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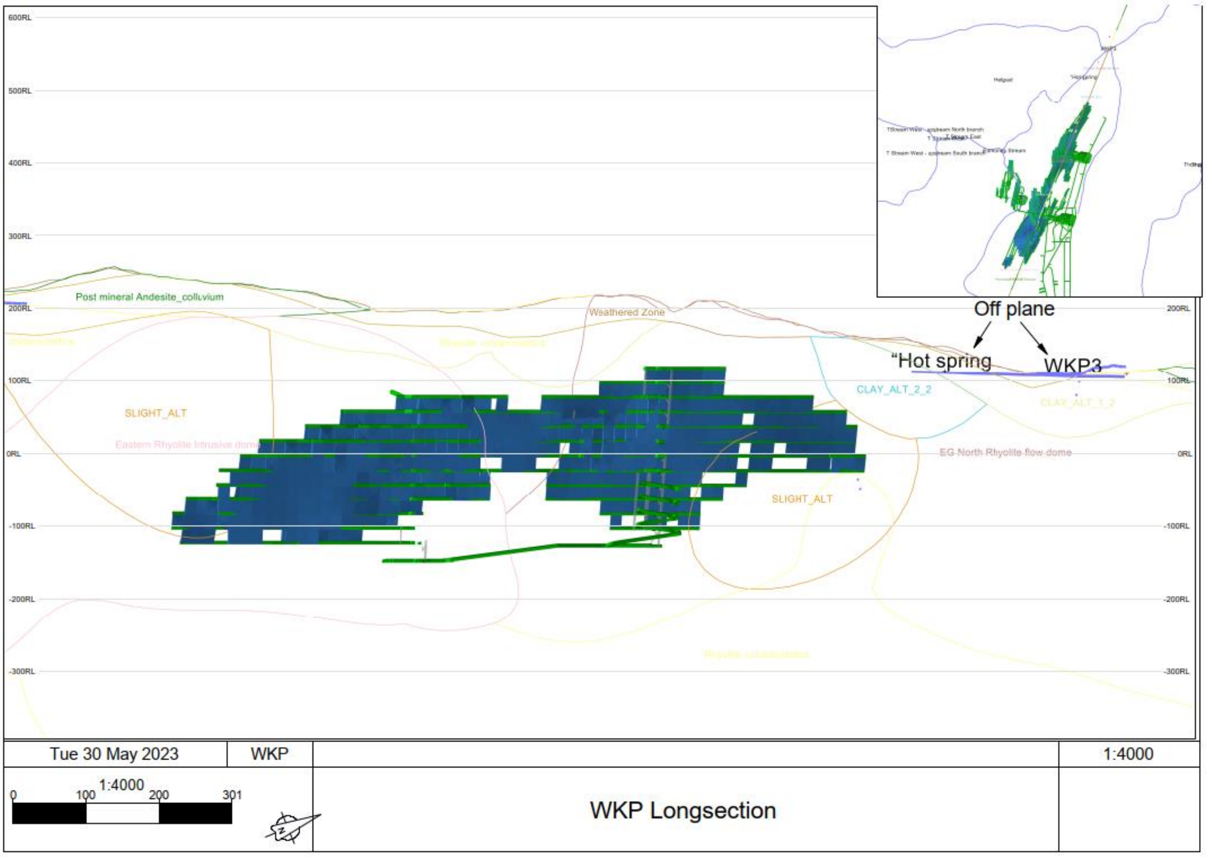
Dear Euan

WKP Post-Closure Geochemistry Modelling

1.0 Introduction

OceanaGold Waihi Operation requested AECOM New Zealand to complete water quality modelling post Wharekirauponga Underground Mine (WUG) mine closure to predict the concentrations over time at the warm spring north-west of the pit (refer to the long-section in **Figure 1**).

Figure 1 WKP Long-Section



2.0 Methodology

2.1 Conceptual Geochemical Model

AECOM reviewed available borehole logs, geological models, groundwater and surface water chemistry data and the groundwater flow model developed by FloSolution. A conceptual geochemical model (CGM) was developed with the following two paths:

1. Warm Spring CGM: between the WUG and the warm spring
2. Deep groundwater flow path CGM: between the WKP mine pit and the deep groundwater within the vein system at the downgradient boundary of FloSolution's groundwater model, assuming ultimate discharge to surface water in the Lower Wharekirauponga Stream.

