AMULSAR GOLD PROJECT

Hydrogeological Risk Assessment Proposed Heap Leach Facility

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REPORT

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1.0 INTRODUCTION

Golder Associates (UK) Ltd (Golder) has been commissioned by Lydian International Ltd (Lydian) to undertake the surface water and groundwater components of an Environmental and Social Impact Assessment (ESIA) for the Amulsar Gold Project in central Armenia. The Amulsar Project is a proposed open pit gold mine development, with a heap leach facility (HLF) and processing plant. The operational life of the mine is proposed to be nine years.

This report presents an assessment of the risk to groundwater receptors as a result of the construction, operation, reclamation and closure of the proposed HLF.

The risk assessment is supported by a probabilistic solute transport model using the solute transport module of the GoldSim^{TM} dynamic modelling environment. The objective of the modelling is to quantify future impacts and risks to groundwater and surface water receptors as a result of constituent migration from the HLF.

1.1 Heap Leach Facility Design

The location of the proposed HLF is shown in the project description incorporated within the ESIA. The proposed HLF layout and its location relative to potential groundwater receptors are shown in Drawing 1. The HLF comprises a geosynthetically lined pad approximately 110 ha (approximately 2 km long and between 300 m and 1,000 m wide oriented approximately northeast/southwest) divided into three phases, developing upstream to the northeast.

A geosynthetically lined pregnant leach solution (PLS) storage pond is located at the toe of the facility, and two lined stormwater ponds are located downslope of the PLS pond. The first of these ponds, Storm Pond 1, is likely to receive overflow from the PLS pond during Phase 2 and 3 of operation based on the current facility water balance. Upgrading of the liner of this pond will be completed at the end of Phase 1 to address the use of this pond for PLS in the later phases of operation. This pond is therefore treated as a pregnant solution pond in Phase 2 and 3 of operation in this assessment. The second pond, Storm Pond 2, will not receive PLS unless an extreme event occurs and are not considered in this evaluation.

The Heap Leach Pad (HLP; GRE, 2014a), has a nominal capacity of 104 Mt and a maximum ore height of 120 m above the pad. The leach solution will percolate through the ore to the pad liner where it will be collected in a network of perforated drainpipes installed within a 0.6 m thick granular cover drain fill layer above the liner. Leach solution will be collected in the PLS pond, directed to the processing plant for recovery of gold and silver, and barren solution will be recycled for subsequent leaching cycles. Engineered containment of the pad and collection ponds is described further below.

The process pond are sized to contain eight hours of normal operational solution flow and 24 hours of solution draindown flow from the ore heap for the final pad extent in case of operational shutdown due to pump failure or power loss.

A groundwater and surface water monitoring plan will be implemented during operations and closure. The purpose of the monitoring will be to evaluate the operational performance of the heap leach system and identify any adverse trends in the facility water balance or changes in downgradient groundwater or surface water quality (potential leakage) that would require the implementation of modifications to the leaching system or additional mitigation measures.

The mine closure plan is not yet complete, but preliminary closure concepts for the HLF include:

■ Placement of a vegetated soil cover system, including a low permeability clay cover component, over the over-heap to minimise long-term infiltration;

■ Reduction of leach pad effluent volumes within the heap through draindown prior to capping and reclamation;

■ Detoxification to reduce cyanide concentration in the heap through rinsing with hydrogen peroxide prior to cover placement;

■ Surface water management and erosion control features designed to minimise erosion and to promote run-off from the cover system, thereby further minimising long-term infiltration; and

■ Treatment of post-closure seepages from the reclaimed facility for a minimum period of five years via a passive water treatment system located downstream of the facility until the fluids meet acceptable end-of-pipe discharge criteria.

The nominal closure period for the facility is five years following the ten year operational period.

It has been assumed that the PLS pond will cease to be present following closure of the mine: either the passive treatment system will be constructed in the vicinity of the pond, or the pond will be breached to allow free discharge at the end of the managed closure period.

Modelling work presented in this assessment and in the remainder of this report has been based on the feasibility level design for the HLF issued in May 2014 (GRE, 2014a). Assumptions have been made regarding aspects of the design and closure, based on our understanding of the design. Primary features of relevance to the groundwater risk assessment, such as the footprint of the facility, operational maximum head and liner design are not expected to change during final design.

1.1.1   HLF Development Phasing

Phasing is described as follows in GRE (2014a):

"The Phase 1 pad will accommodate the Stage 1 heap of approximately 22.7 Mt, which will constitute the first seven heap lifts to a nominal top surface elevation of 1688 m, and will be stacked during the initial 2.2 years of operations.

The Phase 2 pad expands the pad uphill to the east, providing for the stacking of the Stage 2 heap above the Stage 1 heap and Phase 2 pad. The Stage 2 heap will consist of eight additional horizontal lifts above the Stage 1 heap level and will have a nominal top surface elevation of 1752 m. The Stage 2 heap will be approximately an additional 35.8 Mt, which is projected to be stacked till near the end of Year 6 of operations.

The Phase 3 pad also expands the pad uphill to the east, providing for the stacking of the Stage 3 heap above the Stages 1-2 heap and Phase 3 pad in 13 additional lifts to a nominal top surface elevation of 1856 m. Stacking of the Stage 3 heap will continue till just before the middle of Year 11 of operations to provide an approximate total ore heap capacity on the Phases 1-3 pad of 104 Mt (excluding haulage and conveyor bench setback considerations)."

Cover and reclamation of all phases will occur at the end of the rinsing and detoxification period, approximately 18 months following the end of leach operations. Following a period of management using a passive treatment system, discharge of fluids to the Arpa River in accordance with appropriate discharge quality criteria will occur. The phasing and dimensions of the HLF based on feasibility level design drawings for the HLF (GRE, 2014a) is summarised in Table 2.

Table 1: HLF Phasing Summary and Modelled Areas

	Operational Period	Area Overlying Shallow Groundwater(m^2)	Area Overlying Deeper Groundwater(m^2)
Phase 1	27 months	323,550	156,960
Phase 2	43 months	134,920	142,030
Phase 3	55 months	8,990	337,630

1.2   Site Setting

The proposed HLF is situated approximately 1,500 m east of the Arpa River on the lower slopes of the Arpa River catchment west of Amulsar, approximately 1.5 km south of the town of Gndevaz. The HLF Site is valley-shaped and undulating in some areas, with the valley generally dipping to the southwest. The site

grades range from 6% in the valley bottom near the downgradient toe of the planned leach pad to 55% on the upper valley sides. Site grading fill will be placed in the valley bottom in the pad downgradient toe area to establish a toe bench with a 1% pad downhill grade to facilitate ore heap stability. The ground elevation is between 1,600 masl at the southwestern boundary and 1,800 masl at the northeastern boundary. The site is approximately 180 m in elevation above the Arpa River at its southwestern limit and 350 m above the Arpa River at its northeastern limit.

A stream valley containing an unnamed ephemeral water course runs southwest through the centre of the site, the stream channel extends 1.6 km from the southwestern boundary of the Site to discharge into the Arpa River. Surface water monitoring (ESIA Chapter 4.9) indicates that this stream does not flow in winter, and it is likely that it is also dry in late summer/early autumn. Monitoring and site observations indicate that continuous flow occurs at Monitoring Location G1, a tributary to the central drainage through the site to the north of the main channel and the site footprint. However, this water infiltrates to ground before reaching the southwestern extent of the HLF footprint.

2.0   HEAP LEACH CONCEPTUAL MODEL

The conceptual model of solute migration in groundwater from the HLF is shown schematically in Drawing 1.

The hydrogeology of the HLF site and hydrogeological conceptual model for groundwater flow is described in detail in the ESIA Chapter 4.8, Groundwater Baseline.

The purpose of the conceptual model description is to describe the groundwater pathways linking the source (substances within the HLF) to potential groundwater receptors (groundwater abstractions or groundwater-fed surface water bodies located hydraulically downgradient of the HLF), and the mechanisms of solute migration and attenuation in each pathway.

2.1   Source

2.1.1   Engineered Containment

The following engineered containment is proposed for the HLF:

■   The HLP will be lined by a 1.5 mm to 2.0 mm low density polyethylene (LLDPE) flexible membrane liner (FML) beneath the pad underlain by minimum thickness of 0.3 m of compacted low permeability soils with a permeability of less than $1x10^{-8}$ m/s, or geosynthetic clay liner (GCL) in steeper areas;

■   The liner will be overlain by a 0.6 m thick drainage layer comprising free-draining, hard and durable granular material inlaid with a drainage pipe network. The pipe network is comprises a three tier drainage spacing with tertiary drains at intervals of 7 m; and

■   Solution storage ponds will be lined with a double liner system comprising a 2.0 mm LLDPE FML upper liner, an interstitial geocomposite drainage layer and a composite lower liner comprising 1.5 mm LLDPE lower liner underlain by 0.3 m of compacted low permeability soil with a permeability of less than $1x10^{8}$ m/s.

The interstitial drainage layer in the double lined solution storage pond(s) will drain to a sump, assumed to be located at one corner of the pond, and be removed via a pump. During Phase 1 of operation there will be a single pregnant solution pond and two stormwater ponds. During Phases 2 and 3, the first storm water pond (Storm Pond 1) may receive PLS, and is treated for design purposes and in this assessment as a PLS pond. The lining of this pond will be upgraded at the end of Phase 1 to reflect the storage of PLS in the later phases of operation.

Underdrains consisting of a network of drain trenches with pipes will be constructed at the locations of existing drainages and seeps within the leach pad footprint to drain groundwater/subsurface seepage to downgradient of the pad. Piped clean surface/groundwater flows will be carried from the point of seepage to

and allowed to discharge downstream of the HLF. The quality of the discharge from the underdrain will be monitored, and if quality is not suitable for discharge, will be pumped to the PLS pond.

The performance of the underdrains with respect to the capture of any leakage from the facility is not known with confidence. Observation indicates that under existing conditions, flow in the drainages upstream of the HLF site and discharge from the spring on the northwestern side of the site infiltrate to ground before reaching the downstream side of the facility, such that the main drainage is dry in the autumn and winter months. The impact assessment therefore assumes that all discharge from the basal liner will infiltrate to ground rather than discharging along the underdrains. Discharge from the underdrains will be monitored (flow and quality) during operations and underdrain discharge pumped back to the solution ponds if required, therefore any leakage which is intercepted by the underdrains will not be released to the environment.

The HLF modelling has considered a 0.3 m compacted clay liner under the entire HLP. GCLs are typically 10 mm thick with a hydraulic conductivity less than 1×10^{-11} m/s. The transmissivity (thickness multiplied by hydraulic conductivity) of a typical GCL is less than 1×10^{-13} m^2/s, whilst that of the 0.3 m compacted clay liner with a permeability of 1×10^{-8} m/s original proposed is 3×10^{-9} m^2/s. The leakage through a GCL will therefore be less than that through the 0.3 m compacted low permeability soil liner originally proposed under equivalent conditions. The modelling is therefore conservative.

2.1.2   Source Quality

The solute source associated with operation of the HLF includes:

■   Sodium cyanide solution applied to the heap as part of the gold extraction process; and

■   Substances, metals and major ions, present in the ore which are leached into the sodium cyanide solution as a result of the leaching process.

Leaching of ore produces PLS. PLS is assumed to be present throughout the HLP and the pregnant solution pond (PSP).

The engineering design of the HLF is to prevent leakage of PLS in the leaching process. PLS will be collected in the HLP drainage system overlying the basal liner and will be collected in the PSP and pumped to the treatment plant or recirculated to the heap.

Evidence from heap leach operations indicates that some PLS may leak into the underlying soils ultimately reaching groundwater. The quantity of leakage from the HLP and PSP is a function of the head of liquid on the liner of each component, the liner construction and the quantity of water infiltrating to or applied to the facility. Flexible plastic membrane liners will degrade with time as a result of oxidation and breakdown of the liner material, resulting in an increase in leakage with time under constant head conditions. This process is critically dependent of temperature and conditions surrounding the liner, but at ambient temperatures (15 to 30°C), is estimated to take hundreds of years (for example, Koerner *et al,* 2011 indicate a period of 238 years to onset of degradation at 20°C and a service life to 50% degradation of 446 years, US National Research Council (2007) quotes a service life of 565 years to 900 years at 20°C).

The HLP is designed to minimise head on the base, reducing leakage. Head within the heap will be controlled within the 0.6 m drainage blanket thickness. However, actual head on the base of the facility is likely to be considerably lower than this design maximum. Estimates of the maximum head on the base of the facility during operation, in open but inactive phases and following closure and reclamation have been made based on the drainage design and estimated infiltration rates, and are presented in Section 3.2.1.

The irrigation rate to the 287,400 m^2 active leaching area during operations will be 0.01 m^3/hr/m^2. Following active leaching, the phases will remain open until the facility is closed at the end of operation. Solution applied in the actively irrigated area will be captured by the drainage system local to the area of application. Water balance calculations (GRE, 2014c) indicate that infiltration to the open area will be an average of 485 mm/yr.

Following reclamation and closure, infiltration to the facility will be dependent on flow through the vegetated soil cover. The post-closure infiltration rate will be much lower than operational conditions (thousands of

times lower than the solution application rate, and tens of times lower than the infiltration to the open heap) resulting in a much lower head on the base of the facility. Unsaturated flow modelling of the infiltration through the post-closure cover is being undertaken GRE, but was not complete at the time of this assessment. Similar modelling for the proposed cover for the Barren Rock Storage Facility (GRE, 2014b) indicates that due to the high summer evaporation rates in the Amulsar Project area and the influence of soil moisture storage, infiltration rates following closure may be low, less than 1 mm/yr.

