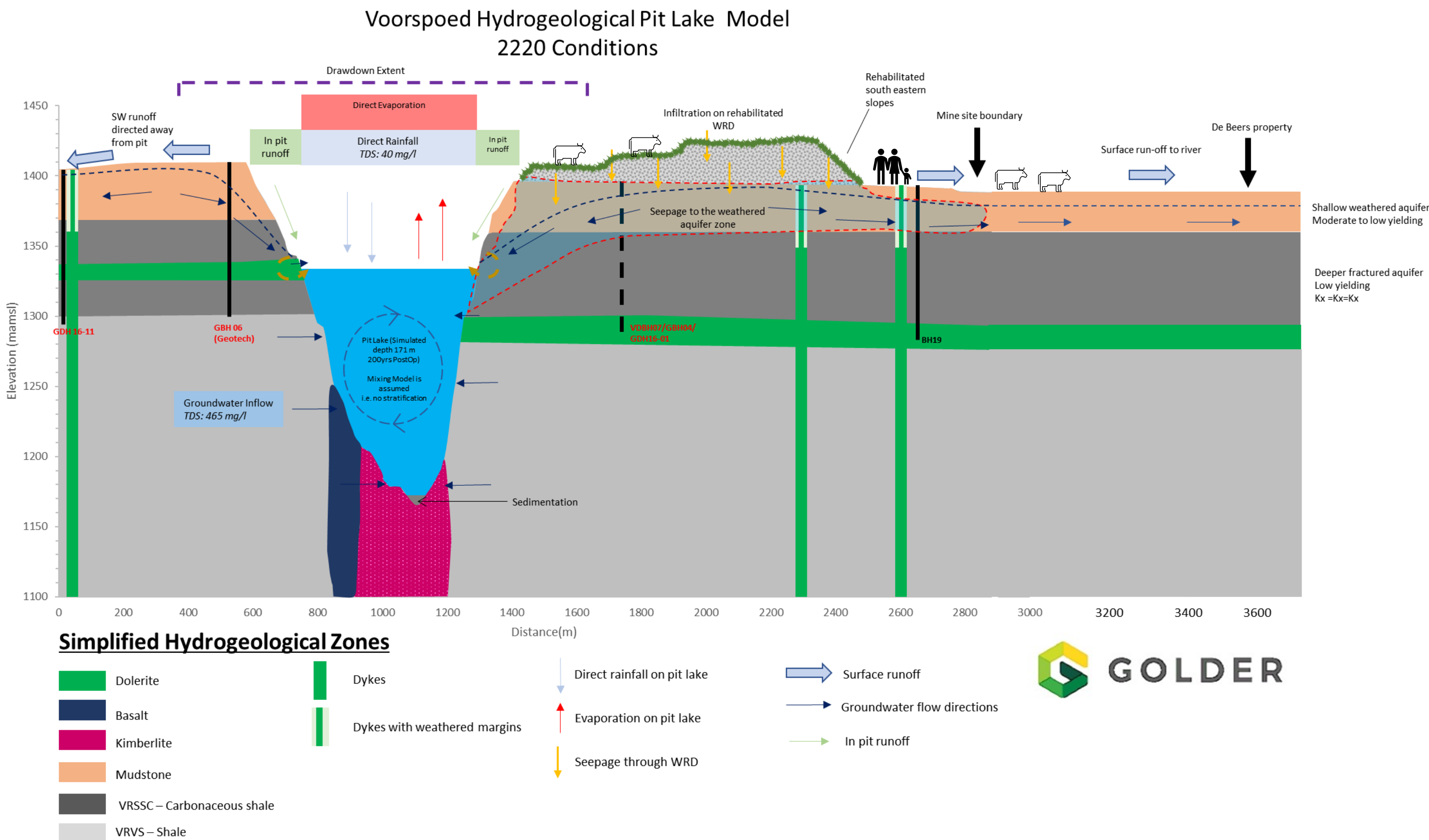
CONCEPTUAL MODEL – VOORSPOED MINE 2020



SPR Model for Final Land Use

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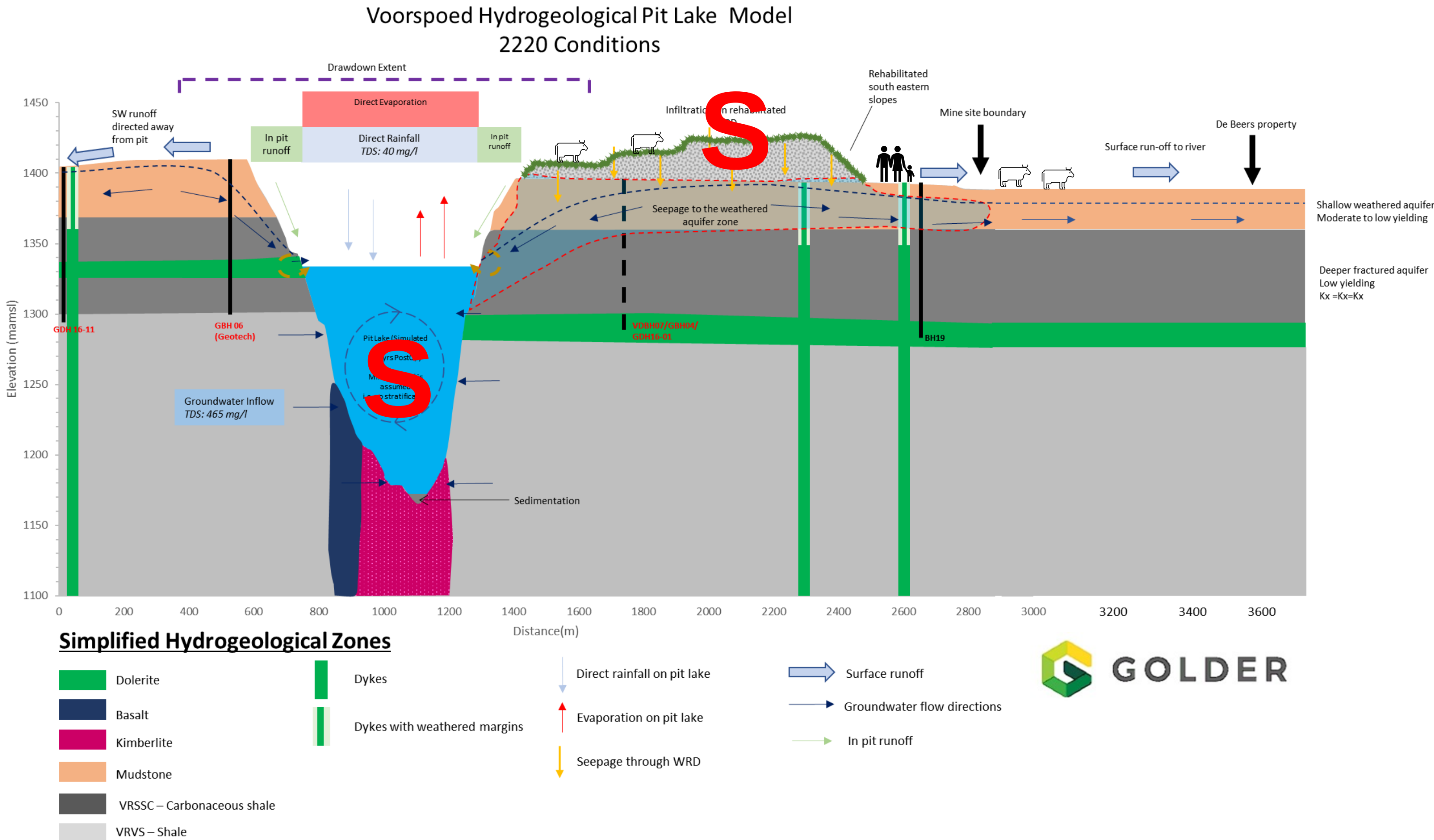
CONCEPTUAL MODEL – VOORSPOED MINE 2020