2.2 Modelling Steps – Warm Spring

The warm spring CGM was developed using the following assumptions:

- Post closure, the backfilled mine will flood with groundwater from the shallow and deep systems.
- Backfill placed within the mine will be comprised of rock stockpiled within the Willows farm, which is lime amended to maintain a neutral pH, and rock used as stope backfill directly from the underground mine.
- Once flooded, groundwater from within the backfilled mine moves to the north within the vein system (deep groundwater).
- While no connection to the warm spring is apparent from FloSolution's groundwater model, the warm spring CGM assumed lateral movement within the country rock to the warm spring (point of discharge). This assumption is conservative as it is possible that other mixing is happening or that the vein system is not the source of the warm spring.

To determine water quality of the warm spring, AECOM used the geochemical modelling software PHREEQC Interactive version 3.7.3. The warm spring CGM was used to determine the number of modelling steps which are summarised below and presented in **Table 1** and **Figure 2**.

- The porewater with the mine backfill is determined by mixing the column leachate samples in equal proportions. These samples are then equilibrated with oversaturated phases and calcite to reflect lime amendment.
- Groundwater moves from the WKP mine domain along the vein approximately 100 m initially. The system is unoxidized (no evidence of oxidation in borehole logs or photos) and will equilibrate with sulphide minerals. These minerals are slow to form (equilibrate), however groundwater model travel times suggest adequate timeframes for these sulphide phases to form. The limited groundwater chemistry data obtained from wells screened within the vein is not sufficient to reliably derive actual redox condition. The currently available data used in the modelling indicates reducing conditions are not sufficiently reducing to form sulphides. No trace element removal as sulphides is predicted by the current model.
- Groundwater from the vein then moves laterally through country rock about 100m to the warm spring. This is not shown to be the case in FloSolution's groundwater model but is assumed as a conservative measure for the purposes of this CGM. Weathering and associated iron oxides extend to about 100m below ground surface based on the borehole logs. Adsorption onto iron oxides (HFo modelling) with this modelling step was assumed to provide significant absorption and trace element removal.
- The warm spring CGM assumed limited lateral dispersion between the source and the warm spring.

Table 1 Modelling Steps – Warm Spring

Step	Conceptual Model Stepic	PHrREEQC Model Step	Purpose
1.	Porewater in WKP backfill.	Mix column leachate samples.	To determine porewater within flooded backfill.
		Equilibrate Porewater.	To allow for precipitation of oversaturated species and lime amendment of waste and surface storage.
		Adsorption on to iron hydroxides.	Allow for trace element adsorption on to oxidation products within backfill.
2.		Mix porewater with deep groundwater.	Initial saturation of waste will be with deep groundwater.
3.		Mix shallow groundwater with other waters.	This represents the porewater discharging from the underground mine via the vein system.
4a	Groundwater moves from the WKP mine domain along the vein.	Equilibrate water to deep groundwater redox.	Determine whether trace elements are removed as sulphides.
		Adsorption modelling.	Lateral movement via country rock will involve trace element adsorption onto oxidised country rock.
		Increase redox conditions to match spring discharge.	Inverse modelling used to define redox (pe) to be achieved in the spring discharge. Iteratively modelled this step to calibrate to this pe in the spring discharge.
5a	Groundwater moves laterally about 100m to the warm spring through country rock.	Increase redox conditions to match spring discharge.	Inverse modelling used to define pe to be achieved in the spring discharge. Iteratively modelled this step to calibrate to this pe in the spring discharge.
		Adsorption on to iron hydroxides.	Allow for trace element adsorption in spring discharge zone.
		Equilibrate water.	Allow for removal of oversaturated species in spring discharge zone.

2.3 Modelling Steps – Deep Groundwater Flow Path

To determine the water quality of the deep groundwater flow path, AECOM used the geochemical modelling software PHREEQC Interactive version 3.7.3. The deep groundwater flow path CGM was used to determine the number of modelling steps which are summarised below and presented in **Table 2** and **Figure 2**:

The deep groundwater flow path CGM was developed using the following assumptions:

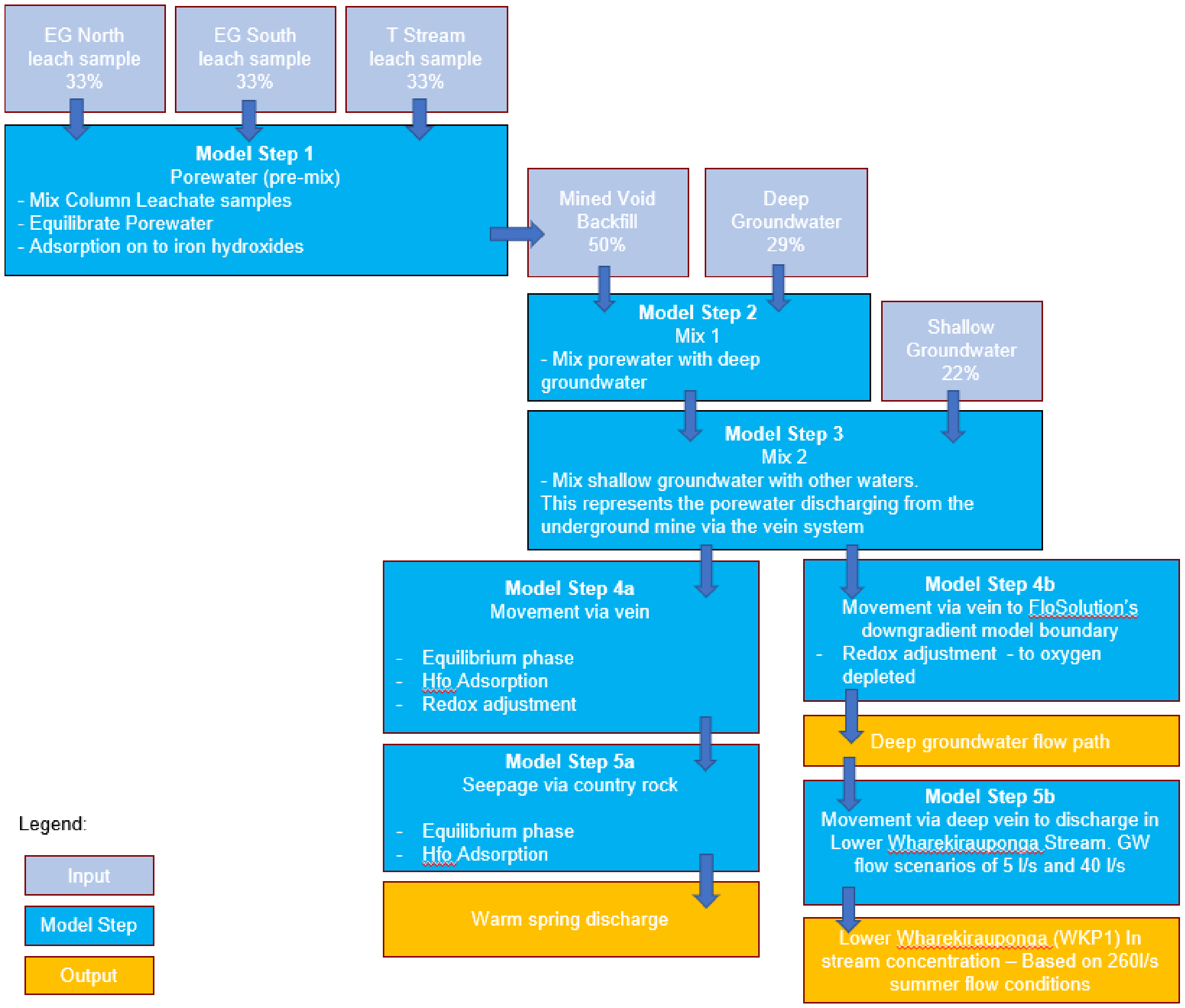
- Post closure, the backfilled mine will flood with groundwater from the shallow and deep systems.
- Backfill placed within the mine will be comprised of rock stockpiled within the Willows farm, which is lime amended to maintain neutral pH, and rock used as stope backfill directly from the underground mine.
- Once flooded, groundwater from within the backfilled mine moves to the north within the vein system (deep groundwater) and ultimately discharges to surface water within the Wharekirauponga Stream.

- The groundwater discharge to surface waters is fully mixed with surface water. No allowance is made for further attenuation of trace elements along the groundwater flow path.
- Surface water is oxygenated and at equilibrium with atmospheric oxygen as suggested by WKP1 water quality data. Flow scenarios of 5 L/s and 40 L/s are based on groundwater discharge assessment data provided by Williamson Water Limited (ref) with a low flow of 260 L/s at WKP1.