In order to address uncertainty in the modelled post-closure infiltration rate, the impact assessment has assumed an infiltration through the final cover of approximately 10 mm/yr. This is equivalent to the leakage through a 1 m clay soil cover with a permeability of 1×10^{-9} m/s from a 1 m thickness of saturated cover soils for a period of two months. The HLF facility has been modelled with a calculated 0.01 m head on the base during closure based on a 10 mm/yr infiltration rate, with the maximum head limited to the assumed post-closure infiltration rate of 10 mm/yr.

The engineered containment and calculation of leakage rates through the basal liners of the HLP and PSP are discussed further below.

2.1.2.1 Pregnant Leach Solution Quality

Chemical analysis of the PLS from leaching test work is not currently available. The design (GRE, 2014a) indicates that a leach solution containing 500 mg/l sodium cyanide concentration (equal to 265 mg/l of cyanide and 235 mg/l of sodium) will be applied to the heap. However, attenuation of weak acid dissociable (WAD) cyanide will occur due to reactions within the heap (volatilisation, complexation, precipitation). The mechanisms of this attenuation are complex and a function of the ore mineralogy, and therefore can only be reliably assessed through laboratory testing of the leach process or in heap operation. Analysis from pilot studies (Table 2) indicates that cyanide consumption will result in cyanide concentrations between 34 mg/L and 66 mg/L in the active heap.

The source term for other constituents of potential concern for this assessment is based on chemical analyses of metal concentrations in the barren leach solution supplied by Lydian (Lydian, 2014). This analysis is presented in comparison to Republic of Armenia MACs (maximum acceptable concentrations) (Category II for the Arpa Basin) in Table 2.

The source term considered in modelling has been based on the following assumptions:

■ The concentrations of metals in each of the barren solution analyses reported are equally likely to be representative of the operational barren solution quality (which is assumed, in turn, to be representative of the PLS), such that the source term should be represented as the range of the values, rather than their average; and

■ Concentrations of metals (excluding sodium) in the PLS may be higher (assumed up to two times) than the concentrations reported in the barren solution due to: the potential loss of some metals to the carbon residue (difference between concentrations in pregnant and barren solution), natural variation of the ore mineral composition (significant variation is observed in the two samples analysed), recirculation of the barren leach solution and progressive concentration of the leachate with respect to metals which are not removed by the gold recovery process.

2.1.2.2 Closure Water Quality

GRE indicates that the following processes occur following cessation of ore deposition on the heap:

■ For a period of six to ten months, "rinsing" of the heap occurs: this comprises continued irrigation of the heap with sodium cyanide solution and circulation of leach solutions to the processing plant, to recover any remaining precious metals from the ore. No source term attenuation is anticipated during this period. It is assumed that active evaporation to reduce solution volumes may be undertaken toward the end of this period;

■ Following the rinsing period, a detoxification process is undertaken where the heap is rinsed with hydrogen peroxide solution to destroy the cyanide in the heap and solution, this process will continue

for six months to one year until cyanide concentrations are reduced to permissible levels for discharge; and

■ Following rinsing and detoxification, the facility is covered and passive draindown of the leach solution occurs. Closure management continues for a further five years during which drainage from the heap is sent to a passive treatment system and is monitored prior to discharge.

Table 2 presents the chemical composition of the predicted final detoxified leach solution (Lydian, 2014). Concentrations of most metals are similar at the end of the detoxification period to those in the barren leach solution. Cyanide concentrations are lower, and nitrate concentrations are higher than during operations, likely as a result of cyanide degradation.

The final detoxified leach solution represents the source term concentration associated with the HLF at the end of closure. It is assumed that the concentration of all constituents of potential concern in the leach solution on the leach pad will decrease exponentially with time after the cessation of operation due to leaching into water percolating through the heap.

Transport of ammonium nitrate residue in the HLF ore is also likely to contribute ammonium and nitrate to the HLF leach solution. The mass load of ammonium and nitrate has been calculated in Golder (2014). It is assumed that ammonium will degrade rapidly to nitrate within the heap. The ammonium concentration has been estimated as 50 mg/L. This is the approximate concentration arising from dilution of the continuously added mass of ammonium nitrate into five days of solution volume at the operational application rate. The nitrate concentration has been estimated at 250 mg N/L as it will be generated as a result of both cyanide and ammonium oxidation. Should higher operation nitrate concentrations be measured, operational adaptive management mitigation measures may be required.

Table 2: Barren Solution and Detoxified Solution Analysis (Lydian, 2014)

Parameter	Units	Project Assessment Criteria*	Final Barren Solution		Final Detoxified Solution	
			Test 61781	Test 61790	Test 61781	Test 61790
Alkalinity, Total	mg/L as CaCO₃		490	330	360	170
Bicarbonate	mg/L as CaCO₃		83	<1	130	120
Carbonate	mg/L as CaCO₃		260	190	160	43
Hydroxide	mg/L as CaCO₃		<1.0	3.4	<1.0	<1.0
Aluminium	mg/L	0.144	1.1	6.6	0.38	2.4
Antimony	mg/L	0.00028	0.12	0.04	0.19	0.061
Arsenic	mg/L	0.02	0.63	0.15	0.70	0.18
Barium	mg/L	0.028	<0.010	0.016	<0.010	0.016
Beryllium	mg/L	0.000038	<0.0010	<0.0010	<0.0010	<0.0010
Bismuth	mg/L		<0.10	<0.10	<0.10	<0.10
Boron	mg/L	0.45	<0.10	<0.10	<0.10	<0.10
Cadmium	mg/L	0.001014	<0.0010	<0.0010	<0.0010	<0.0010
Calcium	mg/L	100	1.6	7.8	4.2	13
Chloride	mg/L	6.88	41	27	28	27
Chromium	mg/L	0.011	0.014	0.01	0.013	0.0055
Cobalt	mg/L	0.00036	0.026	0.021	0.016	0.014
Copper	mg/L	0.021	1.4	1.5	0.58	0.5
Cyanide (WAD)	mg/L	0.5	34	66	0.044	0.036
Cyanide (Total)	mg/L	1	42	67	0.66	0.61

Parameter	Units	Project Assessment Criteria*	Final Barren Solution		Final Detoxified Solution	
			Test 61781	Test 61790	Test 61781	Test 61790
Fluoride	mg/L		1.8	2.9	1.9	2.6
Gallium	mg/L		<0.10	<0.10	<0.10	<0.10
Iron	mg/L	0.072	0.24	0.91	0.2	0.12
Lead	mg/L	0.01014	0.0059	0.0019	<0.0025	<0.0050
Lithium	mg/L	0.003	<0.10	<0.10	<0.10	<0.10
Magnesium	mg/L	50	<0.50	<0.50	<0.50	<0.50
Manganese	mg/L	0.012	<0.0050	<0.0050	<0.0050	<0.0050
Mercury	mg/L		0.072	0.019	0.0043	0.028
Molybdenum	mg/L	0.82	1.0	0.3	0.74	0.23
Nickel	mg/L	0.01034	<0.010	<0.010	<0.010	<0.010
Nitrate + Nitrate Nitrogen**	mg/L	11.1	1.4	0.96	3.0	2.5
Total Kjeldahl Nitrogen	mg/L		76	80	20	29
Total Nitrogen	calculated		78	81	23	31
pH	pH units		9.99	9.74	9.91	9.23
Phosphorus	mg/L	0.2	<0.50	<0.50	<0.50	<0.50
Potassium	mg/L	3.12	14	45	15	48
Scandium	mg/L		<0.10	<0.10	<0.10	<0.10
Selenium	mg/L	0.02	0.0056	0.049	0.0071	0.047
Silver	mg/L		<0.0050	<0.025	<0.0050	<0.0050
Sodium	mg/L	10	310	400	260	340
Strontium	mg/L		<0.10	<0.10	<0.10	<0.10
Sulphate	mg/L	16.04	45	390	140	590
Thallium	mg/L		<0.010	<0.010	<0.010	<0.010
Tin	mg/L	0.00008	<0.10	<0.10	<0.10	<0.10
Titanium	mg/L		<0.10	<0.10	<0.10	<0.10
Total Dissolved Solids	mg/L		770	1200	720	1200
Vanadium	mg/L	10	0.034	<0.010	0.018	<0.010
Zinc	mg/L	0.1	0.24	0.36	<0.010	0.028

Final Barren Solution – considered equivalent to PLS

*Republic of Armenia maximum acceptable concentrations based on Decree N-75N, 2011; Category II for the Arpa Basin, except for cyanide standard; see ESIA Chapter 2. Less than detection results are screened at half the detection limit. Constituent concentrations shaded grey exceed the Project Assessment Criteria.

**an additional source term of ammonium and nitrate is considered to arise from ammonium nitrate explosives residues, which would not be present in the pilot samples analysed.

2.1.3   Constituents of Potential Concern

The Republic of Armenia (RA) has no defined standards for groundwater protection and there are no groundwater users located between the HLF and the Arpa River receiving groundwater base flow. Constituents entering groundwater beneath the HLF may ultimately discharge to surface water. The Project

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Assessment Criteria protective of surface water are considered appropriate for assessment of the potential impacts of the HLF on the water environment.

Based on the analysis presented in Table 2, the following constituents are considered of potential concern due to their presence above standards for discharge to surface water: aluminium, ammonium, antimony, arsenic, beryllium, chloride, chromium, cobalt, copper, cyanide, iron, lithium, molybdenum, nitrate, phosphorous, potassium, selenium, sodium, sulphate, tin and zinc.

It is not considered necessary to model transport of all species present in the leachate, as the risk to groundwater and surface water will be defined by the constituents which are most mobile, present at highest concentration, or more toxic. The following constituents were therefore assessed in solute transport modelling:

- Cyanide: ecotoxic and highly mobile anion present at more than 130 times the IFC discharge standard (0.5 mg/l);

- Sodium: highly mobile cation, present above Armenian water quality standards;

- Arsenic, antimony: ecotoxic and relatively mobile cations present at concentrations significantly above water quality standards; and

- Copper, cobalt: relatively mobile metallic cations which may form weakly soluble complexes with cyanide, present above water quality standards in the PLS.

Cyanide may undergo aerobic biodegradation in the groundwater pathway, ultimately to ammonium and carbon dioxide (Smith and Mudder (1991), Kjeldsen (1999)). Ammonium also undergoes biodegradation to nitrate under aerobic conditions (England and Wales Environment Agency, 2003a). The accumulation and transport of ammonia and nitrate in the unsaturated zone and groundwater pathway as a result of biodegradation is represented in the solute transport model.

2.2 Transport Pathways and Processes

2.2.1 Pathways

The primary pathways for migration of constituents in groundwater from the HLF are as follows:

- Vertical leakage through the FML and clay (double) liner from the HLP and lined PSP;

- Vertical flow via gravity in the unsaturated zone through Colluvium and upper bedrock;

- In the area of the HLF around the main drainage, advection in shallow perched groundwater in the Colluvium and upper Lower Volcanics horizontally to the southwest to discharge to the surface water drainage downstream of the HLF; and

- On the valley margins away from the main drainage, advection in groundwater in the Lower Volcanics westward to the Arpa River.

Solution ponds situated downgradient the HLP are assumed to overlie the shallow colluvium/upper bedrock groundwater and discharge only to this pathway.

The conceptual model of solute migration from the facility is illustrated in Drawing 1. The area of the HLF footprint which is considered to potentially discharge to the localised perched water body flowing to the local drainage, and the HLF footprint area potentially discharging to deeper groundwater and subsequently to the Arpa River is illustrated in Figures 1 and 2.

2.2.1.1 Unsaturated Zone

The calculated unsaturated zone thickness for each HLF phase in each pathway is presented in Appendix B. Calculations are based on depth to groundwater recorded in October/November 2013 and May/June 2014 presented in the ESIA.

2.2.1.2   Saturated Zone

Groundwater data and groundwater elevation contours for the HLF site are presented in the ESIA Chapter 4.8 Groundwater Baseline.

Hydraulic gradients in saturated flow pathways within the shallow perched groundwater system and the groundwater system have been calculated based on groundwater elevations recorded in October/November 2013 and May/June 2014.

Saturated pathway lengths from the upgradient side of the HLF to the point of discharge and mean hydraulic gradients in each groundwater body beneath the site are presented in Appendix B.

For the purposes of the impact assessment, it is assumed that the shallow groundwater has a mean saturated thickness of 5 m, and that groundwater discharges from this system to the main drainage approximately 260 m southwest of Storm Pond 1.

Discharge to the Arpa River from the groundwater pathway occurs 1,580 m west of the western boundary of the HLF.

2.2.2   Retardation and Biodegradation Processes

2.2.2.1   Environmental Fate and Transport of Cyanide

The toxicity and mobility of cyanide is highly dependent on the form that cyanide takes in solution or as a solid. Ecological and human health risks arising from potential pollution of groundwater or surface water by cyanide and cyanide compounds are governed by the concentration of ecotoxic forms of cyanide (cyanide and thiocyanate) or weak or unstable complexes which may readily dissociate or break down to free cyanide (weak metal complexes, iron complexes which are subject to photolysis). The total concentration of potentially ecotoxic cyanide is usually measured as WAD cyanide: i.e. the concentration of cyanide liberated at pH 4.5.

The chemistry of cyanide in the environment is complex, and is described in published literature and regulatory guidance, including reviews provided by Smith and Mudder (1991), Lodgson et al (1999), Kjeldsen (1999) and in NICNAS (2010). A brief overview is provided here.