SPR Model for Final Land Use



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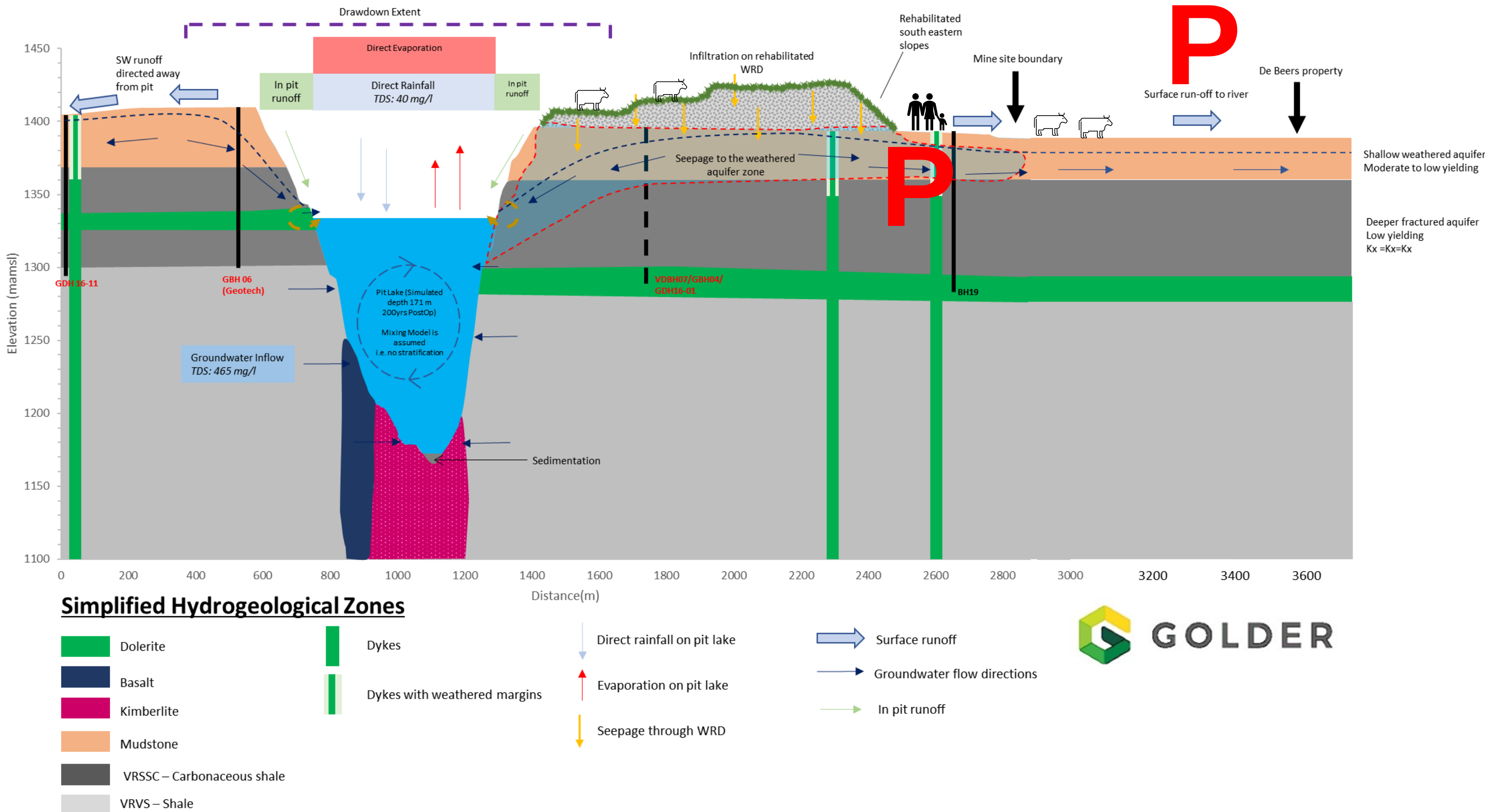
CONCEPTUAL MODEL – VOORSPOED MINE 2020

SPR Model for Final Land Use

Voorspoed Hydrogeological Pit Lake Model
2220 Conditions



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CONCEPTUAL MODEL – VOORSPOED MINE 2020

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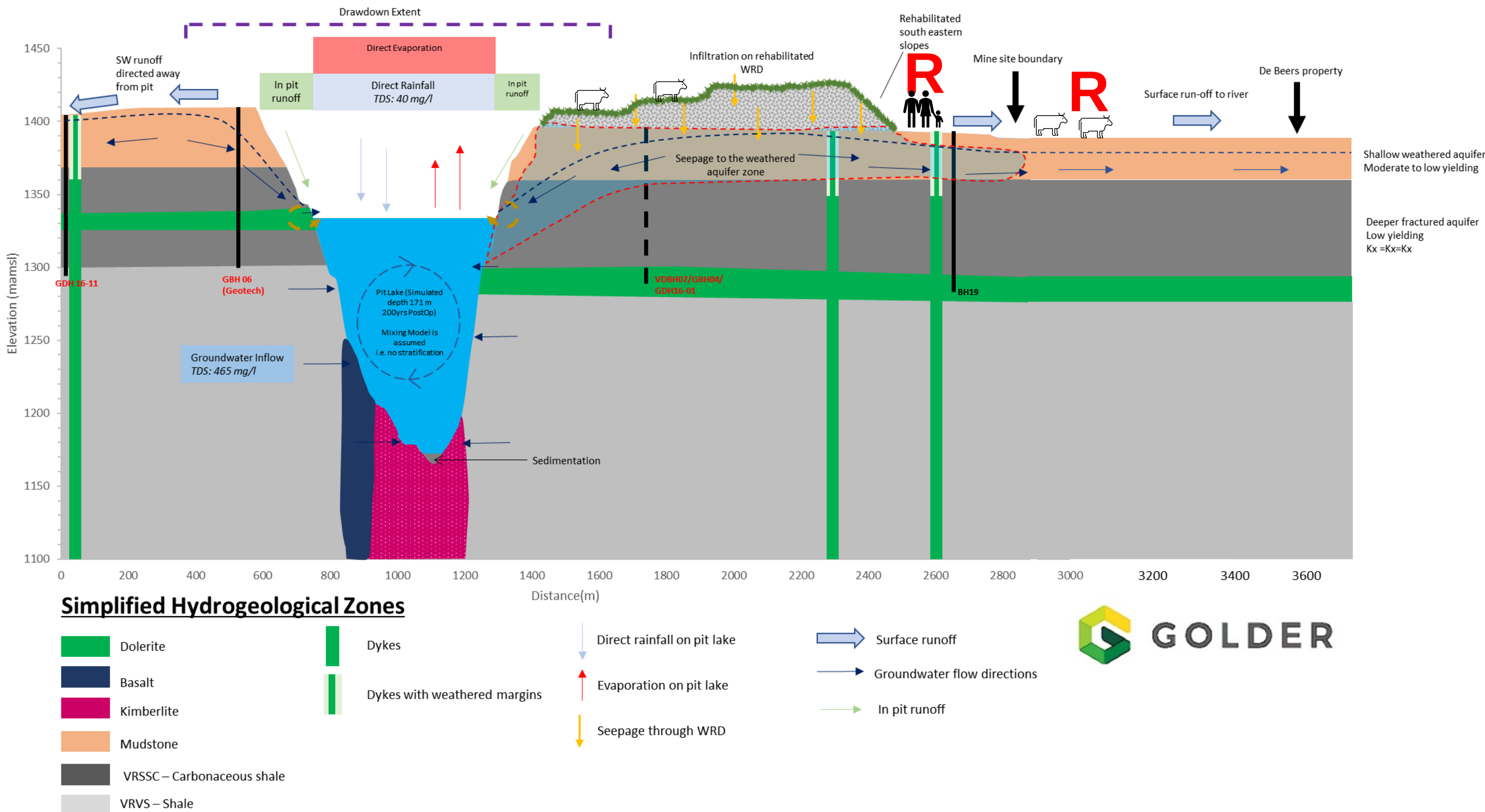