Table 2 Modelling Steps – Deep groundwater flow path

Step	Conceptual Model Stepic	PHREEQC Model Step	Purpose
1.	Porewater in WKP backfill.	Mix column leachate samples.	To determine porewater within the flooded backfill.
		Equilibrate porewater.	To allow for precipitation of oversaturated species and lime amendment of waste.
		Adsorption on to iron hydroxides.	Allow for trace element adsorption on to oxidation products within the backfill.
2.		Mix porewater with deep groundwater.	Initial saturation of waste will be with deep groundwater.
3.		Mix shallow groundwater with other waters.	This represents the porewater discharging from the underground mine via the vein system.
4b	Groundwater moves from the WKP mine domain along the vein.	Adjust redox in the vein to oxygen depleted.	Determine deep groundwater chemistry at the downgradient boundary of the FloSolution groundwater model.
5b	Groundwater moves through the deep vein system and discharges to the Lower Wharekirauponga Stream.	Adjust redox to surface water at equilibrium with atmospheric oxygen.	Two flow scenarios assessed; discharge at 5 L/s and 40 L/s to surface water.
		Adsorption on to iron hydroxides.	Allow for trace element adsorption on to oxidation products within shallow groundwater.

Figure 2 Conceptual Geochemical Model – WKP Closure



2.4 Inverse Modelling

The warm spring chemistry data used for the inverse modelling is presented in **Table 3**.This solution was iteratively modelled using the PHREEQC model to determine the degree of equilibrium present with respect to atmospheric oxygen, and thereby the redox (pe) required to achieve the proportion of iron present in solution. The pe determined from multiple iterations was then used as the target pe for modelling step 5 (refer to **Table 1** for modelling steps).

Table 3 Warm Spring Data

Parameter (mg/L)	Minimum	Maximum	Mean	n
pH	6.5	7.2	6.78	16
Alkalinity	41	46	44.44	16
Bicarbonate	49	56	53.94	8
EC (mS/m)	15.6	16.7	16.15	16
Hardness	39	43	40.25	16
NO_3-N	0.002	0.1	0.008	8
NO_2-N	0.002	0.1	0.008	8
SO_4	13	19	15.38	16
Al - Dissolved	0.003	0.03	0.01	16
As - Dissolved	0.0184	0.03	0.025	8
B - Dissolved	0.01	0.013	0.011	8
Cd - Dissolved	0.00005	0.00005	0.00005	8
Ca - Dissolved	13.3	15	13.94	16
Cr - Dissolved	0.0005	0.0005	0.0005	16
Co - Dissolved	0.0002	0.0002	0.0002	16
Cu - Dissolved	0.0005	0.011	0.002	8
K - Dissolved	6.1	6.6	6.44	7
Hg - Acid Soluble	0.00008	0.00008	0.00008	15
Hg - Dissolved	0.00008	0.00008	0.00008	8
Fe - Dissolved	0.02	1.25	0.77	16
Li - Dissolved	0.033	0.038	0.03	16
Mg - Dissolved	1.27	1.44	1.34	7
Mn - Dissolved	0.17	0.184	0.18	16
Mo - Dissolved	0.0002	0.0002	0.0002	8
Na - Dissolved	11.2	12.6	11.82	16
Ni - Dissolved	0.0005	0.0005	0.0005	16
Pb - Dissolved	0.0001	0.00018	0.0001	8
Sb - Dissolved	0.0002	0.0006	0.0004	8
Sn - Dissolved	0.0005	0.0005	0.0005	16
V - Dissolved	0.001	0.001	0.001	7
Zn - Dissolved	0.001	0.0049	0.002	7

2.5 Model Input Solutions

To enable modelling, the ion balance of all five input solutions were assessed by entering them in the PHREEQC model. In all cases, sodium and chloride concentrations were adjusted to balance solutions as these have the least influence on oversaturation of modelled species.

It is noted that the proportions of trace element leached as a percentage of total concentration for the parameter arsenic is unusually high (ranging from 3 to 29%). This suggests that arsenic is present as a discrete mineral, rather than present as inclusions within other sulphide minerals. Further data on arsenic distribution within backfill should be considered to assess how representative these leaching columns are for the flooded mine backfill.