Attenuation of concentrations of aqueous WAD cyanide in the subsurface may occur through many processes:

■   Volatilisation as hydrogen cyanide (HCN) gas in solutions at low to moderate pH where there is a vapour pathway or exposure to air (below approximately pH 8, all aqueous cyanide is present at HCN, above pH 12 it is present as CN⁻). Volatilisation will be limited where there is no vapour migration pathway or limited exposure to air, or where the solution is at high pH;

■   Aerobic and anaerobic biodegradation, ultimately to ammonia and carbon dioxide. Published information suggests that in unsaturated soils, cyanide is readily biodegraded through a number of mechanisms in aerobic conditions (Smith and Mudder (1991), Kjeldsen (1999)), and that biodegradation may also occur (after a period of acclimatisation) in anaerobic conditions. However, rates are very much slower in saturated conditions;

■   Precipitation as salts of strong cyanide complexes (ferrocyanides and ferricyanides). The ferro- and ferricyanide salts of the abundant cations (calcium, magnesium, sodium, potassium, and ammonium) are highly to moderately soluble, but the majority of salts with other metals (including iron, nickel, copper and zinc) are insoluble;

■   Sorption to mineral surfaces during transport: studies summarised by Smith and Mudder (1991) suggest that cyanide sorbs to organic carbon, feldspars and clay minerals, but the authors note that separation of the effects of precipitation and sorption is difficult. Kjeldsen (1999) reports limited sorption based on two studies and concludes that sorption is of minimal importance in transport of cyanide in soils.

Sorption is a reversible process and serves to attenuate migration in the subsurface rather than permanently remove cyanide from solution; and

■ Hydrolysis under low pH conditions to formic acid or ammonium formate.

Smith and Mudder (1991) note firstly that studies have shown volatilisation and biodegradation to be the two most effective mechanisms of cyanide degradation occurring in the vadose and unsaturated zone, and secondly that in closed systems where no volatilisation occurs, geological materials may have little or no capacity for cyanide degradation.

The attenuation of cyanide in the subsurface will be a function of:

■ Cyanide concentration;

■ Concentration of cosolutes;

■ pH;

■ Moisture content (saturation conditions);

■ Soil permeability (and other controls on vapour migration such as meteorological factors);

■ Redox conditions; and

■ Mineralogy (affecting both retardation and precipitation).

Modelling has assumed that volatilisation will be limited in the unsaturated zone due to limited vapour migration and high cyanide concentrations in comparison to available pore space. Most likely, any pregnant solution potentially entering the subsurface is likely to be buffered to neutral pH, allowing some volatilisation to occur, but connectivity with any surface water pathways is uncertain so it is difficult to quantify.

Aerobic biodegradation of cyanide has been assumed to occur in the unsaturated zone, but not in the saturated zone.

Sorption reactions are modelled through a retardation coefficient applied to transport in the unsaturated and saturated zone. Partition coefficients have been based on figures reported in Smith and Mudder (1991). These partition coefficients are derived from migration rates of observed cyanide plumes in the natural environment. Removal of cyanide through precipitation as insoluble complexes is not considered in the model.

2.2.2.2   *Other Constituents of Potential Concern*

The solute transport model considers attenuation of metals as a result of sorption and retardation. The effect of redox conditions and pH on the solubility and mobility of metals is not explicitly considered in the model, metals present in the PLS are assumed to remain in solution except where sorbed to geological materials. This approach has the potential to overestimate concentrations in groundwater of metals such as arsenic, where mobility is a strong function of valency/redox conditions.

The aerobic biodegradation of ammonia (a product of cyanide biodegradation) to nitrate in the unsaturated zone is represented in the model. It is considered that groundwater conditions in the saturated zone have the potential to become anaerobic if impacted by significant cyanide discharge, and biodegradation of ammonium is limited in anaerobic conditions (England and Wales Environment Agency, 2003a). It is assumed that no biodegradation of ammonium occurs in the aquifer pathway.

2.3   Receptors

Groundwater receptors for the entire Project Area are described in Chapter 4.8 of the ESIA. There is no groundwater use between the HLF site and groundwater discharge to the Arpa River downgradient of the site. The steep topography of the Arpa gorge and proximity of the HLF to the river also makes it unlikely that any future exploitation of groundwater between the site and area of discharge to surface water could occur.

Groundwater provides baseflow to the Arpa River, and potentially to the stream passing southwest through the HLF valley.

Groundwater elevation data and field observations indicate that groundwater discharges locally to the main drainage in the HLF site (Figure 1) and regionally to the Arpa River west of the site (Figure 2). Surface water flow data indicates that the main drainage downstream of the HLF site is dry in winter when surface water run-off is low. This suggests that if shallow groundwater discharge to this drainage does occur within the site footprint, it is seasonal in nature occurring primarily during the wetter periods of spring and summer. The depth to groundwater is approximately 3 m at GGDW016/A downgradient of Storm Pond 2. It is therefore reasonable to assume that the main drainage intersects the water table slightly southwest of the proposed HLF site.

For the purposes of the impact assessment, impacts on the Arpa River and water quality in the local surface water drainage have been determined under the following scenarios:

■ Scenario 1: Shallow groundwater discharges to the local surface water drainage approximately 260 m southwest of Storm Pond 2. No additional permanent flow occurs in the stream southwest of the HLF footprint, such that under low flow conditions there is no mixing in this water course; and

■ Scenario 2: Shallow groundwater does not locally discharge to surface water, and the entire constituent mass from the facility may discharge to the Arpa River as a diffuse groundwater discharge to the west and southwest of the site.

The location of the assumed zone of groundwater discharge to the HLF valley stream is illustrated on Figure 1. In the model, the constituent mass discharged to the shallow groundwater in Scenario 1 is not subsequently discharged to the Arpa River as this is considered in Scenario 2.

Flow in the Arpa River downstream of the Kechut Reservoir is controlled by discharge from the reservoir. For the purpose of the impact assessment, low (Q95) flows in the Arpa River are estimated at 2.5 m^3/s based on existing monitoring (ESIA, Chapter 4.9). A range between 2.0 m^3/s and 3.0 m^3/s has been placed around possible estimates to allow for uncertainty associated with the limited monitoring record and measurement accuracy.
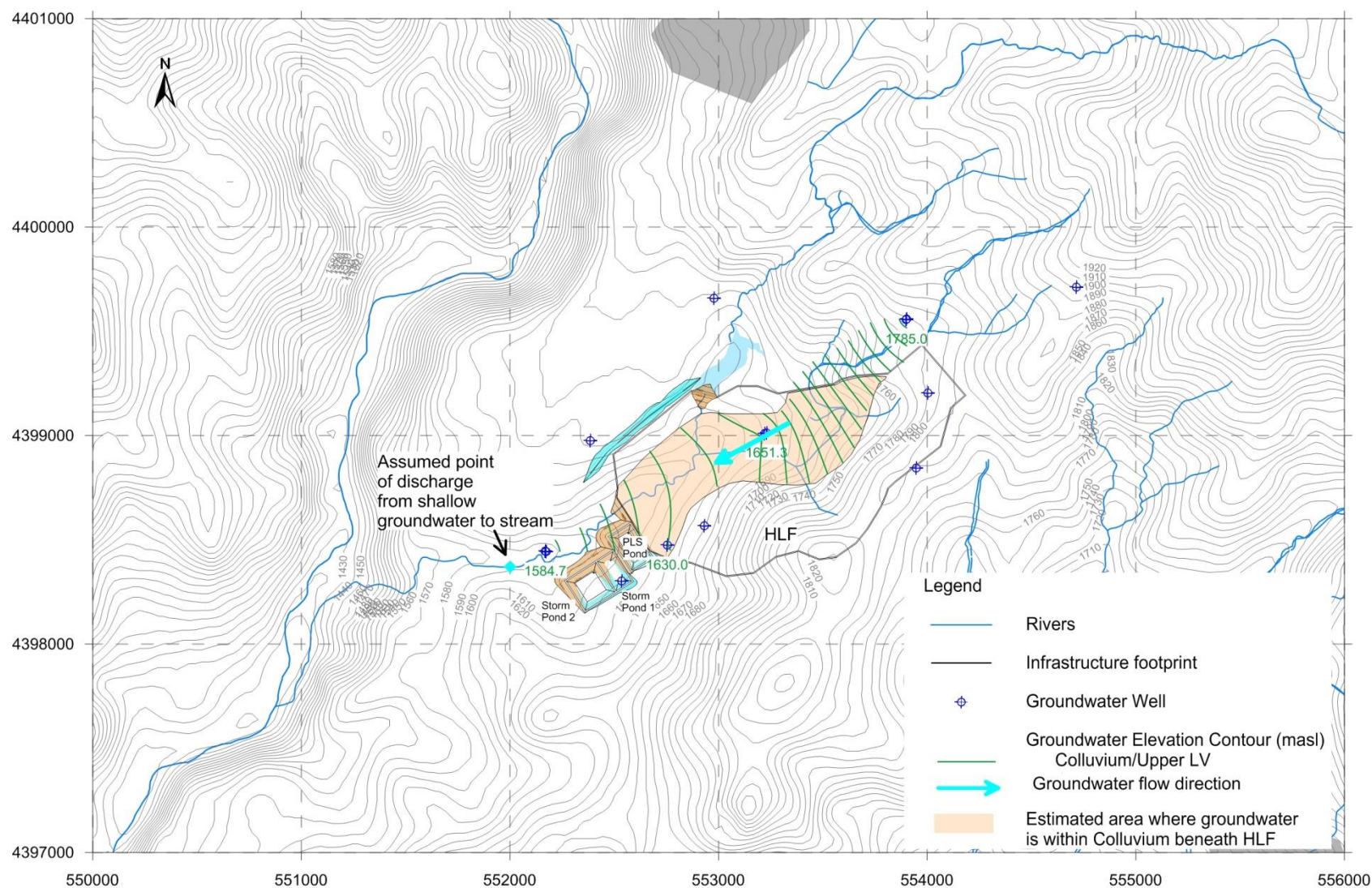
Figure 1: Groundwater Elevation Contours May 2014 and Indicative Flow Direction, Shallow Groundwater
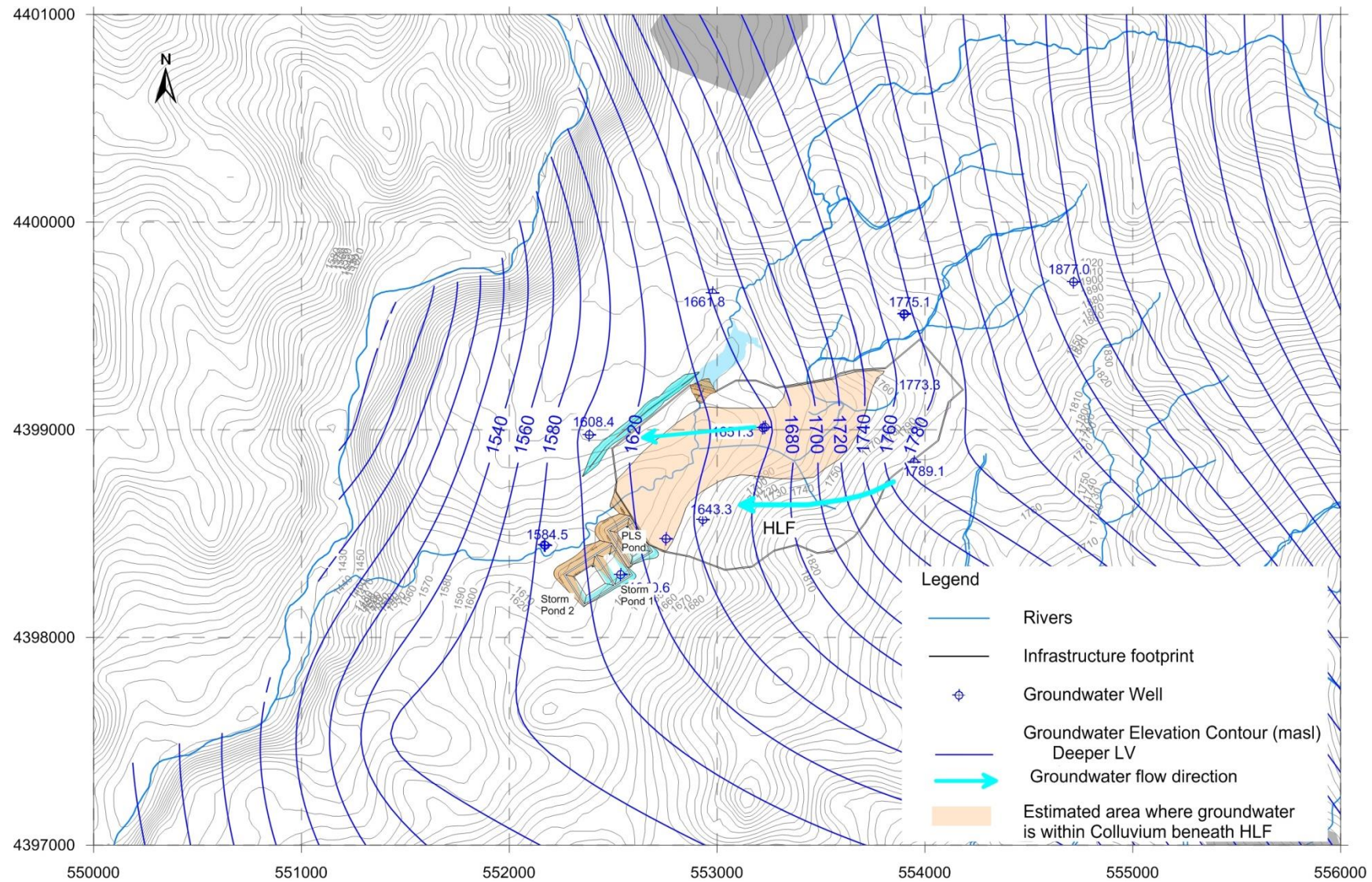
Figure 2: Groundwater Elevation Contours May 2014 and Indicative Flow Direction, Deep Groundwater

2.3.1 Groundwater Quality

Baseline groundwater quality in the Lower Volcanics surrounding the HLF site is discussed in Chapter 4.8 of the ESIA. Groundwater wells were installed at the HLF site in 2013; results from two monitoring rounds are currently available.