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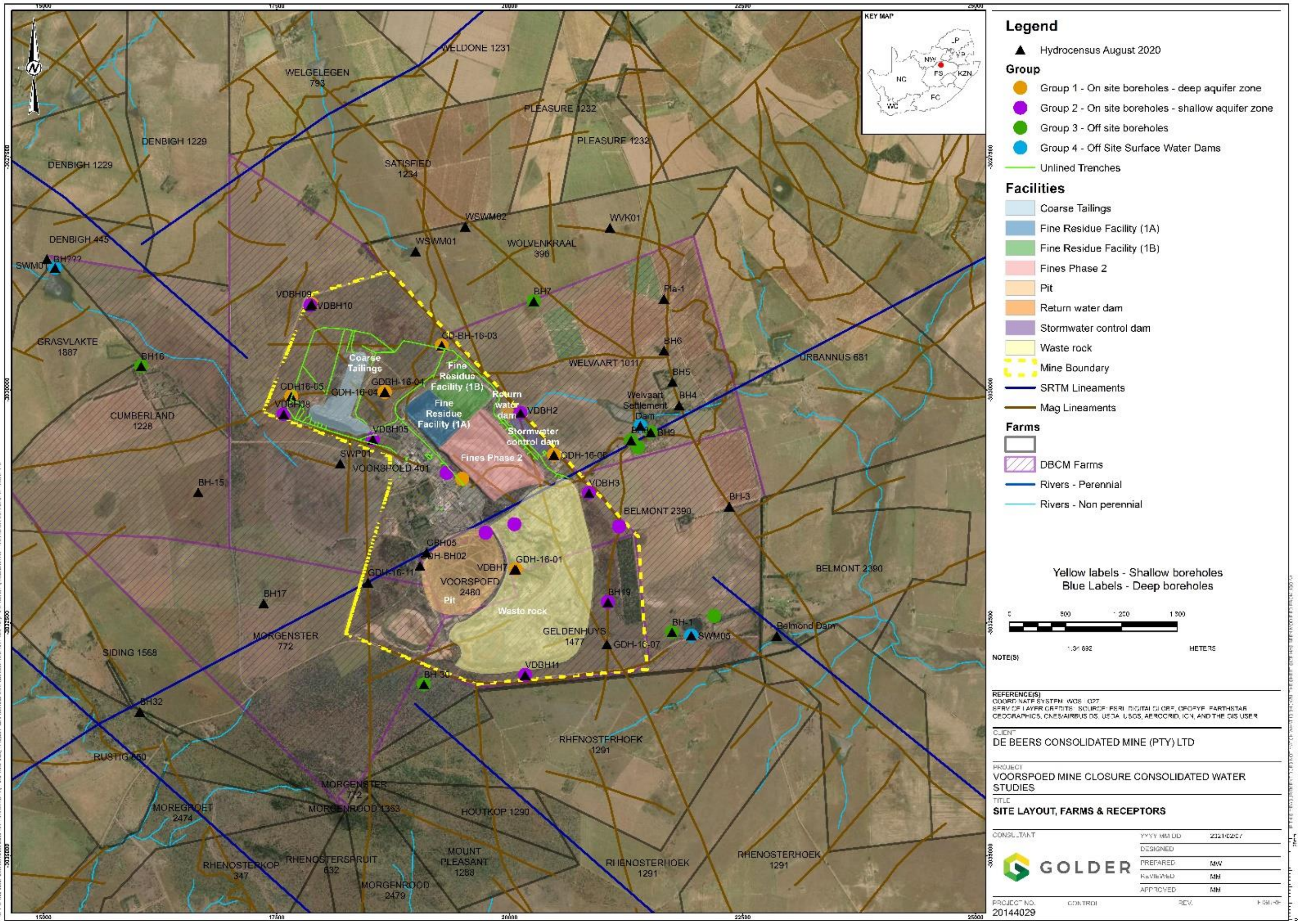
VOORSPOED RECEPTORS

Land ownership and potential receptors



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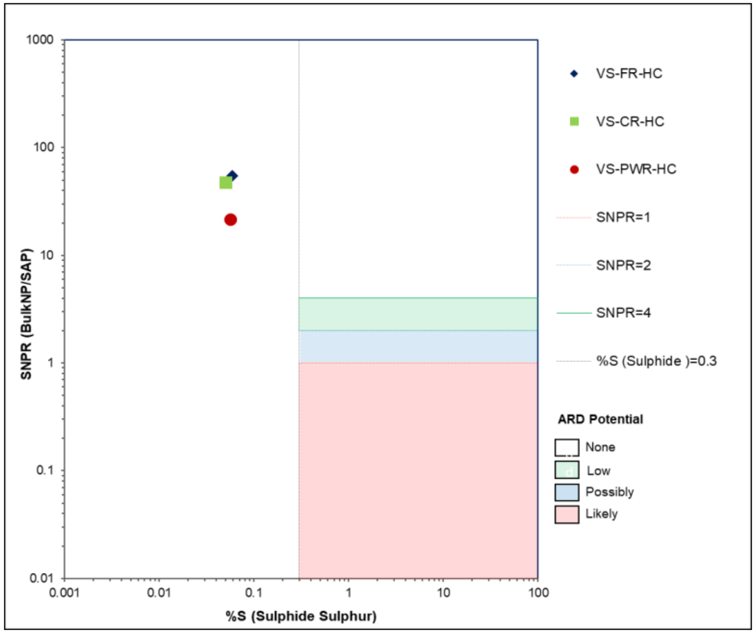
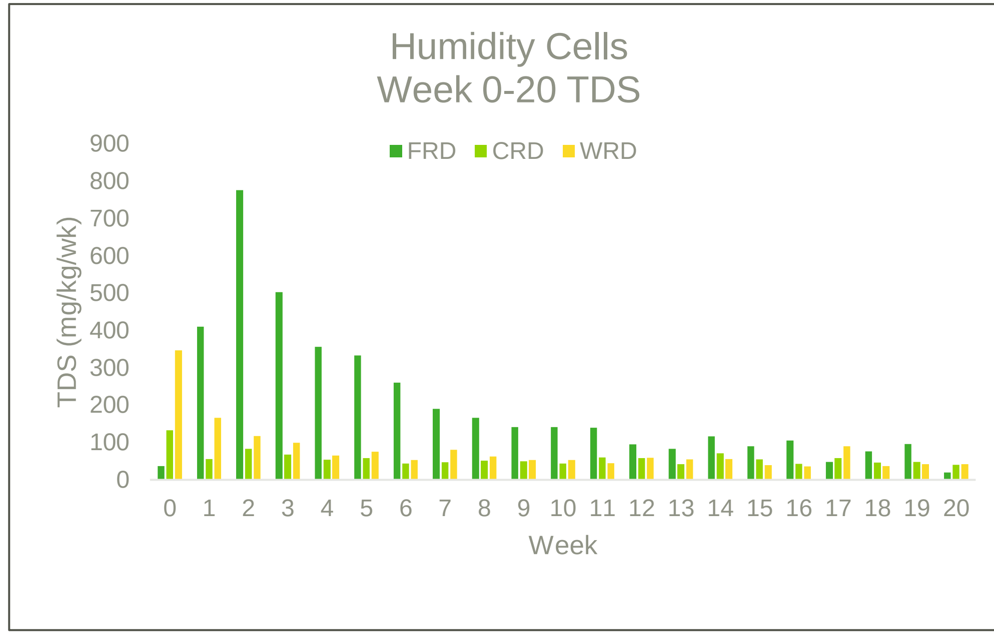
TASK 3 – KINETIC TESTING PROGRAM

Quantifying the Source term characteristics





- Acid generation is unlikely
- The waste rock, coarse residue and fine residue Voorspoed samples were found to be enriched with **antimony, arsenic**, boron, barium, **bismuth**, lanthanum, lithium, **selenium**, tellurium and thorium
- Humidity cells - circumneutral, with a low TDS.

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TASK 3 – KINETIC TESTING PROGRAM

Quantifying the Source term characteristics

Outcomes

Post closure leachate generation expected to exceed baseline and irrigation guidelines but concentrations are expected to be suitable for domestic and livestock.

Parameter	Time period	Baseline (Golder 2020)	SANS:241 2015 Drinking Water Quality Guidelines	DWAF Livestock Watering Limits (1996)	DWAF Irrigation Watering Limits (1996)	FRD	CRD	WRD
TDS	Operational					1800	1800	136
	Post Operational - Not rehabilitated	**528**	**1200**	**1000**	**260**	**283**	**30.7**	**12.26**
Chloride	Operational					230	230	1.8
	Post Operational - Not rehabilitated	**36**	**300**	**1500**	**100**	**3.31**	**0.15**	**0.05**
Sulphate	Operational					690	690	64
	Post Operational - Not rehabilitated	**40**	**500**	**2000**	**NA**	**70.89**	**2.86**	**2.9**

Exceeding drinking water quality guidelines

Exceeding Livestock water quality guidelines

Exceeding irrigation water quality guidelines

Without rehabilitation the impact of leachate is likely to be low due to the quality of the leachate expected to develop.