The samples used in column leaching are from the immediate vicinity of the vein systems and are therefore considered conservative regarding trace element leaching expected from backfill, which will be generated from development works largely in the footwall host rock.

The water quality for the input solutions is presented in **Table 4**.

Table 4 Input solutions

	Pre-Mix			Mix 1	Mix 2
Parameter (mg/L)	**EG North**	**EG South**	**T Stream**	**Deep Groundwater**	**Shallow Groundwater**
pH	2.550	2.896	4.250	6.700	6.538
Alkalinity	1.096	1.583	2.441	19.600	68.735
Hardness - Total	-	-	-	-	73.338
EC (mS/m)	458.950	635.283	624.670	7.650	27.050
Chloride	-	-	-	9.000	11.071
SO_4	2216.500	5166.783	6427.652	4.150	50.367
Ag - Dissolved	0.00057	0.001091	0.001094	<0.0001	-
Al - Dissolved	125.309	197.776	194.446	0.023	0.183
As - Dissolved	18.613	30.593	18.956	0.00515	0.016
Ba - Dissolved	0.007	0.021	0.015	0.0255	-
Bo - Dissolved	-	-	-	<0.018	0.0383
Cd - Dissolved	64.036	263.966	262.524	<0.00005	0.000058
Ca - Dissolved	0.010	0.033	20.842	4.200	23.987
Co - Dissolved	0.521	1.681	1.313	0.0011	0.020
Cr - Dissolved	0.309	0.239	0.192	<0.0005	0.00095
Cu - Dissolved	2.274	3.543	6.837	0.00225	0.00465
K - Dissolved	22.859	82.216	28.478	1.505	6.579
Hg - Dissolved	0.000102	0.000115	0.000142	<0.00008	<0.00008
Fe - Dissolved	548.728	716.045	957.505	0.575	5.701
Mg - Dissolved	21.497	125.347	252.931	1.225	3.286
Mn - Dissolved	5.663	41.222	8.263	0.102	0.469
Mo - Dissolved	0.00827	0.00659	0.01888	0.01565	0.00301
Na - Dissolved	15.939	30.707	31.131	8.000	20.319
Ni - Dissolved	0.198	0.686	1.057	0.00505	0.012

	Pre-Mix			Mix 1	Mix 2
Parameter (mg/L)	EG North	EG South	T Stream	Deep Groundwater	Shallow Groundwater
Pb - Dissolved	0.000686	0.003514	0.003217	0.00039	0.00039
Sb - Dissolved	0.002724	0.004988	0.0033	0.0052	0.001
Se - Dissolved	0.014	0.026	0.014	<0.001	-
Sr - Dissolved	0.313	0.809	0.313	0.019	-
U - Dissolved	0.047	0.079	0.047	<0.00002	-
V - Dissolved	0.062	0.160	0.454	<0.001	0.00108
Zn - Dissolved	9.262	22.823	4.661	0.172	0.306

EG – East Graben

3.0 Results

3.1 Equilibrium Phases

Equilibrium phases are used for the following conditions:

- In flooded backfill to assess the over saturation of oxidation products.
- In deep groundwater to assess the removal of sulphides. The pe from current modelling suggests conditions within the vein system will approach conditions that are sufficiently reducing to remove sulphides. More complete deep groundwater quality data is required to reliably assess redox conditions post closure.
- Equilibrating with atmospheric oxygen to match warm spring redox conditions.
- In spring discharge to allow for precipitation of species in surface water.

Solution chemistry at each step is reviewed to determine whether the predicted water is likely to reach geochemical equilibrium.

This is particularly relevant for iron species as multiple iron mineral phases will potentially be over-saturated to varying degrees, however some mineral phases will more rapidly reach equilibrium than others.

Similarly, where sulphide species are assessed, the groundwater modelling indicates travel times are sufficiently slow for these equilibrium conditions to be reached.

3.2 Adsorption

Adsorption of trace elements onto iron hydroxides (HFo) is a significant control on trace element levels in modelled solutions. Sensitivity analysis has been completed for selected model runs around the amount of HFo sites made available for adsorption. In all cases where HFo is modelled, the sites are limited to the amount of the iron mineral phase oversaturated as defined in Section 3.1 with the ratio of strong to weak sites based on Dzombak and Morel.

3.3 Model Output

3.3.1 Warm Spring

The predicted warm spring water quality results generated based on PHREEQC modelling are presented in **Table 5**. The modelled water quality results compared to actual warm spring data are presented in **Table 6**.