Baseline groundwater quality for the HLF site is based on aggregated water quality in all of the monitored wells, to increase the size and statistical reliability of the data set. Groundwater in the deeper Lower Volcanics hydrogeological unit has been sampled in wells GGDW007, GGDW009, GGDW011, GGDW012, GGDW013 and GGDW016. Shallower groundwater in the colluvium and shallow Lower Volcanics has been sampled in GGDW013A and GGDW016A.

Baseline groundwater quality is presented in Tables 3 and 4. Groundwater quality has been compared to Project Assessment Criteria (Republic of Armenia (RA) Category II maximum acceptable concentrations for the Arpa River Basin, Decree N75-N, 2011), both because no dedicated RA standards exist for groundwater, and because groundwater discharges to surface water.

Table 3: Summary of Baseline Groundwater Quality, HLF, Lower Volcanics Groundwater*

Parameter	Unit	Project Assessment Criteria	Minimum	Average	Maximum	Std Deviation	Data Count	Exceedances of MAC
Ammonia and ammonium ions	mg/L	0.51	0.05	0.69	3.52	1.24	12	3
Ammonia as N	mg N/L	0.4	0.018	0.57	2.42	0.92	6	2
Antimony	µg/L	0.28	1	1.17	1.8	0.31	12	12
Arsenic	µg/L	20	1	4.22	15.6	5.38	12	0
Cobalt	µg/L	0.36	0.5	0.55	0.96	0.13	12	12
Copper	µg/L	21	1	2.11	5.8	1.64	12	0
Easily released cyanides	mg/L	0.1	0.005	0.005	0.005	0	12	0
Total Cyanide	mg/L	1	0.005	0.005	0.005	0	12	0
Nitrate as N	mg/L	11.1	2	3.09	7.31	1.98	12	0
Sodium	mg/L	10	6.27	27.1	48.9	12.8	12	9

less than detection results are considered at the detection limit in statistical summaries

Table 4: Summary of Baseline Groundwater Quality, HLF, Shallow Groundwater*

Parameter	Unit	Project Assessment Criteria	Minimum	Average	Maximum	Std Deviation	Data Count	Exceedances of MAC
Ammonia and ammonium ions	mg/L	0.51	0.05	0.15	0.357	0.18	3	0
Ammonia as N	mg N/L	0.4	0.018	0.018	0.018	0	2	0
Antimony	µg/L	0.28	1	1	1	0	3	1
Arsenic	µg/L	20	1	1	1	0	3	3
Cobalt	µg/L	0.36	0.5	0.5	0.5	0	3	3
Copper	µg/L	21	1.2	1.3	1.5	0.17	3	0
Easily released cyanides	mg/L	0.1	0.005	0.005	0.005	0	3	0
Total Cyanide	mg/L	1	0.005	0.005	0.005	0	3	0
Nitrate as N	mg/L	11.1	2	5	11	5.20	3	0
Sodium	mg/L	10	14.4	17.0	19.1	2.38	3	1

less than detection results are considered at the detection limit in statistical summaries

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Detection limits applied for antimony and cobalt in groundwater exceed the Project Assessment Criteria for these substances. For the purposes of the impact assessment, it is assumed that average concentrations of these substances in groundwater are 0.2 µg/L and 0.3 µg/L respectively.

Ammonium and sodium naturally exceed the Project Assessment Criteria in groundwater under baseline conditions.

2.3.2   Surface Water Quality

Baseline surface water quality in the Arpa River is discussed in Chapter 4.9 of the ESIA. For the purposes of this assessment, the baseline concentration of the Arpa River is represented by monitoring location AW009. Baseline surface water quality in comparison to Project Assessment Criteria for maximum discharge concentrations allowable under RA law (RA Category II maximum acceptable concentrations for the Arpa River Basin, Decree N75-N, 2011) are presented in Table 5.

Table 5: Summary of Baseline Surface Water Quality, AW009, Arpa River*

Parameter	Unit	Project Assessment Criteria	Minimum	Mean	Median	Maximum	Std Dev	Data Count	Exceedances of MAC
Ammonia and ammonium ions	mg/L	0.5	0.002	11.6	0.057	327	55.8	44	2
Antimony	µg/L	0.28	1	1.41	1	10	1.92	22	22
Arsenic	µg/L	20	0.259	4.85	4.15	50	6.5	54	1
Cobalt (**all data**)**	µg/L	0.36	0.037	0.428	0.5	2.26	0.394	48	27
Cobalt (**2009 to May 2011**)	µg/L	0.36	0.0365	0.37	0.15	2.26	0.52	27	6
Copper (**all data**)	µg/L	21	0	2263	1.40	18898	5682	54	9
Copper (**excluding 2010 data**)***	µg/L	21	0	1.51	1.14	10	1.63	42	0
Total Cyanide	mg/L	1	0.005	0.0052	0.005	0.01	0.001	25	0
Weak Acid Dissociable Cyanide	mg/L	0.5	0.01	0.01	0.01	0.01	-	1	0
Easily released cyanides	mg/L	0.1	0.005	0.006	0.005	0.01	0.002	25	0
Nitrate as N	mg/L	11.1	0.005	3.3	3.07	7.66	1.86	41	0
Sodium	mg/L	10	1.42	9.77	10.57	16.4	3.77	40	22

*Values at detection limit are considered at the detection limit in summary statistics; **the analytical laboratory for the project was changed in June 2011. Before this, detection limits for cobalt were below the Project Assessment Criterion, subsequently the detection limit of 0.5 µg/l exceeded the criterion; ***extremely high copper concentrations were reported in 2010; these values are outliers in comparison to the remainder of the data set.

Ammonium exceeded the Project Assessment Criterion on two occasions, at 327 mg/L on 3 January 2010 and 181 mg/L on 11 January 2010; these two results are outliers, which also strongly influence the reported mean concentration. Without these outlier values, the mean ammonium concentration at AW009 is 0.084 mg/L. In general, ammonium is not above assessment criteria at AW009, and the mean of 0.084 mg/L is considered more representative of baseline conditions.

The laboratory detection limits for antimony exceeded the Project Assessment Criterion for the entire monitoring period. The antimony concentrations were below the detection limit in all samples. It is assumed for the purpose of the impact assessment that antimony is below the Project Assessment Criterion at AW009, and a theoretical average concentration of 0.2 µg/L is applied in the impact assessment. Arsenic, cyanide and nitrate are also typically below the assessment criteria at AW009.

The detection limit for cobalt from June 2011 until present exceeds the assessment criterion, but analysis prior to June 2011 indicates that the baseline concentration for cobalt occasionally exceeds the assessment criterion.

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Copper is reported to have exceeded the assessment criterion on nine occasions. These occasions are nine analyses undertaken in 2010 which reported total concentrations between 6,000 and 19,000 µg/L. The cause of these elevated concentrations is unknown, but similar concentrations are not a feature of the remaining dataset. Copper did not exceed the assessment criterion at AW009 in 2008, 2009, 2011, 2012 or 2013. Baseline concentration is therefore considered to be more appropriately represented by the mean of the dataset excluding the 2010 analyses.

Sodium exceeded the Project Assessment Criterion at AW009 on approximately 50% of the monitoring occasions. Baseline concentrations of sodium are considered to exceed the assessment criterion under current conditions.

3.0 SOLUTE TRANSPORT MODELLING

3.1 Modelling Approach and Software Selection

GoldSim (GoldSim Technology Group, 2014) was used for the solute transport modelling. GoldSim is a commercially available, graphical, object-oriented dynamic and stochastic modelling platform that is well suited to stochastic simulations of time variant processes in complex water resources systems. GoldSim considers uncertainty in input parameters and the development of the HLF over its life cycle. The model utilises prebuilt analytical solution elements in the GoldSim solute transport module to simulate sorption, advection, dispersion and biodegradation in the geosphere, migration pathways and mixing in flowing systems. Editable elements within the software are used to calculate flows within the system, and these are linked to the solute transport elements to dynamically simulate movement of water and solute mass within the system.

The stochastic modelling approach allows consideration of variations in input parameters that arise either through uncertainty (lack of knowledge) or through natural variation in the geological, hydrogeological or hydrological setting of a site. It allows each parameter to be described by a statistical distribution representing the range and likelihood of possible/probable input values. During a stochastic simulation each input distribution is randomly sampled, and each parameter is assigned a value from within its defined range. After a defined number of model iterations, multiple possible results are obtained and it becomes possible to quantify the likelihood of occurrence of a given outcome. These outcomes are expressed as the percentiles of the resulting distribution. The results are reported at the 95th percentile to be conservative. GoldSim provides "best", "most likely" and "worst" case outcomes and their probability of occurrence enabling risk quantification.

3.2 GoldSim Model Structure

The GoldSim model has six structured "containers":

- *Input Parameters* contains all inputs used in the model;

- *Groundwater Flow* calculates leakage rates and flow in the unsaturated and pathways;

- *SoluteTransport* contains elements which simulate advection, dispersion, retardation and biodegradation in each pathway and calculates the total constituent mass discharged to the receiving watercourse(s); flows in the advective transport pathways are defined from the 'Groundwater Flow' container;

- *Arpa River Flow* contains calculations of mixed concentrations in the Arpa River based on the calculated total mass discharged from the deeper Lower Volcanics groundwater pathway;

- *Stream Discharge* contains mixed concentration in the stream southwest of the HLF based on calculated total mass discharged from the shallow (colluvium/upper bedrock) groundwater pathway; and

- *Results* contains time history graphs of constituent concentrations in groundwater and surface water.

Flows within the geosphere and groundwater system must be defined outside the solute transport element net. These flows are calculated separately and used to define the flow rate in each pathway of the transport model. Solute velocity in each pathway is then calculated based on the defined flow rate and cross-sectional area of the pipe or groundwater pathway. Where pipe, groundwater and cell pathways are directly linked, the mass entering and leaving the pathway is defined by the fluid transfer rate.

Pipe and groundwater pathway elements of the GoldSim solute transport model simulate partitioning, advection and (if required) diffusive mass flux and biodegradation in a pathway of defined cross-sectional area and length. These pathways are linked so that solute mass and water flows move continuously between them. Cell pathways simulate partitioning, mixing and (if required) diffusive exchange between volumes of water or rock in which water is freely circulating. These elements are combined in the model to represent the liner and unsaturated zone pathways, mixing of leakage in groundwater underflow beneath the Site, lateral migration of solutes in the groundwater pathway, and mixing follow discharge to the Arpa River.

Example screenshots of the models are provided in Appendix A.

3.2.1   Flow Calculations

3.2.1.1   *Calculation of Leakage Rates*

Composite Liner

Leakage through the membrane liners underlying the heap and the PLS pond is a function of the head on the liners, the connection between the liners and any underlying soil barrier, and the number and size of defects in the membrane.

Leakage through the composite liner beneath the HLP is calculated using the method presented by Giroud (1997). Defects are assumed to be circular, and leakage is calculated as:

$$q = C_d i_{av} h^{0.9} a^{0.1} K^{0.74}$$

Where q is leakage per defect (m³/s), C_d is a coefficient describing the contact between the membrane and underlying strata, i_{av} is the average vertical hydraulic gradient, h is the head of leachate on the defect (m), a is the area of the defect (m²) and K is the hydraulic conductivity of the material directly underlying the membrane (m/s). The contact coefficient has a value 0.21 (good contact) and 1.15 (poor contact) (Giroud *et al*, 1997). Defect occurrence rates applied in the modelling are described in Section 3.3.

The average vertical hydraulic gradient is given by the equation:

$$i_{av} = 1 + 0.1 \left(\frac{h}{t_s}\right)^{0.95}$$

Where t_s is the thickness of the low permeability soil component of the composite liner. Simulation of FML degradation is described below, the maximum leakage through the FML is limited to leakage through the underlying low permeability soil liner calculated based on Darcy's Law:

$$Q = K \left(\frac{h}{h + t}\right) A$$

Where Q is leakage, h is head on the liner, t the liner thickness and A the basal area of the facility.

The leakage rate from the facility calculated by the methodology above is limited by the maximum (saturated) permeability of the underlying unsaturated zone. Following the operational period, the leakage rate is limited by the estimated recharge to the reclaimed facility.

Modelled liquid depths on the basal liner are based on calculated maximum heads under known or estimated infiltration rates during each phase of the life cycle. The head on the liner will be governed by the infiltration rate, pipe spacing, drainage blanket permeability and angle of slope on the base of the facility. The maximum head on the base above the elevation of the base of the drains can be approximated (neglecting the basal slope) using the Dupuit Equation (described below).

During the operational period the proposed solution application rate is 10 L/hr/m^2 over a 110 day leaching cycle comprising an active period of 55 days and a recirculation for a subsequent 55 days (GRE, 2014a). Assumptions regarding the post leaching and post closure infiltration rates are described in Section 2.1. Given the 7 m drain spacing and assuming a minimum permeability of the drainage media (allowing for clogging during operation) of 10^{-3} m/s, head on the base during operation could approach the 0.2 m design depth at its maximum point. Head will increase with distance from the drainage pipes; the maximum head will occur at the point between the two drainage pipes. The average head in the active area is assumed to be 0.1 m, half of the maximum head.

The head of in each phase of the HLF is therefore modelled throughout the lifecycle as follows:

■ A head of 0.1 m is applied in the active area during the leaching phase;

■ In areas which are inactive but have not been restored, a calculated head of 0.04 m has been applied; and

■ During the period following closure, a maximum head of 0.01 m is applied, up to a maximum infiltration/leakage of 10 mm/yr.

No limitation on leakage based on liquid supply is present in the model for the active and open phase leakage calculations, primarily because predicted leakage rates are significantly lower than liquid supply (leaching) rates, rendering such a limitation unnecessary. Leakage is limited to liquid supply (infiltration) during the post-closure phase.

The assessment of leakage from the HLF on this basis is considered conservative as the assessment considers active operation of the entirety of each phase in turn.