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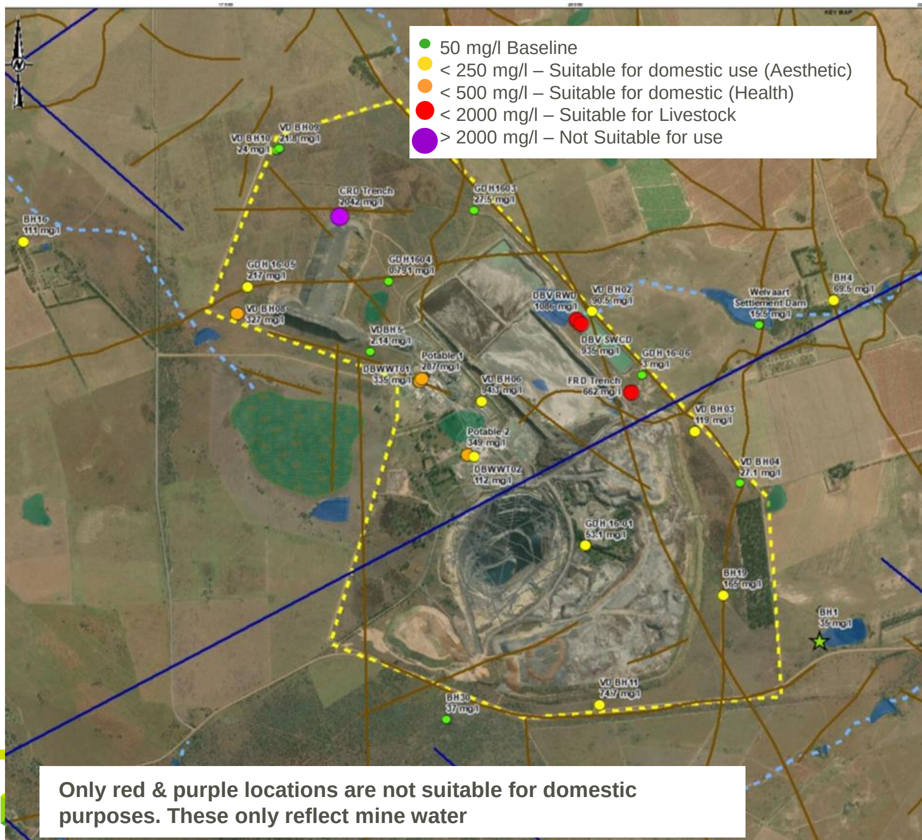
TASK 7 – BASELINE ASSESSMENT

Quantifying the Source term characteristics

Objectives

- Confirm the baseline groundwater quality status to be used as a measure against which closure monitoring should be compared.
- Identify any gaps where additional groundwater monitoring



Only red & purple locations are not suitable for domestic purposes. These only reflect mine water

Baseline characterisation

Sample	Unit	Proposed Baseline	
		Group 3 - Off Site Boreholes	Group 4 - Off Site Surface Water
pH @ 25°C	pH	8.34	9.57
Electrical conductivity (EC) @ 25°C	m S/m	88.73	54.2
Total dissolved solids (TDS)	mg/l	528.2	391.98
Total alkalinity	mg CaCO3/l	417.1	183.36
Chloride (Cl)	mg/l	35.89	84
Sulphate (SO_4)	mg/l	41.06	51.65
Nitrate (NO_3) as N	mg/l	2.36	1.3
Ammonium (NH_4) as N	mg/l	0.33	0.07
Ammonia (NH_3) as NH_3	mg/l	0.38	3.57
Orthophosphate (PO_4) as	mg/l	0.081	0.765
Fluoride (F)	mg/l	0.37	0.91
Calcium (Ca)	mg/l	73.21	25.04
Magnesium (Mg)	mg/l	29.19	9.6
Sodium (Na)	mg/l	89.9	86.58
Potassium (K)	mg/l	9.88	22.11
Aluminium (Al)	mg/l	0.007	12.938
Iron (Fe)	mg/l	0.019	9.191
Manganese (Mn)	mg/l	0.009	1.707
Chromium (Cr)	mg/l	0.004	0.011
Copper (Cu)	mg/l	0.031	0.041
Nickel (Ni)	mg/l	0.012	0.024
Zinc (Zn)	mg/l	0.128	0.136
Cobalt (Co)	mg/l	0.004	0.009
Cadmium (Cd)	mg/l	0.003	0.002
Lead (Pb)	mg/l	0.018	0.017

De Beers Integrated WUL
SANS:241 2015 Drinking Water Quality Guidelines
DWAF Livestock Watering Limits (1996)
DWAF Irrigation Watering Limits (1996)

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TASK 8 – PIT LAKE GEOCHEMICAL MODEL

Quantifying the Source term characteristics
Pit Lake

Objectives

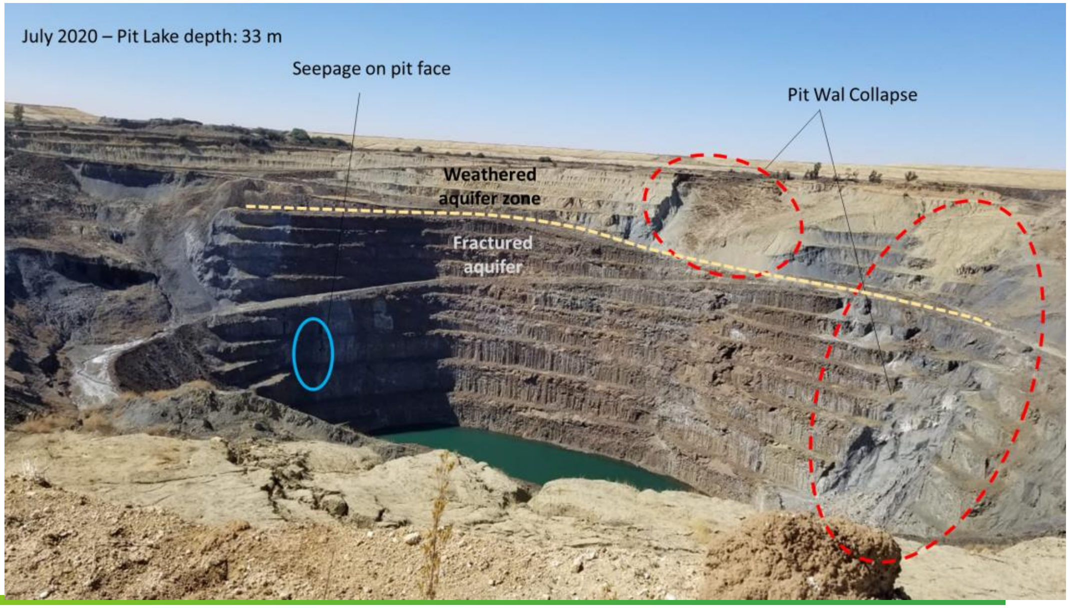
- Update the post mining pit lake pit quality predictions
- Previous modelling used a mass balance approach and used static leach test data
- The updated models are based on the (**Task 3**) Kinetic test data and a geochemical model to holistically evaluate water quality.