Table 5 Modelled Warm Spring Water Quality Predictions

Parameter (mg/L)	Estimated Groundwater Quality in Deep Vein System	Country Rock Shallow Groundwater Quality at Warm Spring Discharge	Predicted Warm Spring Discharge
pH	7.25	6.84	7.34
pe	(2.89)	3.13	0.10
C	8.8	7.4	7.4
Al	0.001	0.001	0.001
As	<0.001	<0.001	<0.001
Ba	0.007	0.007	0.007
Ca	244	245	243
Cd	0.229	0.229	0.018
Cl	12	12	12
Co	0.129	0.129	0.033
Cr	<0.001	<0.001	<0.001
Cu	0.45	0.45	0.007
Fe	5.35	<0.01	<0.01
Hg	<0.0001	<0.0001	<0.0001
K	26	26	26
Mg	64	64	60
Mn	9.56	9.56	9.56
Mo	0.003	0.003	0.001
Na	282	282	282
Ni	0.009	0.009	0.001
Pb	<0.0009	<0.0009	<0.0009
S	1,442	1,442	1,418
Sb	0.002	0.002	0.002
Se	0.007	0.007	0.000
Sr	0.4	0.4	0.4
U	0.034	0.034	0.034
V	0.114	0.114	0.112
Zn	0.027	0.027	<0.001
Hardness (mg/L CaCO3)	876	876	857

Table 6 Modelled Water Quality Compared to Actual Warm Spring Data

Parameter (mg/L)	Mean	Range	Modelled Warm Spring Discharge
pH	6.78	6.5 – 7.2	7.34
Al	0.01	0.003 – 0.03	*<0.03*
As	0.025	0.018 – 0.03	*<0.03*
Ca	13.94	13.3 – 15	243
Cd	0.00005	-	0.018
Co	0.0002	-	0.033
Cr	0.0005	-	<0.001
Cu	0.002	0.0005 – 0.011	*<0.011*
Fe	0.77	0.02 – 1.25	*<1.25*
Hg	0.00008	-	<0.0001
K	6.44	6.1 – 6.6	26
Mg	1.34	1.27 – 1.44	60
Mn	0.18	0.17 – 0.18	9.56
Mo	0.0002	-	0.001
Ni	0.0005	-	0.001
Pb	0.0001	-	<0.0009
S	19	13 – 19	1,418
Sb	0.0004	0.0002 – 0.0006	0.002
V	0.001	-	0.112
Zn	0.002	0.001 – 0.0049	*<0.0049*
Hardness (mg/L CaCO3)	40	39 – 43	857

Note: *Italics* denotes no measurable change to background

3.3.2 Deep Groundwater Flow Path

The predicted quality of the deep groundwater within the vein system at the downgradient boundary of FloSolution's groundwater model generated, based on PHREEQC modelling, is presented in **Table 7**.

The results presented in **Table 7** represent water quality in the vein systems and are therefore comparable to the first column in **Table 5**. Similar attenuation for the warm spring would be expected for any scenario that could result in discharge to surface waters.

Table 7 Modelled Deep Groundwater Flow Path Quality Predictions

Parameter (mg/L)	Deep Groundwater Flow Path at Downgradient Boundary of FloSolution's Model
pH	7.13
pe	(2.60)
C	8.802
Al	0.001
As	<0.001
Ba	0.007
Ca	244
Cd	0.23
Cl	12
Co	0.129
Cr	<0.001
Cu	0.449
Fe	4.707
Hg	<0.0001
K	26
Mg	64
Mn	9.56
Mo	0.003
Na	282
Ni	0.009
Pb	<0.0009
S	1,441
Sb	0.002
Se	0.007
Sr	0.4
U	0.034
V	0.114
Zn	0.015
Hardness (mg/L CaCO3)	876