Double Liner (Membrane and Composite)

Where a double membrane and composite liner is present, the upper membrane liner is underlain by a permeable material, such that the equation described above for flow through defects does not apply. In this case, assuming that there is no limit on liquid supplied to the defect and head above the defect is known (both considered to be valid in the case of the collection ponds) leakage is calculated using the Bernoulli equation (as proposed in Giroud and Bonaparte (1989) and Giroud et al (1997)):

$$q = 0.6a\sqrt{2gh}$$

Where *g* is acceleration due to gravity and other variables are as previously described. It is noted that this equation works well when leakage rates are relatively small in relation to the capacity of the underlying material to transmit flow. The equation is not valid at late time where defect sizes are large as a result of liner decomposition and calculated leakages exceed both the liquid supply and the ability of the underlying permeable membrane to transmit water. Limitations on the calculated leakage rate which control the application of this equation are discussed further below.

Leakage passing through the upper membrane liner enters the intermediate drainage layer (leak detection system) and flows to the sump located in the corner of the ponds (PLS pond and Storm Pond 1), from where it is pumped out. The head within the intermediate drainage layer has been estimated in the GoldSim model as follows:

1) The HLF design (Golder, 2011) indicates that the drainage medium will be a geocomposite drainage layer; the properties of ABG Geosynthetics Finesse Deckdrain 600 (ABG Geosynthetics, undated) have been used to represent the behaviour of this layer in the model. The permeability of the drainage layer has been calculated based on specifications for the in-plane water flow of the material under a hydraulic gradient of between 0.1 and 1 at a pressure of 100 KPa (equal to 10 m of water).

2) The head within the drainage layer as a result of the leakage through the overlying membrane is approximated using the Dupuit equation (e.g. Fetter, 2001), describing discharge per unit width between two fixed heads located at an origin, O, and a distance, L from the origin:

$$q' = \frac{K}{2}\left(\frac{h_L^2 - h_0^2}{L}\right)$$

Where K is permeability of the material in which flow occurs (m/s), h is the liquid head (m) and L is the separation of the two points. In the case under consideration, the distance L is taken as the longest flowpath across the base of the collection pond, and the problem is simplified to a two dimensional problem with flow parallel to the longest flowpath. In order to approximate the discharge per unit width, the total leakage is converted to an equivalent recharge rate (w) and multiplied by the flow path length, L. The equation can then be rearranged as:

$$h_L = \sqrt{\frac{2q'L}{K} + h_0^2} = \sqrt{\frac{2wL^2}{K} + h_0^2}$$

In this case, the head at the origin can be taken as zero (the purpose of the calculation is to find the difference in head), further simplifying this equation. This calculation neglects the effect on any basal slope on head on the liner.

3) Under conditions where the drainage layer between the two membrane liners is saturated, the head acting on the lower liner is in continuity with the overlying pond. In this case, the head considered in leakage calculations should be the depth of the pond (plus the drainage layer thickness). Where the drainage layer is unsaturated, the head on the lower liner is equal to the head within the drainage layer. It is conservatively assumed for the purpose of the leakage calculations that where the maximum head calculated above exceeds the drainage layer thickness, the drainage layer is saturated. Leakage through the lower liner is calculated using the Giroud (1997) equations described above.

The maximum leakage rate through the double liner is limited to the permeability of both the underlying clay liner and underlying unsaturated zone as described above with regard to the composite liner. Leakage is not explicitly limited to liquid supply in the model because this is only relevant during the operational period, during which the membrane is performing well and leakage rates are low. In late time, when the liner has potentially degraded, leakage rates are limited to infiltration.

Defect Occurrence and Performance

FMLs comprising the composite and double liners beneath the ore heap and collection ponds are assumed to be present and perform as follows:

■ It is assumed that the FML is constructed with an industry-standard QA/QC testing program and there are few defects. It is assumed that defects are formed gradually (linear increase) as a result of damage during construction and operation, such that at the end of operation the number of defects is equivalent to the 'Stage 2' values indicated in England and Wales Environment Agency (2004);

■ The number of defects is then considered to remain constant until the onset of oxidation of the FML (formation of stress cracks is neglected); and

■ After the onset of oxidation the area of the holes is considered to double on a half-life basis until the membrane no longer inhibits leakage (leakage is controlled by the underlying clay liner).

Predicted leakage rates are sensitive to the defect occurrence rate. It has been assumed for the purposes of the impact assessment that an 'excellent' construction quality assurance (CQA) standard will be achieved in construction of the facility. 'Excellent' CQA is defined in Environment Agency (2004) as follows:

■ "*The geomembrane material meets the requirements of the Geosynthetic Research Institute (GRI) GM13 specification with the added criterion that the stress crack failure time should be well in excess of the 300 hours currently specified in GRI GM13;*

■ *The oxidative induction time value and oven ageing procedure should meet the GRI GM13 and BAM certification requirements;*

■   *The design has been subjected to independent design quality assurance;*

■   *Mineral geomembrane protection is provided;*

■   *Installation of the liner system by installers certificated under the British Geomembrane Association* [or equivalent] *scheme together with experienced CQA* [construction quality assurance] *supervision until the first layer of waste* [ore] *has been placed; and*

■   *A fixed electric leak location system is installed and monitored quarterly (or more frequently) until the completion of waste disposal.*"

Other studies (e.g. Forget *et al*, 2005) indicate that the best standards of modern CQA in North America, inclusive of an electric leak location survey performed after placement of the over-liner drain gravel component in the leach pad, achieve defect rates in the 'excellent' range described by Environment Agency (2004) without installation of a fixed leak detection system (required by the definition of the 'excellent' standard). The assessment assumes that Lydian will meet apply best practice CQA and will complete an electrical leak detection survey after placement of the over-liner drainage layer prior to operation.

3.2.1.2   Unsaturated Zone Flow

In the pathway representing bulk flow within the unsaturated zone, flow is modelled based on plug flow (displacement of water downward under gravity based on the leakage rate with no change in saturation). This is considered conservative on the basis that if wetting of the unsaturated zone occurs, travel times will be slower than simulated based on unsaturated conditions.

The area of the unsaturated zone in which flow is occurring beneath the membrane liner is calculated using wetted area equations based on the method presented in Giroud and Badu-Tweneboah (1992).

3.2.1.3   Groundwater Flow

Flow in the groundwater pathway is calculated using Darcy's Law. Hydraulic gradients in each pathway and scenario are calculated based on groundwater elevations from the groundwater flow model along the flow pathlines indicated in Section 2.2.

3.2.2   Solute Transport

3.2.2.1   Source

It is assumed that the source term remains constant within the ore heap and collection ponds during operation. It is assumed that the source associated with the collection ponds ceases to exist at the end of leaching operations. Attenuation of the source term during the detoxification period (including attenuation of cyanide to environmentally acceptable concentrations) is represented as a linear change from the operational to the end of detoxification concentrations during this period.

It is assumed that ammoniacal nitrogen and nitrate are leached from the heap during the five year post closure monitoring (managed closure) period, and that at the end of this time concentrations of ammoniacal nitrogen and nitrate in the heap are negligible (less than 0.5 mg/l).

It is conservatively assumed that, for species other than ammoniacal nitrogen and nitrate, the source term within the heap leach will decline from the final detoxification concentration as a result of attenuation due to ongoing leaching into infiltrating precipitation in the reclaimed facility during closure. The source term decline is simulated as a function of time and solid to liquid ratio as follows (England and Wales Environment Agency, 2003b):

$$C_t = C_0 e^{-\lambda t}$$

and

$$\lambda = \frac{i}{W_{thickness} W_{fc}}$$

Where C_t is concentration at time t, C_0 is initial concentration, i is infiltration, $W_{thickness}$ is waste (ore) thickness (m), W_{fc} is water field capacity. This model is used for all constituents within the heap leach source except nitrate and ammonium. Nitrate and ammonium do not (predominantly) derive from the ore solids, but are a primarily a product cyanide breakdown. Once the cyanide is no longer provided during operations, the concentrations of these parameters within the source is expected to rapidly decline. The model assumes ammonium and nitrate in the heap leach source attenuate to zero within ten years of reclamation.

3.2.2.2   Pathways

The solute transport pathways are represented in the model using three elements:

■ Pipe pathways: for short pathways where constituent mass is transported within a fixed volume based on a known flow rate, travel time is calculated based on pathway dimensions, flow rate and partition coefficients defined between the solid and liquid in the pathway;

■ Groundwater pathways: behave similarly to pipe pathways but are discretized into a number of units to provide additional resolution; and

■ Cell pathways: Cell pathways are typically used to describe partitioning (e.g. between air, one or more liquid phase and one or more solid phases) within a uniformly mixed volume and may be used to describe diffusive and advective fluxes between defined volumes. In this model, cell pathways are used only to mix one of more incoming sources of clean or process-influenced water for onward transport.

The liner and unsaturated zone are simulated as pipe and groundwater pathways respectively, carrying mass discharged from the four source areas to the saturated zone. Leakage and unsaturated zone migration from the ponds and pad in each phase are calculated separately, but the sources are combined into a single flow pathway from each phase in the saturated zone.

In the saturated zone, mixing is simulated in the groundwater pathway beneath the upgradient Phase 3 within a defined mixing zone thickness using cell pathway, liquid and mass flows from both unsaturated zone pathways are combined with the upgradient groundwater flow to calculate an average concentration in the mixing zone.

Phases 1 and 2 are located downgradient of Phase 3 in both scenarios. Water and mass flowing under Phase 3 then enters the modelled pathway beneath Phase 2 where any discharges from Phase 2 are added. The combined flow then enters the pathway under Phase 1. During the period when Phases 2 and 3 are not operational, there are no additional discharges from these phases and flow in the Phase 2 and Phase 3 pathways is equal to just the upgradient groundwater flow.

Transport in each hydrogeological unit with the unsaturated zone and groundwater pathways beneath each source (Phases 1, 2 and 3, and the collection ponds) is simulated by the GoldSim aquifer pathway elements, linked in series. Further groundwater pathway elements represent transport from the downgradient boundary of the facility to the point of discharge to surface water.

3.2.2.3   Receptors

Scenario 1

In the Arpa River, the surface water concentration is calculated based on the upgradient surface water flow and the groundwater discharge mass. The model results represent the increase in constituent concentration as a result of the HLF. Actual maximum concentrations are calculated externally to the GoldSim model based on mean baseline concentrations.

Under current conditions, flow in the surface water drainage within the HLF footprint is ephemeral at the downstream monitoring location. The model therefore reports the concentration in groundwater at the point of discharge to this channel estimated to be 260 m southwest of Storm Pond 2 assuming no additional surface water flow enters the stream channel.

Scenario 2

This pathway assumes that groundwater in the shallow groundwater merges with the deeper groundwater flow system southwest of the site and that all groundwater discharges to the Arpa River without any local discharge to surface water southwest of the HLF footprint. Water quality in the Arpa River has also been assessed assuming that the mass in both the shallow and deeper modelled groundwater pathways discharges to the Arpa River.

3.3   Model Input Parameters

Model input parameters and justifications are provided in Appendix B.

3.4   Results

The model simulation was run for a period of 1,000 years, 501 realisations were completed. The calculated change in concentrations of constituents of potential concern in groundwater at the point of discharge to surface water courses are reported, and the resultant impact on surface water quality is assessed.

3.4.1   HLF Leakage Quantities

3.4.1.1   *Leakage from HLF Area Overlying the Shallow Groundwater*

The modelled leakage rate from the facility to the shallow groundwater is illustrated in Figure 3. Leakage from the HLP is small during operations and reduces significantly at 15 years at the end of the managed closure period. The median post closure leakage rate is between 0.012 L/s at closure to 0.013 L/s at 1,000 years.
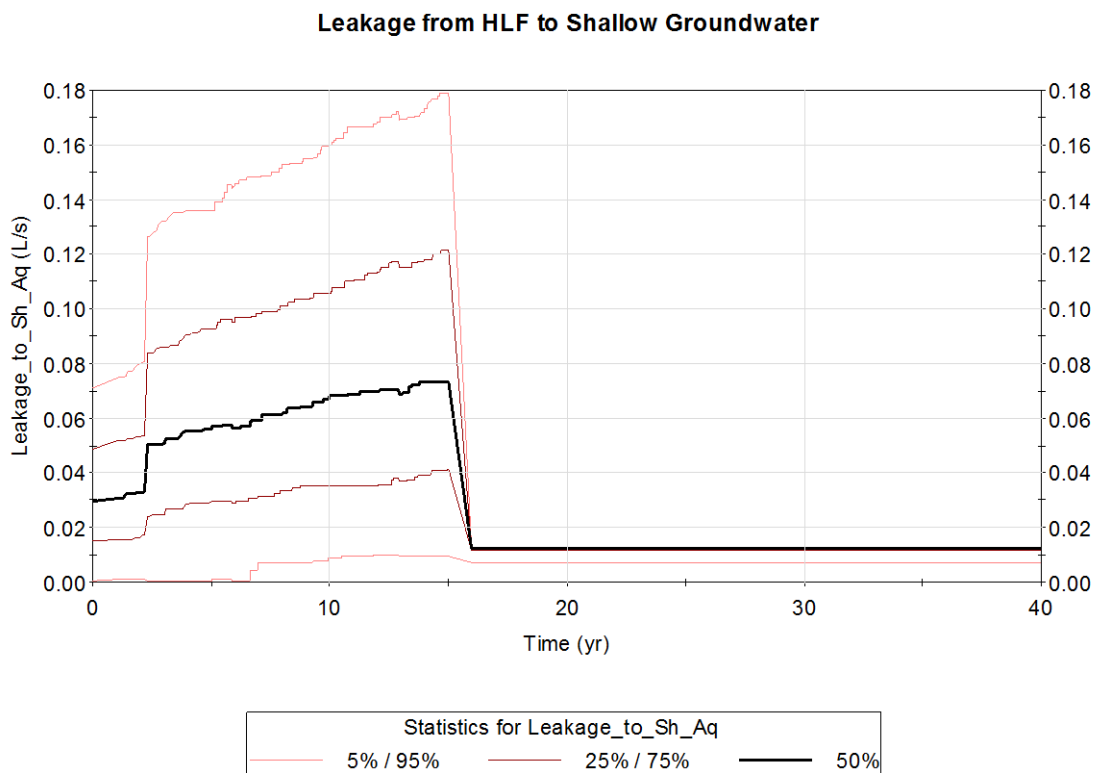
Leakage from HLF to Shallow Groundwater

Figure 3: Modelled Leakage Rate from HLF to Shallow Groundwater, Operations and Post-Closure

Upgradient groundwater flow (underflow) in the shallow groundwater is calculated based on the estimated width of the aquifer, the observed hydraulic gradient and an assumed saturated thickness of 5 m. This yields a mean underflow of 2.8 m^3/day (0.03 L/s), with an uncertainty ranging between a 5th percentile of 1.2 m^3/day

and 95th percentile of 5.9 m^3/day. It is assumed that the entire leakage and underflow volume potentially discharges to the stream. The total assumed discharge to the HLF valley stream is shown in Table 6.