Outcomes – Pit Lake Water Balance

- Multiple scenarios evaluated indicate the range in pit lake elevation at steady state is between 1330 and 1360 mamsl. **Therefore the pit is expected to remain as sink post closure** (i.e. evaporation > (precipitation + groundwater+ in pit runoff)

Goldsim Mass Pit Lake Flooding Model

PhreeqC Geochemical Model



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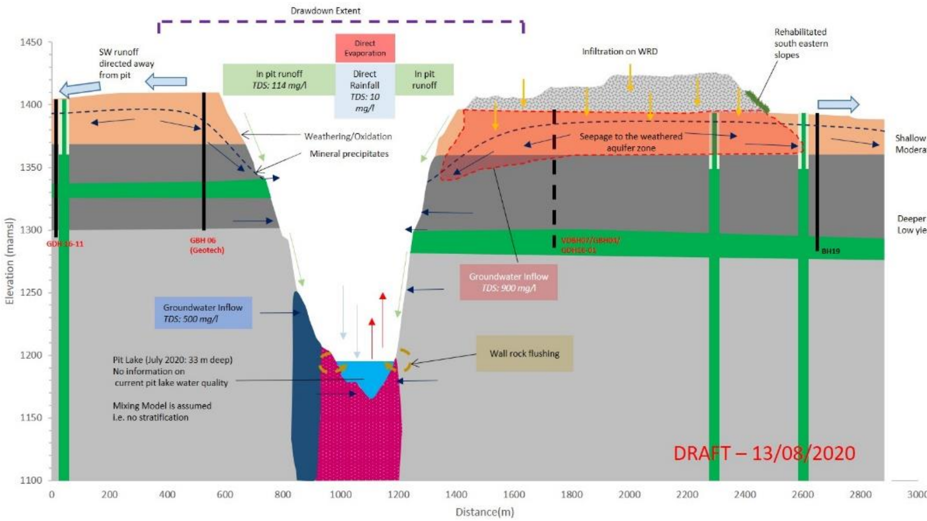
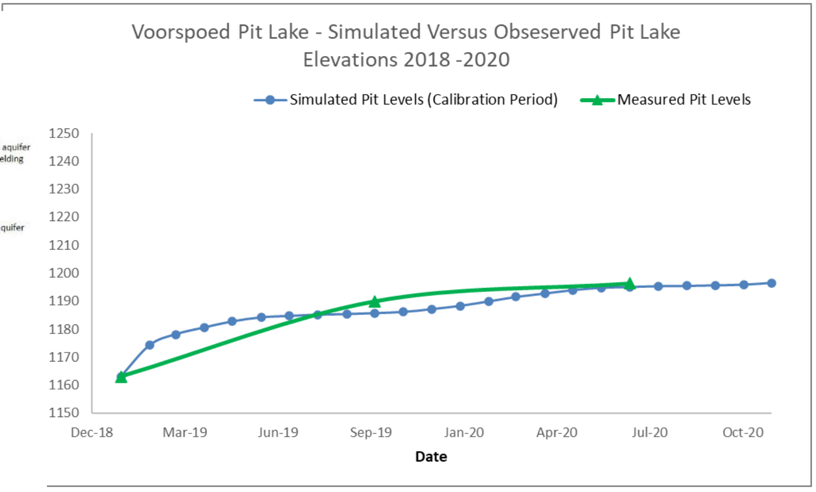
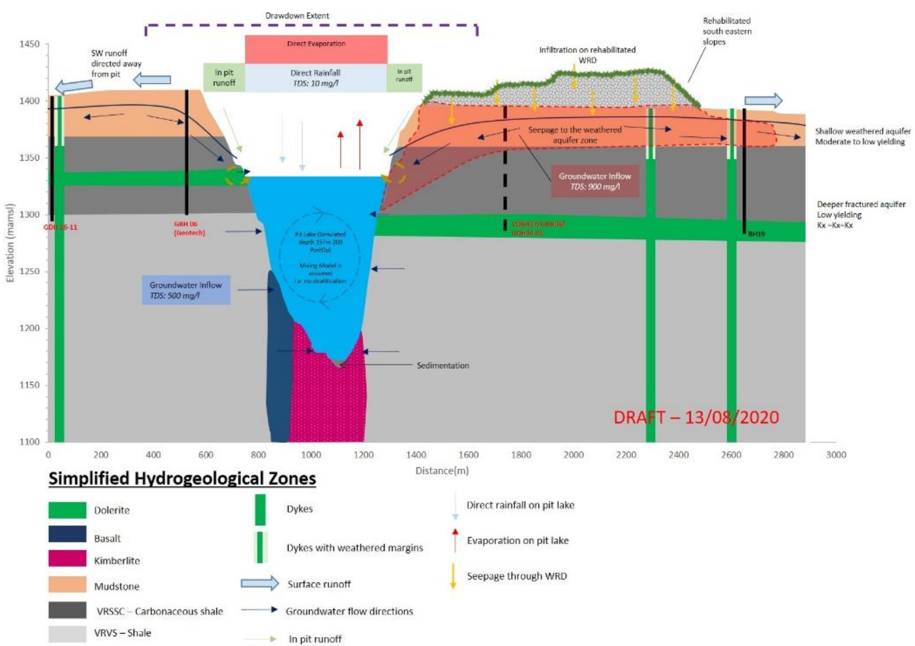
TASK 8 – PIT LAKE GEOCHEMICAL MODEL