Table 8 Deep Groundwater Post Discharge to Wharekirauponga Stream

Parameter (mg/L)	Discharge scenario with point source discharge of 5 l/s @ confluence	Discharge scenario with diffuse discharge of 40 l/s @ WKP1	WKP1 Actual Data (range)
pH	7.42	7.45	7.0 – 7.2
Al	*0.03 - 0.128*	*0.03 - 0.128*	0.03 - 0.128
As	*0.01 – 0.012*	*0.01 – 0.012*	0.01 – 0.012
Ca	6.2 – 6.7	6.2 – 6.7	1.8 – 2.5
Cd	*<0.00005*	*<0.00005*	<0.00005
Cl	*7 - 10*	*7 - 10*	7 - 10
Co	*<0.0002*	*<0.0002*	<0.0002
Cr	*<0.0007*	*<0.0007*	<0.0007
Cu	*<0.0005*	*<0.0005*	<0.0005
Fe	*0.02 – 0.06*	*0.02 – 0.06*	0.02 – 0.06
Hg	*<0.00008*	*<0.00008*	<0.00008
K	1.8	1.8	1.26 – 1.68
Mg	2.5 – 2.9	2.5 – 2.9	1.53 – 1.91
Mn	0.18	0.18	0.0007 – 0.0095
Mo	*<0.0002*	*<0.0002*	<0.0002
Na	12.3	42	8.7 – 11.3
Ni	*<0.0005*	*<0.0005*	<0.0005
Pb	*<0.0001*	*<0.0001*	<0.0001
S	28	181	<5
Sb	*<0.0002*	*<0.0002*	<0.0002
V	*<0.0025*	*<0.0025*	<0.0025
Zn	*<0.0054*	*<0.0054*	<0.0054

Note: *Italics* denotes no measurable change to background

4.0 Sensitivity Analysis

The sensitivity of the PHREEQC model runs has been assessed for a number of input variables. In terms of the modelled geochemical process the degree of lime amendment and thereby iron precipitation in the porewater from mined backfill has the most influence on the mobilisation of trace elements of environmental concern.

While model results for trace elements are influenced by HFo adsorption there is an abundance of iron precipitate within the mined backfill. As such model results are not limited or thereby sensitive to this parameter.

To assess the sensitivity of the model predictions to iron precipitation, the amount of oxygen available is varied, as shown in **Table 8**.

The process of addition of limestone to maintain neutral pH of the backfill in the stockpiles will result in exposure atmospheric oxygen levels well in excess of the sensitivity scenario assessed in **Table 8**. The sensitivity analysis therefore demonstrates that provided neutral pH is maintained with lime amendment, the storage of stockpiled waste will have sufficient oxygen exposure to ensure iron precipitation and thereby trace element removal.

Table 8 Sensitivity Scenarios for Iron Precipitation

pH	pe	pO2	Mole 02	Iron Concentration
7.2	-0.68	0.0032	-1.94	27.68
7.18	-0.68	0.0033	-1.34	10.693
7.12	-0.68	0.0034	-0.56	3.867
7.03	-0.68	0.0035	13.87	0
7.03	-0.68	0.004	14.36	0
7.03	-0.68	0.005	14.42	0

5.0 Conclusions

The following conclusions are presented based on the outcome of the water quality modelling:

- Lime amendment is necessary to prevent high concentrations of trace elements developing in the backfilled mine post flooding.
- Based on the current model predictions and the conservative assumptions that they are based on, trace elements are unlikely to be measurably different in the warm spring discharge.
- Elevated sulphate concentrations predicted for warm spring discharge suggest an increased potential for precipitate deposition in the discharge/mixing zone of the warm spring. These effects would be localised in the oxidising surface water environment immediately downstream of the spring.
- Based on the current model predictions and the conservative assumptions that they are based on, trace elements are unlikely to be measurably different in surface water at WKP1.

All of these findings are highly dependent on the assumptions made in the model setup outlined in Section 2. Recommendations outlined in Section 6 around monitoring should therefore be implemented to address these significant uncertainties.

6.0 Recommendations

Several modelling inputs provided are not sufficient to support a robust geochemical model.

The following are recommended to improve the reliability of the current modelling predictions:

- The three columns' leachates results used for this geochemical model are not representative of mine backfill material. The columns are largely of orebody and hanging wall units, whereas the vast majority of backfill will be from within the footwall which are different lithologies. Further column tests should be completed with samples representative of the bulk backfill material and the model rerun. This will help confirm the arsenic leachate results. Once a lime amended leachate is available rerun model predictions with this input.
- Obtain a more comprehensive and reliable deep groundwater chemistry data set.
- Continue to monitor the warm spring to build a more detailed data set that fully assesses seasonal variability.
- Obtain temperature measurements as close as possible to the spring discharge point, as it is a good indicator of deep groundwater.

Yours faithfully

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