Table 6: Shallow Groundwater Discharge to HLF Valley Stream

Percentile	Peak Operational Flow (L/s)	Post Closure Flow (L/s)
5%ile	0.023	0.021
50%ile	0.097	0.039
95%ile	0.248	0.082

3.4.1.2 Leakage from HLF Area Overlying the Deeper Groundwater

The modelled leakage rate from the facility to the deeper groundwater is illustrated in Figure 4. Leakage from the HLP is very small and reduces significantly at ten years (at the end of the operation). Leakage to deep groundwater is lower during operation of Phase 2 is only slightly greater than Phase 1, this is a function of the area of Phase 2 which overlies the deep aquifer. The median post closure leakage rate is from 0.0009 L/s to 0.0015 L/s.

Leakage from HLF to Deep Groundwater
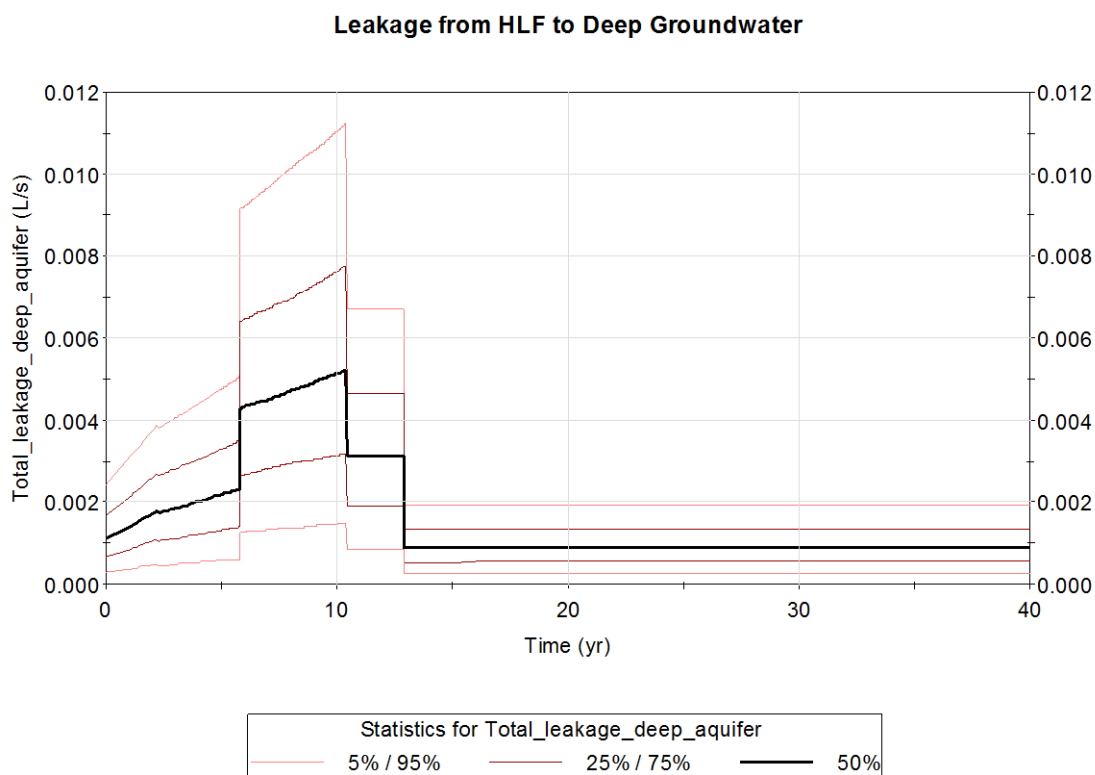
Figure 4: Modelled Leakage Rate from HLF to Deep Groundwater, Operations and Post-Closure

Upgradient groundwater flow (underflow) in the deeper groundwater system into which leakage from the site is mixed before reaching the Arpa River is calculated based on the width of the site perpendicular to groundwater flow, the observed hydraulic gradient and a mixing zone thickness of 30 m (based on a vertical dispersivity of 1% of the pathway length). This yields a mean underflow at the maximum facility extent (Phases 1 to 3) of 430 m^3/day (5th percentile of 185 m^3/day (2.1 L/s), 95th percentile of 1,680 m^3/day (19.4 L/s)).

Groundwater is assumed to discharge to the Arpa River over a 1,040 m discharge zone, the width of the facility perpendicular to groundwater flow.

3.4.2   Quality of Groundwater Discharging to Surface Water

Groundwater is not used as a drinking water resource in the vicinity of the HLF, and there is no groundwater use between the HLF and the discharge to surface water at the Arpa River. Groundwater as a source of supply is therefore not considered to be a receptor in the context of this assessment. Groundwater discharging to surface water (baseflow) is considered to be a receptor in the context of impact assessment.

The calculated change in groundwater concentrations in groundwater in the deeper Lower Volcanics, and in shallow groundwater in the colluvium and upper bedrock is presented Tables 7 and 8. Results are reported to a precision at which the calculated model results are replicable at 501 iterations. The 50th percentile value is considered the 'most likely' outcome, whilst the 95%ile concentration is the conservative estimate of the possible maximum impact.

Table 7: Modelled Maximum Change in Concentration in Deep Groundwater at Point of Discharge to the Arpa River*

Constituent	50%ile Peak Concentration (mg/l)	Time to Peak Concentration (years)	95%ile Peak Concentration (mg/)	Time to Peak Concentration (years)
Arsenic	$<1\times10^{-10}$	1,000	5.6×10^{-6}	1,000
Copper	N/A	>1,000	N/A	>1,000
Cobalt	N/A	>1,000	N/A	>1,000
Antimony	N/A	>1,000	$<1\times10^{-10}$	1,000
Sodium	0.015	59	0.064	81
WAD Cyanide	N/A	>1,000	$<1\times10^{-10}$	840
NH_3+NH_4 as N	$<1\times10^{-10}$	780	$<1\times10^{-10}$	384
Nitrate as N	0.018	41	0.11	33

*N/A – not applicable, constituent did not arrive at receptor inside the simulation period. >1,000 – travel time to the receptor for the contaminant is more than 1,000 years.
Positive values indicate an increase in concentration above existing conditions

As described in Section 3.4.1.2, the groundwater mixing zone for the discharge from the HLF to the deeper groundwater is assumed to be an area 1,040 m long (the width of the facility perpendicular to groundwater flow) and 30 m deep. In closure, the contribution of groundwater underflow to discharge in this zone is estimated to be between 2.1 L/s and 19.4 L/s, whilst the contribution of leakage to discharge in this zone is between 0.0002 L/s and 0.002 L/s, giving a total discharge at the concentrations in Table 7 between 2.1 L/s and 19.4 L/s.

Table 8: Modelled Maximum Change in Concentrations in Shallow Groundwater at Point of Discharge to Stream*

Constituent	50%ile Peak Concentration (mg/l)	Time to Peak Concentration (years)	95%ile Peak Concentration (mg/)	Time to Peak (years)
Arsenic	$<1\times10^{-10}$	1000	0.006	960
Copper	N/A	>1000	N/A	>1000
Cobalt	$<1\times10^{-10}$	1000	$<1\times10^{-10}$	1000
Antimony	$<1\times10^{-10}$	1000	$<1\times10^{-10}$	1000
Sodium	80.5	20	168	15
WAD Cyanide	$<1\times10^{-10}$	1000	9.30×10^{-5}	960
NH_3+NH_4 as N	2.10×10^{-4}	1000	0.57	470
Nitrate as N	152	28	319	14.9

*N/A – not applicable, contaminant did not arrive at receptor inside the simulation period. >1000 – travel time to the receptor for the contaminant is more than 1000 years.
As described in Section 3.4.1.1, the predicted discharge to the HLF valley stream is between 0.02 L/s and 0.24 L/s in operation and 0.02 L/s and 0.08 L/s in closure. The peak concentrations above occur in closure.

The potential peak concentrations in groundwater discharging to surface water for the constituents of potential concern in each hydrogeological unit have been calculated based on the predicted change and mean baseline concentration. Impacts on groundwater quality, based on comparison to project water quality assessment criteria (WQAC) are presented in Tables 9 and 10.

Table 9: Modelled Peak Impact on Groundwater Quality Discharging to Arpa River

Constituent	Unit	Average Baseline Concentration**	95%ile Change in Concentration	Predicted Peak Concentration	Percentage Change
Arsenic	mg/L	0.0042	5.6×10^{-6}	0.0042	0%
Copper	mg/L	0.0021	0	0.0021	0%
Cobalt	mg/L	3.0×10^{-4}	0	3.0×10^{-4}	0%
Antimony	mg/L	2.0×10^{-4}	0	2.0×10^{-4}	0%
Sodium	mg/L	27.1	0.064	27.1	0%
WAD Cyanide	mg/L	0.005	0	0.005	0%
ammonium as N	mg/L	0.54	$<1 \times 10^{-10}$	0.54	0%
Nitrate as N**	mg/L	0.70	0.1	0.8	16%

*Water quality assessment criteria
**see text

Table 10: Modelled Peak Impact on Groundwater Quality Discharging to HLF Stream

Constituent	Unit	Average Baseline Concentration**	95%ile Change in Concentration	Predicted Peak Concentration	Percentage Change
Arsenic	mg/L	0.0049	0.006	0.011	124%
Copper	mg/L	0.0013	0	0.0013	0%
Cobalt	mg/L	3.0×10^{-4}	0	3.0×10^{-4}	0%
Antimony	mg/L	2.0×10^{-4}	$<1 \times 10^{-10}$	2.0×10^{-4}	0%
Sodium	mg/L	17.0	168	185	990%
WAD Cyanide	mg/L	0.005	9.3×10^{-5}	0.0051	2%
ammonium as N	mg/L	0.1	0.6	0.7	481%
Nitrate as N	mg/L	1.1	319.0	320.1	>1000%

*Water quality assessment criteria
**see text

Retardation of the less soluble metals considered in the HLF risk assessment (copper, cobalt and antimony) means that these metals do not reach the Arpa River or the assumed groundwater discharge to the HLF stream within 1,000 years.

Arsenic is more mobile and does reach the Arpa River within 1,000 years at undetectable concentrations, although groundwater with a maximum (peak) arsenic concentration has not arrived within 1,000 years. For unretarded species (nitrate and sodium) the peak groundwater concentration at the discharge to the Arpa River occurs after 30 to 80 years and 14 to 20 years at the discharge location to the stream southwest of the HLF. Differing contaminants have differing concentrations in the operational and closure source terms, resulting in the peak concentration occurring at different times. High concentrations of nitrate are observed in the stream southwest of the HLF as a result of accumulation in the groundwater pathway due to cyanide and ammonium degradation. The possible range in retardation factors for ammonium transport result in some uncertainty regarding the travel time for ammonium in the groundwater pathway, ranging between 400 years and 800 years in the deep groundwater and 400 years and 1,000 years in the shallower groundwater.

While the amount of modelled leakage from the HLF is very small, the model predicts a significant change in the quality of groundwater discharge to the stream southwest of the HLF with respect to arsenic, sodium, ammonium and nitrate (Table 10). Detectable, but very low, concentrations of cyanide are possible if degradation does not occur in shallow groundwater.

3.4.3 Surface Water Quality Impacts

3.4.3.1 Arpa River, Scenario 1

In this scenario, a proportion of the constituent mass from the HLF discharges to surface water in the stream southwest of the HLF, where it is captured before discharge to the Arpa River.

The calculated peak increase in concentrations above baseline quality in surface water following mixing under low flow conditions and times to peak concentration in each scenario are presented in Table 11. Results are reported to an accuracy at which the model results are replicable at 501 iterations. However, the range of likely concentrations in surface water based on the calculations undertaken is indicated by the two values (50th percentile and 95th percentile) presented.

Table 11: Modelled Peak Water Quality Change in the Arpa River

Constituent	50%ile Peak Concentration (mg/l)	Time to Peak (years)	95%ile Peak Concentration (mg/)	Time to Peak (years)
Arsenic	$<1\times10^{-10}$	1000	$<1\times10^{-10}$	1000
Copper	N/A	>1000	N/A	>1000
Cobalt	N/A	>1000	N/A	>1000
Antimony	N/A	>1000	$<1\times10^{-10}$	1000
Sodium	4.26×10^{-5}	53	0.00019	28
WAD Cyanide	N/A	>1000	$<1\times10^{-10}$	960
NH$_3$+NH$_4$ as N	$<1\times10^{-10}$	780	$<1\times10^{-10}$	216
Nitrate as N	5.45×10^{-5}	35	0.0004	28

N/A – not applicable, contaminant did not arrive at receptor inside the simulation period. >1,000 – travel time to the receptor for the contaminant is more than 1,000 years.