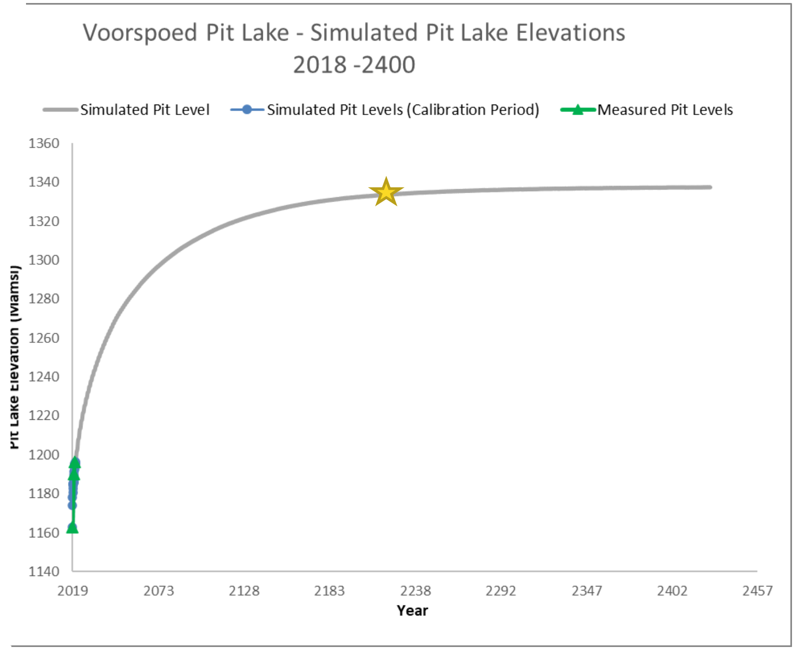
2020 Conditions





2220 Conditions





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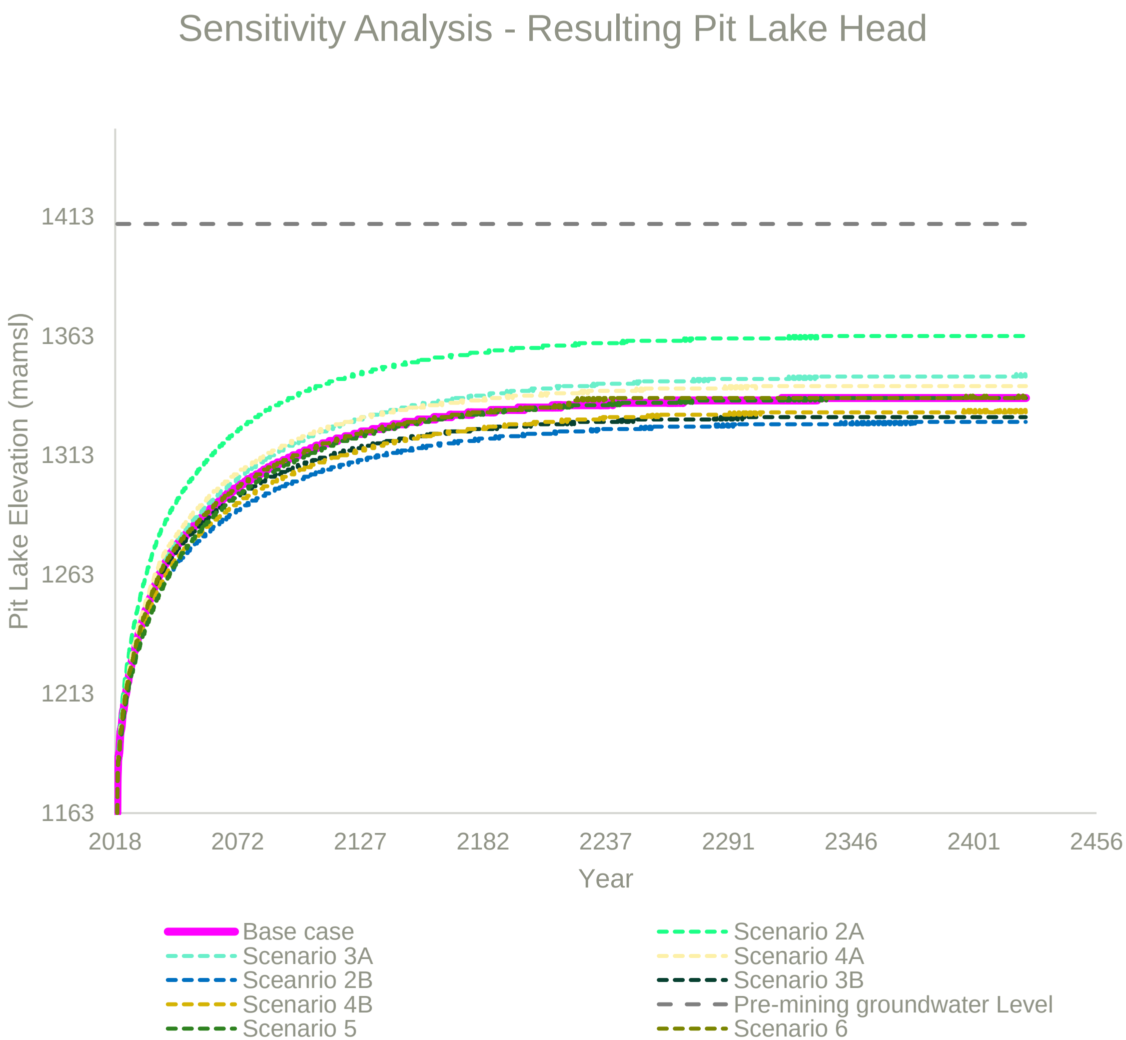
TASK 8 – PIT LAKE GEOCHEMICAL MODEL – SENSITIVITY ANALYSIS



Scenario	Description
Base Case	Refers to the base case model as described in the preceding sections.
Scenario 2A	3 x Estimated groundwater ingress (Peak: Approx. 6 l/s) The mean inflows during the operational period were 6 l/s. This however included groundwater and rainwater ingress. The median of 1.2 l/s i.e comparable to the base case model.
Scenario 2B	Base case ground water inflows reduced by 70%. i.e. groundwater inflow peak is approximately 0.5 l/s.
Scenario 3A	10% Reduction in S-pan to Dam Evaporation factor
Scenario 3B	10% increase in S-Pan to Dam Evaporation Factor
Scenario 4A	Due to the steep slopes and hard rock environment it is plausible that the run-off factor could be 0.8. (The base case is 0.7)
Scenario 4B	Comparatively, a second scenario was ruin where the in-pit runoff factor was reduced to 0.6 i.e. greater capturing of water occurs on slopes of the pit.
Scenario 5	No inflow from FRD Trench
Scenario 6	Five-year flood 200-year post operations

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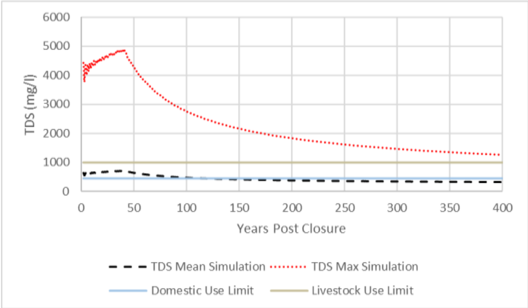
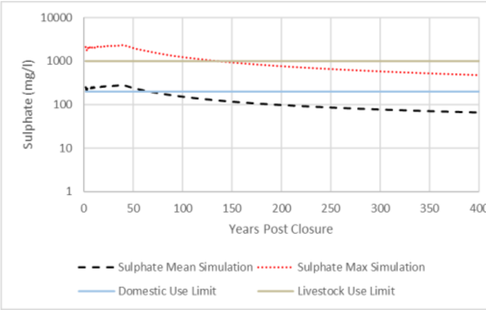
TASK 8 – PIT LAKE GEOCHEMICAL MODEL

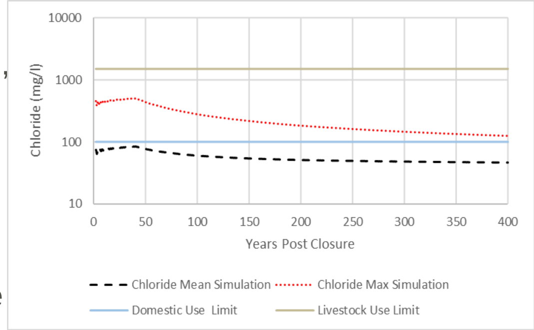
Quantifying the Source term characteristics
Pit Lake

Outcomes – Pit Lake Water Chemistry

- The majority of the modelled constituents meet the water quality guidelines for domestic, livestock and irrigation use.
- It was found that twelve (12) constituents (i.e., Chloride, Nitrate, Sulphate, Arsenic, Calcium, Cadmium, Potassium, Magnesium, Manganese, Sodium, Selenium and Vanadium) exceeded the domestic water quality guideline and one (1) constituent (i.e., Molybdenum) exceeded the livestock and irrigation water quality guideline for the simulated pit lake quality (post closure).
- Based on the modelling work completed, the post closure pit lake quality is not suitable for domestic purposes. Due to elevated Molybdenum, use of the pit lake water for livestock watering is not recommended without treatment.







Post Closure Pit Lake Concentrations

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TASK 4 – UNSATURATED FLOW MODEL

Quantifying the pathway characteristics

Objective

- Unsaturated flow models to simulate infiltration through the CRD, FRD and WRD.

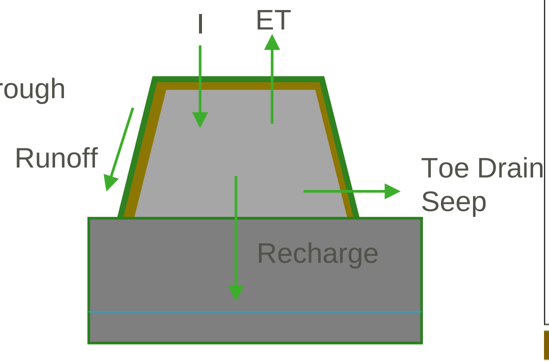
Methodology

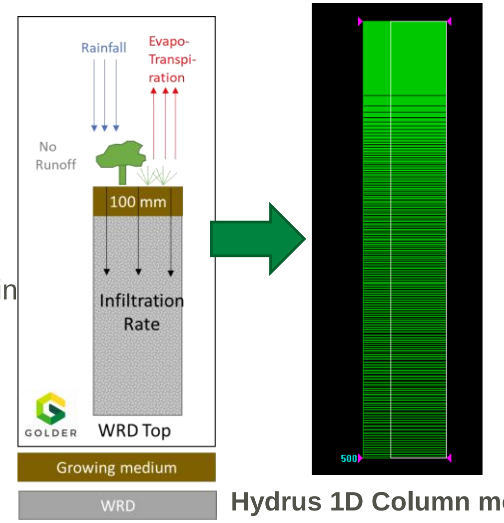
- Infiltration was calculated using Hydrus 1D, hourly rainfall and material properties obtained from field testing.
- Three scenarios were considered: (1) Unrehabilitated (2) rehabilitated with grasses (3) Rehabilitated, grasses and trees.

Final Results

- As expected highest infiltration is anticipated through the unrehabilitated WRD of the three MRD.
- Recharge on the rehabbed CRD estimated to be 25% of MAP
- Recharge on the rehabbed FRD estimated to be 7% of MAP
- Once rehabbed, recharged on WRD is approximately 3% of MAP.

Conclusion: Proposed cover designs effectively reduce infiltration to the facility





Hydrus 1D Column model

Results Table – Unsaturated Flow Modelling

Scenario	Facility	Approximated footprint areas (m2)	Infiltration rate (cm/a)	Run-off (cm/a)	Total infiltration (l/s)	Total Runoff (l/s)
Unrehabilitated						
Base Case	WRD	2 061 678	50.3	0	32.9	0
	CRD	349 514	15	1	1.7	0.1
	FRD	1 238 566	4.1	1.58	1.6	0.6
Rehabilitated - Growth Medium & Grasses						
Grass	WRD top	1 459 224	2.2	*	1.0	*
	WRD slope	602 454	0.0	0.5		0.1
	CRD top	121 975	0.3	*	0.01	*
	CRD slope	227 539	0.0	0.8		0.05
	FRD top	889 006	0.2	*	0.09	*
	FRD slope	349 560	0.3	0.5		0.06
Rehabilitated – Growth Medium & Grasses & Trees						
Grass & Trees	WRD top	1 459 224	2.2	*	1.0	*
	WRD slope	602 454	0.0	0.6		0.1
	CRD top	121 975	0.1	*	0.02	*
	CRD slope	227 539	0.3	0.8		0.05
	FRD top (grass only)	889 006	0.0	*	0.05	*
	FRD slope	349 560	0.3	0.6		0.06

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TASK 5 – SW & GW MODEL

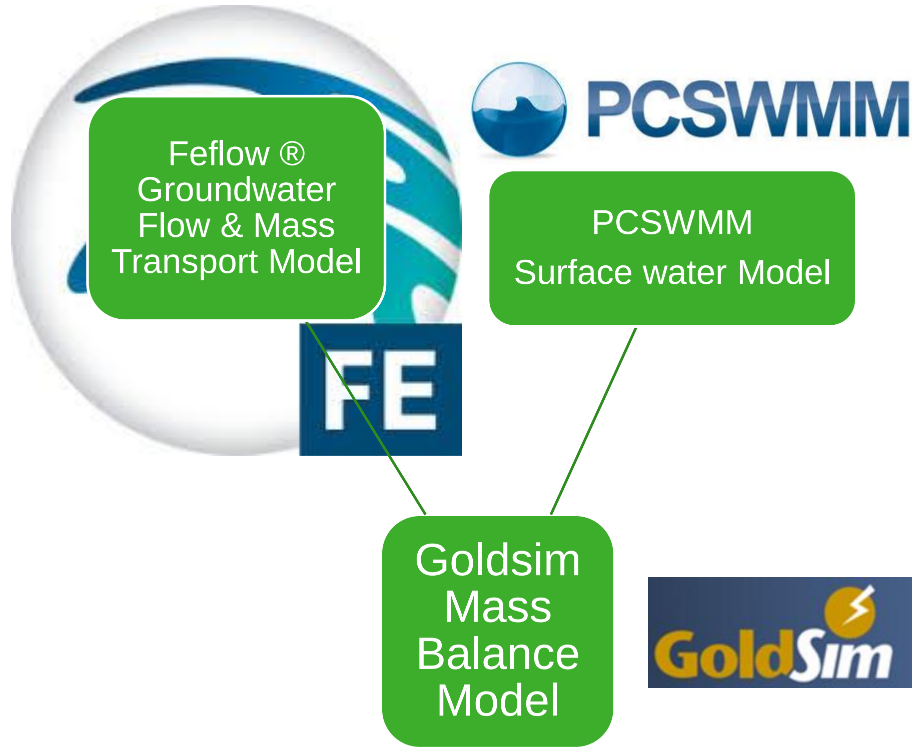
Quantifying the pathway characteristics

Objectives

- Update the feflow model to simulate mass transport plume developing in the subsurface which are associated with seepage from the FRD, CRD and WRD.
- Simulate post closure runoff in the mining areas that will report to the surface water bodies in proximity of the mine.
- Utilise a mass balance mixing model to predict post closure water quality at surface water bodies (Considers GW & SW contributions)

Outcomes

- The mass transport modelling demonstrates that negligible impact on groundwater related receptors is expected post closure.
- The post closure plumes result in dilution relative to baseline.
- Negligible impact on downstream water course are expected to occur.



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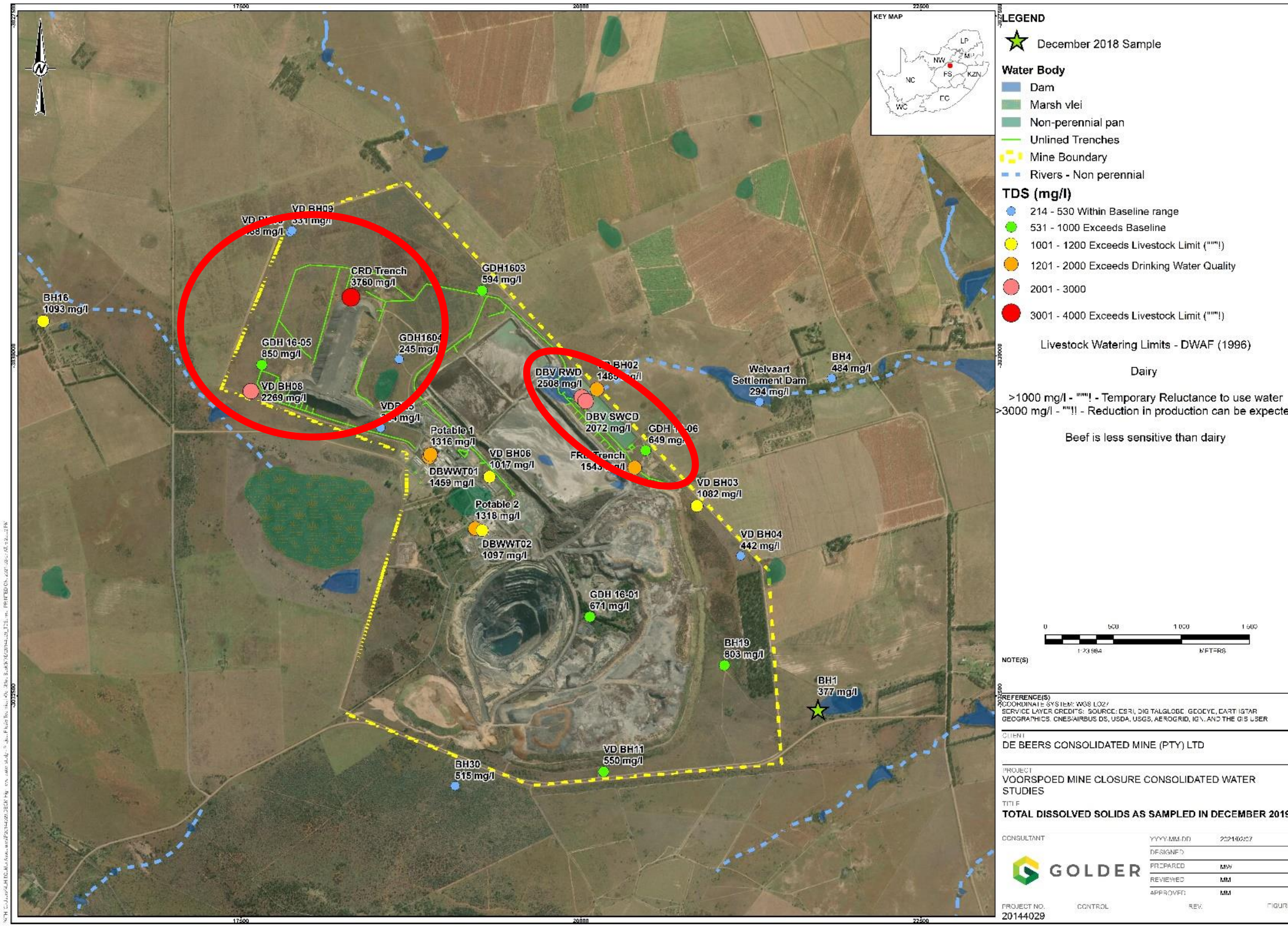
VOORSPOED GROUNDWATER QUALITY- MEASURED