The potential peak concentrations of the constituents of potential concern in the Arpa River have been estimated based mean concentrations in AW009 and calculated 95th percentile peak concentrations in the water course is indicated in Table 12.

Table 12: Modelled 95th Percentile Water Quality Impacts to the Arpa River

Parameter	Unit	WQAC	Average Baseline Conc'n*	95%ile Change in Conc'n	Predicted Peak Conc'n	Above WQAC?	Above WQAC in Baseline?	Percentage Change
Arsenic	mg/L	0.02	0.0049	$<1\times10^{-10}$	0.0049	No	No	0.0%
Copper	mg/L	0.021	0.0015	0	0.0015	No	No	0.0%
Cobalt	mg/L	3.6×10^{-4}	3.7×10^{-4}	0	3.7×10^{-4}	Yes	Yes	0.0%
Antimony	mg/L	2.8×10^{-4}	2.0×10^{-4}	0	2.0×10^{-4}	No	No	0.0%
Sodium	mg/L	10	9.77	1.9×10^{-4}	9.77	No	No	0.0%
WAD Cyanide	mg/L	1	0.0060	0	0.0060	No	No	0.0%
Ammonium as N	mg/L	0.4	0.065	$<1\times10^{-10}$	0.065	No	No	0.0%
Nitrates as N	mg/L	2.5	0.75	3.6×10^{-4}	0.75	No	No	0.0%

*see text

A positive value is an increase in concentration

The modelling indicates that assuming a portion of the leakage from the HLF reaches the stream southwest of the facility, there is a 95% probability that no measurable change in water quality in the Arpa River will occur.

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3.4.3.2 *Arpa River, Scenario 2*

In this scenario, all of the constituent mass released from the HLF to the shallow and deep groundwater pathways enters the Arpa River.

Predicted change concentrations over time in the Arpa River are presented graphically in Appendix C.

The calculated peak increase in concentrations above baseline quality in surface water following mixing under low flow conditions and times to peak concentration in each scenario are presented in Table 13.

Table 13: Modelled Peak Water Quality Change in the Arpa River

Parameter	50%ile Peak Concentration (mg/l)	Time to Peak (years)	95%ile Peak Concentration (mg/)	Time to Peak (years)
Arsenic	$<1 \times 10^{-10}$	1000	1.2×10^{-7}	1000
Copper	N/A	>1000	N/A	>1000
Cobalt	N/A	>1000	$<1 \times 10^{-10}$	1000
Antimony	$<1 \times 10^{-10}$	1000	$<1 \times 10^{-10}$	1000
Sodium	0.0033	15	0.013	15
WAD Cyanide	$<1 \times 10^{-10}$	1000	1.6×10^{-9}	780
$NH_3 + NH_4$ as N	4.4×10^{-9}	1000	9.5×10^{-6}	450
Nitrate as N	0.006	17	0.026	14.6

*N/A – not applicable, contaminant did not arrive at receptor inside the simulation period. >1,000 – travel time to the receptor for the contaminant is more than 1,000 years.
A positive value is an increase in concentration.

The potential peak concentrations of the constituents of potential concern in the Arpa River have been estimated based in mean concentrations in AW009 and calculated 95th percentile peak concentrations in the water courses indicated in Table 14.

Table 14: Modelled 95th Percentile Water Quality Impacts to the Arpa River

Parameter	Unit	WQAC	Average Baseline Conc'n*	95%ile Change in Conc'n	Predicted Peak Conc'n	Above WQAC?	Above WQAC in Baseline?	Percent-age Change
Arsenic	mg/L	0.02	0.0049	1.2×10^{-7}	0.0049	No	No	0.0%
Copper	mg/L	0.021	0.0015	0	0.0015	No	No	0.0%
Cobalt	mg/L	3.6×10^{-4}	3.7×10^{-4}	0	3.7×10^{-4}	Yes	Yes	0.0%
Antimony	mg/L	2.8×10^{-4}	2.0×10^{-4}	0	2.0×10^{-4}	No	No	0.0%
Sodium	mg/L	10	9.77	0.013	9.78	No	No	0.1%
WAD Cyanide	mg/L	0.5	0.0060	2×10^{-9}	0.006	No	No	0.0%
ammonium as N	mg/L	0.4	0.065	9.5×10^{-6}	0.065	No	No	0.0%
Nitrates as N	mg/L	2.5	0.75	0.03	0.77	No	No	3.4%

*see text

The modelling indicates there is a 95% probability that the remaining discharge to surface water quality in the Arpa River with no measurable change in surface water quality. All of the modelled constituents that are below surface water MACs under baseline conditions remain so over the 1,000 year simulation period. Minor changes in concentrations of sodium and nitrate are predicted, but it is unlikely that these changes would be statistically measureable against natural fluctuations. Cobalt exceeds surface water MACs under baseline conditions; no change in cobalt concentration is predicted in surface water.

3.4.3.3   *HLF Valley Stream*

Observations indicate that there is not a continuous flow in the surface water channel at the southwestern perimeter of the HLF site, such that under low flow conditions, no additional surface water mixing will occur for groundwater potentially discharging to this channel downstream of the site. Groundwater quality presented in Tables 8 and 10 therefore also represents potential concentrations in the stream channel in the absence of mitigation measures that are currently planned.

Predicted concentrations over time in groundwater discharging to the HLF stream are presented graphically in Appendix C.

As described in Table 6, the discharge to the stream downgradient of the HLF is predicted to be between 0.02 L/s and 0.24 L/s in operation and between 0.02 L/s and 0.08 L/s in closure. In general, groundwater discharge concentration will be inversely correlated to flow, such that it is reasonable to apply the 50th percentile predicted concentration to the median flow rate, and the 95th percentile predicted concentration to the 5th percentile flow rate.

The quantity of water potentially discharged to the HLF valley stream is of relatively high concentration with respect to certain parameters, but very low in volume. The occurrence of groundwater discharge in this area has not been confirmed and may or may not occur; in the event that it does not, discharge in groundwater has been demonstrated to pose a negligible risk to the Arpa River. Furthermore, other physical and geochemical processes in the unsaturated zone which are not evaluated in the modelling may also reduce constituent concentrations in any leakage from the facility to surface water.

Due to the potential risk identified to shallow groundwater/surface water in the HLF drainage, the final design for the HLF will evaluate in more detail some of the uncertain physical/chemical processes such as unsaturated flow and vapor transport which will influence solute transport. Leakage and solute transport concentration predictions will be updated. The monitoring program for the facility (locations, frequency, parameters and types of monitoring) will be updated following further more detailed design based on the revised understanding of the potential leakage pathways and concentrations.

During operations, monitoring of the stream flow and quality will allow any leakage impacts to be identified. If leakage is detected and modifications to the HLF operations do not result in quality improvements, then other industry-accepted seepage mitigation measures would be implemented to prevent off-site migration of shallow groundwater. The form of these measures, if required, will be dependent on the site hydrogeological conditions, HLF operational and water balance conditions, groundwater quality trends and concentrations.

In closure, during periods of low flow when little dilution is available, high evaporation rates will potentially prevent any discharge to the Arpa River from the small quantities of flow predicted for the HLF stream. During periods of higher flow, non-contact water discharged from the HLF detention pond will provide mixing in the stream and concentrations at the point of discharge to the Arpa River will be much lower than those predicted in discharging groundwater.

3.5   Sensitivity Analysis

The parameters with highest sensitivity in the GoldSim model are entered as stochastic parameters with ranges based on their possible values. Results are assessed at the 95th percentile. For this reason, the results incorporate an assessment of the sensitivity of the model to key parameters such as source term concentration, hydraulic conductivity, retardation factors and biodegradation rates. In addition the assessment has considered uncertainty regarding groundwater flow direction beneath the Site. For this reason no further sensitivity analysis is considered necessary to have confidence in the model outcome.

4.0   CONCLUSIONS

An assessment has been undertaken of potential impacts on the Arpa River and water in the stream southwest of the HLF as a result of the potential leakage from the proposed HLF. Two scenarios were considered:

■ Scenario 1: Shallow groundwater discharges to the local surface water drainage approximately 260 m southwest of Storm Pond 2. No additional permanent flow occurs in the stream southwest of the HLF footprint, such that under low-flow conditions there may be no available mixing in this water course. Mass released to local surface water is captured and does not enter the Arpa River; and

■ Scenario 2: Shallow groundwater does not locally discharge to surface water, and all leakage from the facility may discharge to the Arpa River as a diffuse groundwater discharge to the west and southwest of the site.

Based on the 95th percentile concentrations calculated by the solute transport model, it is concluded that:

■ No measureable change in surface water quality within the Arpa River will occur in the event that all of the leakage from the facility reaches the Arpa River via the groundwater pathways;

■ A slight change (up to 0.1 mg N/L) in the quality of baseflow to the Arpa River could potentially occur as a result of leakage from the HLF with respect to nitrate within 30 to 40 years of the start of operations, although the concentration in groundwater at discharge to the river would remain below surface water quality standards;

■ A significant change in the quality of groundwater discharge to the stream southwest of the HLF with respect to arsenic, sodium, ammonium and nitrate may potentially occur within 15 to 30 years of the start of operations. Detectable, but very low, concentrations of cyanide are possible if degradation does not occur in the unsaturated zone or shallow groundwater; and

■ Due to the limited or ephemeral flow in the stream southwest of the HLF, any groundwater affected by leakage from the HLF that discharges to surface water during autumn or winter months may directly mirror groundwater concentrations, with high nitrate concentrations and high sodium and ammonium concentrations.

The quantity of water potentially discharged to the HLF valley stream is of relatively high concentration with respect to certain parameters, but very low in volume. The occurrence of groundwater discharge in this area has not been confirmed and may or may not occur; in the event that it does not, discharge in groundwater has been demonstrated to pose a negligible risk to the Arpa River. Furthermore, other physical and geochemical processes in the unsaturated zone which are not evaluated in the modelling presented may also act to limit release of leakage from the facility to surface water.

Due to the potential risk identified to shallow groundwater/surface water in the HLF drainage, the final design for the HLF will evaluate in more detail some of the uncertain physical/chemical processes such as unsaturated flow and vapor transport which will influence solute transport. Potential leakage rates and solute transport concentration predictions will be updated. The monitoring program for the facility (locations, frequency, parameters and types of monitoring) will be updated following further more detailed design based the revised understanding of the potential leakage pathways.

In the event that operational monitoring detects trends indicative of HLF leakage, typical mining industry seepage remediation or other mitigation/operational measures will be implemented to protect the environment during operation and in closure. These measures may or may not be required pending any modifications during the final design process and would be determined based on the operational performance of the HLF performance and the site-specific hydrogeological conditions.

This assessment is based on a probabilistic risk assessment approach to incorporate evaluation of the uncertainty in key parameters affecting the outcome of the assessment. The assessment is considered conservative in many aspects, for instance:

■ Evaluation of a head on the base of the HLP across the entire base area of the facility; hydraulic gradients on the margins of the facility make it probable that heads will develop only in the flatter central areas;

■ Potential for discharge to surface water to occur in the drainage southwest of the facility;

■ The use of a probabilistic modelling approach and assessment of results at the 95th percentile;

■ Consideration of metals concentrations in the PLS up to twice those measured in analysis from pilot testing; and

■ Conservative representation of processes contributing to attenuation in the unsaturated zone and groundwater pathway, which neglects processes such as cyanide volatilisation, ferri- and ferrocyanide precipitation, cation exchange and potential biodegradation of both cyanide and ammonia in the groundwater pathway which may reduce impacts from those predicted.

It is therefore considered that whilst there are areas of uncertainty in certain aspects of the assessment, these are accounted for in the range of values applied as input parameters and in the conservatism of the assessment approach. As such these areas of uncertainty are not considered to affect the assessment conclusions regarding potential impacts on receptors.

The HLF will be subject to detailed monitoring during operation, both within the heap (flow and quality monitoring) and in groundwater downgradient of the facility. Any adverse leakage from the facility is therefore likely to be identified during operations should it occur, and remedial action can be taken. Similarly, early-warning monitoring wells in close proximity to the facility will identify any impacts on groundwater before significant impact on surface water occurs, allowing remedial measures to be implemented if required.