Quantifying the impact to receptors



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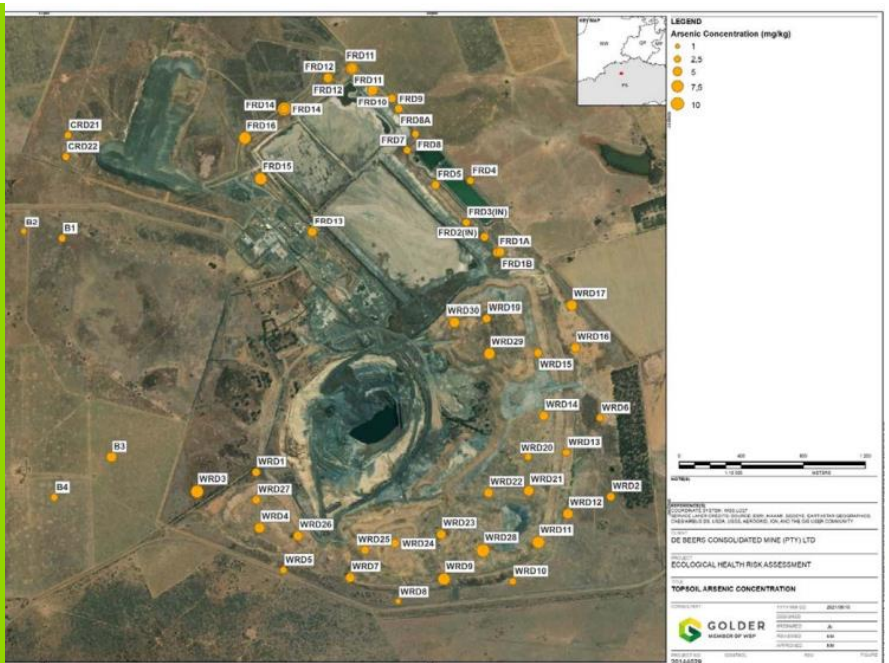
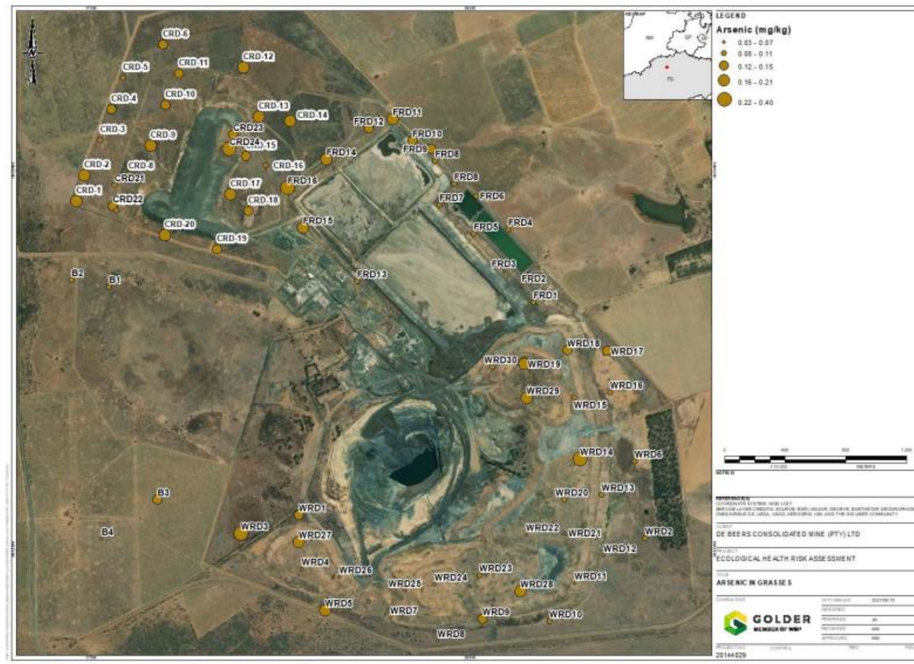
SOIL & GRASS CONTAMINATION

Quantifying the impact to receptors



Measured As in soils



Measured As in grasses

Soils and grasses were collected on and surrounding the waste residue facilities in order to characterize the metal loads available to cattle which will graze within the area.

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HUMAN HEALTH RISK ASSESSMENT

Quantifying the impact to receptors

- Ingestion of soil: Humans, especially farmers, are exposed to soil intake through dust inhalation and working with soil
  - The carcinogenic as well as the non-carcinogenic risk for soil ingestion for both adults and children is acceptable
- Consuming vegetables ground on the soil: Vegetable cultivation at the farmhouse for domestic consumption
  - The carcinogenic risk associated with adults and children consuming vegetables grown on the soils is acceptable.
  - The non-carcinogenic risks associated with adults and children consuming vegetables grown on the soils is potentially unacceptable for children. The assessment is conservative. A human and environmental toxicologist is likely to conclude that the risk is acceptable.
- Washing and consuming groundwater (VB BH08)
  - Risk associated with dermal contact while showering is acceptable
  - Groundwater is not fit for drinking water and an alternative drinking water source should be identified. Alternatively a small treatment system can be installed in the home

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TOXICITY ASSESSMENT

Quantifying the impact to receptors

- To evaluate the potential risks for grazing cattle, the estimated dose is divided by a toxicity reference value (TRV), the ratio of which is the hazard quotient (HQ).
- The availability of a peer-reviewed recommended TRV for each COPC identified in the previous section was evaluated. COPCs with available TRVs were retained for quantitative evaluation in the risk characterization
- COPCs without TRVs were qualitatively evaluated in the Uncertainty Evaluation
- Note: TRV is intended to be aligned with the desired level of protection in the risk assessment and is typically based on either a no-observed adverse effect level (NOAEL) or lowest observed adverse effect level (LOAEL).
- **In this study NOAEL limits were used for risk characterization. It is thus a very conservative approach.**

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TOXICITY ASSESSMENT

Quantifying the impact to receptors

- Daily ingested does:
  - $Dose\left(\frac{mg}{kg/day}\right) = [EPC_{soil}(\frac{mg}{kg}) * 0.46\ \frac{kg}{day}] + [(EPC_{grass}(\frac{mg}{kg}) + 9\ \frac{kg}{day}]$
- The HQ is calculated from these values by the following equation
  - $HQ = \frac{Dose\ (\frac{mg}{kg/day})}{TRV = (\frac{mg}{kg/day})}$
- A HQ greater than one (1) does not mean that effects are likely to occur. Rather, it is simply an indication that the estimated dose is higher than the "safe" dose and therefore, the potential for risk cannot be ruled out without further assessment.
  - HQ > 1 Potential ecological risk
  - HQ < 1 No potential risk

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TOXICITY ASSESSMENT

Quantifying the impact to receptors

- All of the HQs were well below 1 with a maximum of 0.12 for potential exposures to chromium. **Even summing** the HQs for all COPCs results in a total HQ of less than 0.5, **which indicates that adverse effects are unlikely to occur in cattle grazing at the former mine site.**

COPC	EPC_{soil}	Soil Ingestion Rate	EPC_{grass}	Grass Ingestion Rate	Mass Ingested Per Day	Body Weight	Daily Ingested Dose	TRV	HQ
	mg/kg DW	kg/day	mg/kg DW	kg/day	mg/day	kg	mg/kg-day	mg/kg-day	
Antimony	1.4	0.46	0.014	9	0.78	450	0.0	0.059	0.029
Arsenic	5.1	0.46	0.15	9	3.7	450	0.0	1.04	0.008
Barium	249	0.46	47	9	538	450	1.2	51.8	0.023
Boron	0.038	0.46	6.1	9	55	450	0.1	28	0.004
Chromium	110	0.46	9.0	9	131	450	0.3	2.4	0.121
Cobalt	17	0.46	1.0	9	17	450	0.0	7.33	0.005
Copper	31	0.46	5.2	9	61	450	0.1	5.6	0.024
Manganese	682	0.46	194	9	2055	450	4.6	51.5	0.089
Nickel	35	0.46	3.6	9	48	450	0.1	1.7	0.063
Selenium	1.1	0.46	0.078	9	1.2	450	0.0	0.143	0.019
Vanadium	82	0.46	1.2	9	48	450	0.1	4.16	0.026
Zinc	34	0.46	23	9	224	450	0.5	75.4	0.007

Metals such as *Bismuth, Cerium, Cesium, Gold, Hafnium, Neodymium, Tellurium, Tin, Platinum* do not have TRV values. A qualitative assessment was performed which indicated no risk is anticipated.

Thank You