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DRAWINGS
Drawing 1 – Contaminant Transport Conceptual Model

LEGEND

	LOWER VOLCANO-SEDIMENTARY PACKAGE
	COLLUVIUM
	HEAD OF PREGNANT LEACHATE SOLUTION
	GROUNDWATER LEVEL
	GROUNDWATER DISCHARGE TO STREAM / RIVER
	LEAKAGE THROUGH LINER
	INFILTRATION OF RAINFALL
	CONTAMINANT PATHWAY

SOLUTION STORAGE POND

DOUBLE LINER (FML COMPOSITE) WITH LEAK DETECTION DRAINAGE LAYER

PUMPED

LEAKAGE

COMPOSITE LINER WITH UNDER AND OVER DRAINAGE

VLF

STREAM

LOWER VOLCANO-SEDIMENTARY SEQUENCE

ARPA RIVER

SEEPAGE

ELEVATION (m)

DISTANCE (m)

0   250   500

1:12,500   METRES

A	2014-06-30	FIRST ISSUE		AD	SN	CN	CN		
Rev.	YYYY-MM-DD	DESCRIPTION		PREPARED	DESIGN	REVIEW	APPROVED		6.8.1

APPENDIX A
GoldSim Model Structure (Screen Shots)

Figure 1: Top Level Container
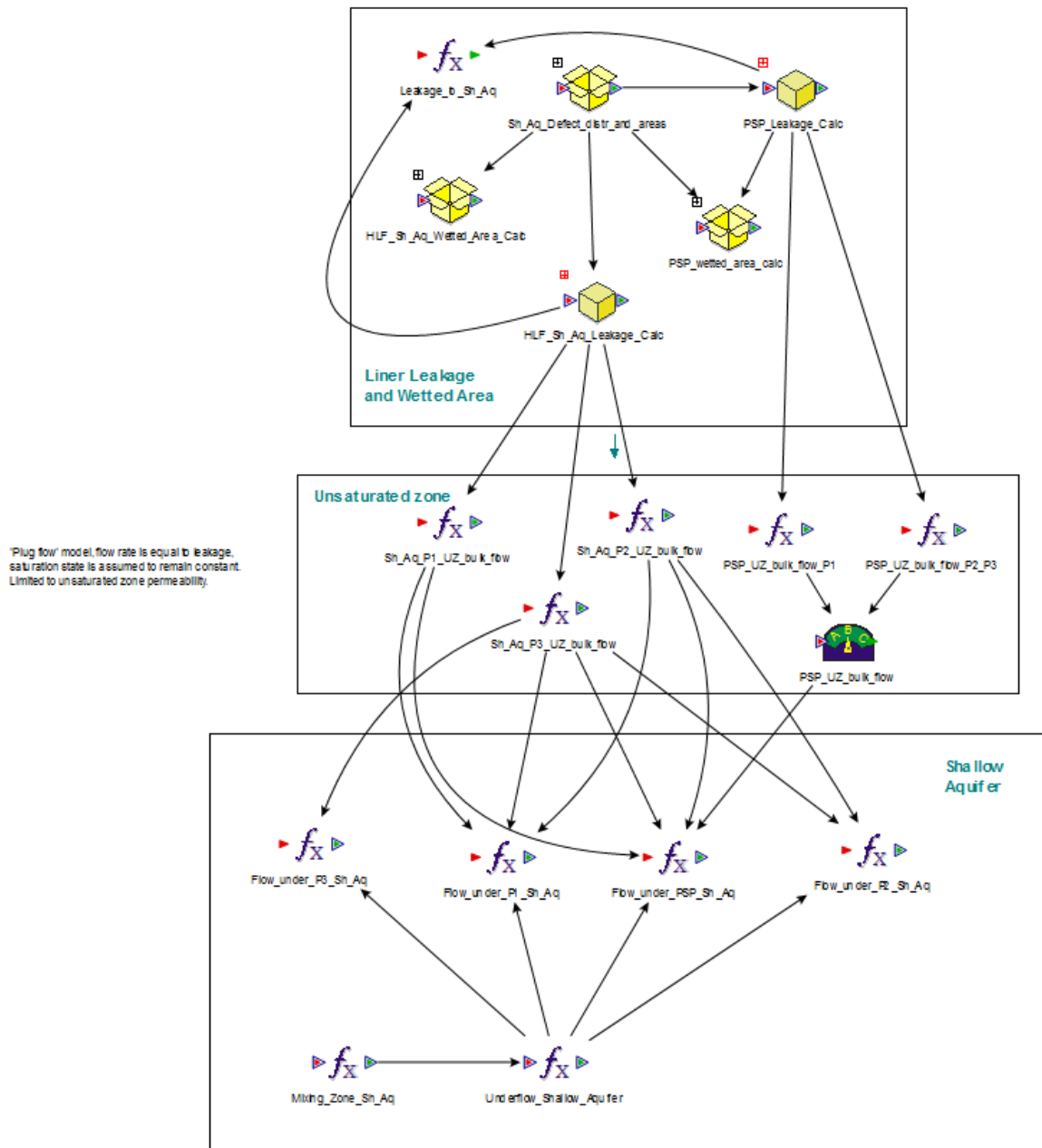
Figure 2: Shallow Aquifer Groundwater Flow Container
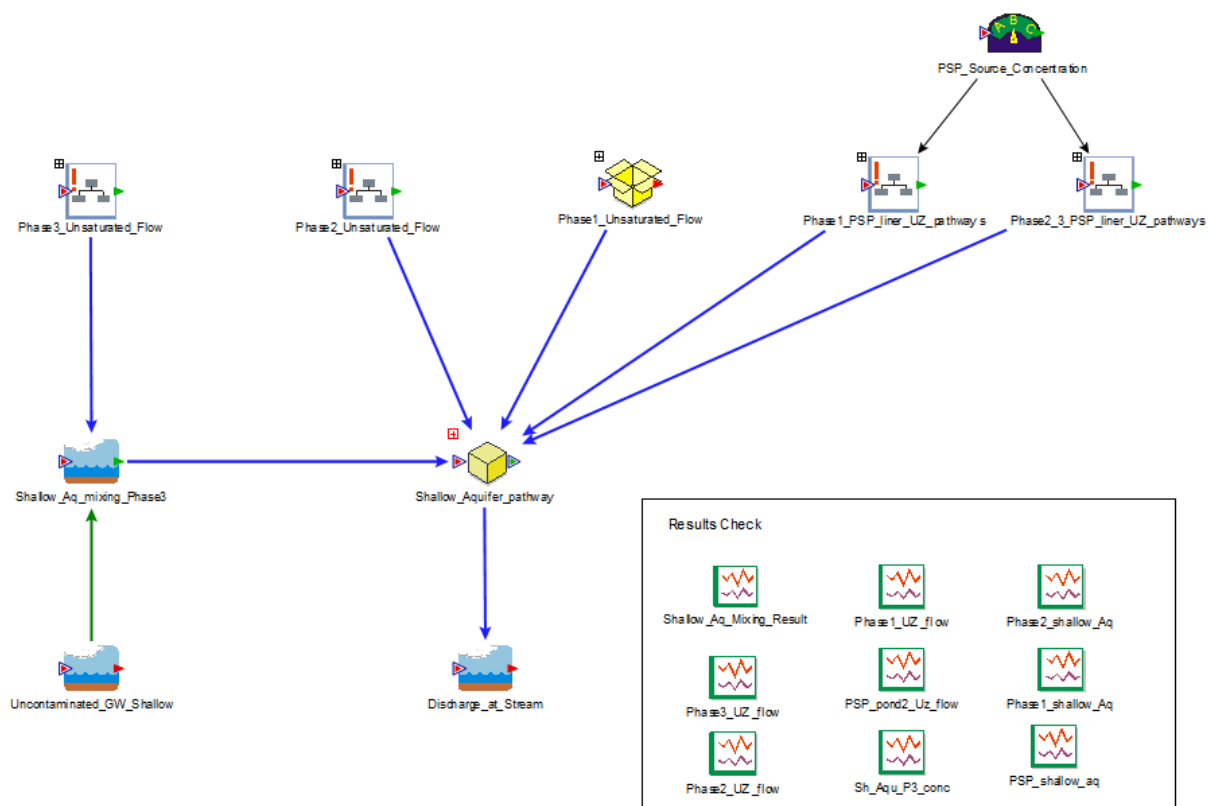
Figure 3: Contaminant Transport Container, Shallow Aquifer
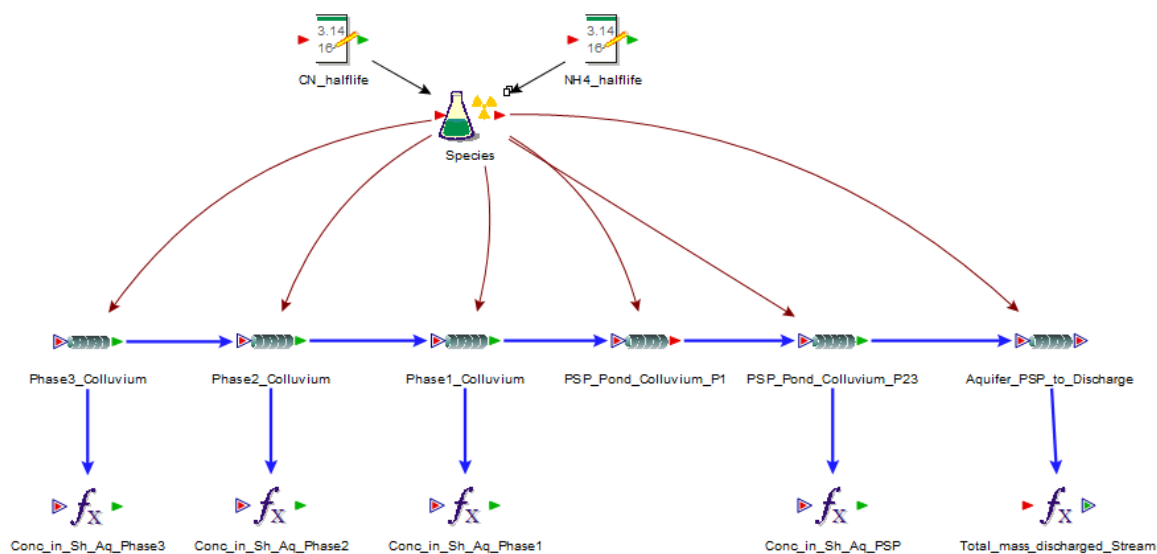
Figure 4: Aquifer Pathway, Shallow Aquifer

APPENDIX B
Model Inputs and Justifications

Amulsar Gold Project
Hydrogeological Risk Assessment

Appendix B
Model Inputs and Justifications

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Parameter	Species/Material	Distribution	Input	Unit	Justification
Contaminants and Materials					
PLS Concentration	Arsenic	Uniform	0.15, 1.26	mg/l	Based on analysis of barren leach solution from 2 test ore samples, as provided by Lydian. maximum equal to double the reported maximum concentration for metals. Taken at reported value for cyanide. See text for further discussion.
	Copper	Uniform	1.4, 3.0	mg/l	
	Cobalt	Uniform	0.021, 0.052	mg/l	
	Antimony	Uniform	0.04, 0.24	mg/l	
	Cyanide	Uniform	34, 66	mg/l	
	Sodium	Single	235	mg/l	Design specification, solution will have 500 mg/L sodium cyanide
	Ammonium	Single	50	mg/l	Based on calculations of nitrogen loading due to ammonium nitrate residues (Golder 2014). Analysis of ammonium or nitrate concentrations in the barren leach solution from pilot testing will not allow for nitrogen derived from explosives residues.
	Nitrate	Single	250	mg/l	
PLS Concentration During Closure	Arsenic	Uniform	0.18, 0.7	mg/l	Based on analysis of barren leach solution from 2 test ore samples, as provided by Lydian. maximum equal to double the reported maximum concentration. See text for further discussion.
	Copper	Uniform	0.5, 0.58	mg/l	
	Cobalt	Uniform	0.014, 0.016	mg/l	
	Antimony	Uniform	0.061, 0.19	mg/l	
	Cyanide	Single	1	mg/l	Cyanide concentrations to be reduced post-closure through the use of Peroxide.
	Sodium	Single	235	mg/l	Calculated from pre-closure concentrations of NaCN.
	Ammonium	Single	50	mg/l	Based on calculations of nitrogen loading due to ammonium nitrate residues (Golder 2014). Analysis of ammonium or nitrate concentrations in the barren leach solution from pilot testing will not allow for nitrogen derived from explosives residues.
	Nitrate	Single	250	mg/l	
Solubility	All		Not limited	mol/l	Source concentrations are based on analysis of actual solutions, although some precipitation is likely to occur due to pH change, metals solubilities are a function of pH and redox conditions which are not well constrained. The assumption that analytes remain in solution is considered conservative
Kd Values, Liner and Colluvium	Arsenic	Uniform	0, 18	ml/g	USEPA, 2004
	Copper	Log Uniform	126.8, 27500	ml/g	Entenmann, W, 1995; USEPA, 1996
	Cobalt	Triangular	45, 55.7, 65	ml/g	Entenmann, W.; In Situ determination of retention processes in artificial and natural min layers under landfills and contaminated sites. Foundation Engineering & Environmental Technology, Hamburg.
	Antimony	Triangular	2, 45, 45	ml/g	USEPA, 1996
	Sodium	Single	0	ml/g	Conservative
	Cyanide	Uniform	0.66, 10.81	ml/g	Smith and Mudder (1991), values for clay and shales
	Ammonium	Triangular	0.1, 0.5, 5	ml/g	Environment Agency (2003a), values for clay materials and mudstones
	Nitrate	Single	0	ml/g	Conservative
Kd Values, LVA	Arsenic	Uniform	0, 18	ml/g	USEPA, 2004
	Copper	Log Uniform	126.8, 27500	ml/g	Entenmann, W, 1995; USEPA, 1996
	Cobalt	Triangular	45, 55.7, 65	ml/g	Entenmann, W.; In Situ determination of retention processes in artificial and natural min layers under landfills and contaminated sites. Foundation Engineering & Environmental Technology, Hamburg.
	Antimony	Triangular	2, 45, 45	ml/g	USEPA, 1996
	Sodium	Single	0	ml/g	Conservative
	Cyanide	Uniform	0.066, 9.6	ml/g	Smith and Mudder (1991), values for limestone (no other rock types reported)
	Ammonium	Uniform	0.05, 2	ml/g	Environment Agency (2003a), range for various sedimentary rock types as no values for igneous rocks reported, and presence of clay infill may affect Kd of basaltic rock.
	Nitrate	Single	0	ml/g	Conservative
Half Lives, Unsaturated Zone	Cyanide	Uniform	0.5, 1	years	Aerobic halflife. Conservative range based on Kjeldsen, 1999 and Howard et al, 1991.
	Ammonium	Uniform	1, 6	years	Aerobic halflife. Environment Agency, 2003a.
Half Lives, Aquifer Pathway	Cyanide	Single	1.00E+09	years	Conservative assumption as degradation may not occur or may be greatly reduced in saturated conditions (Smith and Mudder, 1991).
	Ammonium	Single	1.00E+09	years	Conservative assumption as biodegradation does not occur in anaerobic conditions (Environment Agency, 2003a).
Dry Bulk Density	Low Permeability Soil Liner	Single	1800	kg/m³	Golder experience for clay materials
	Colluvium	Single	1800	kg/m³	Golder experience
	Lower volcano sedimentary sequence	Single	2400	kg/m³	Golder experience
Porosity	Low Permeability Soil Liner	Single	0.15		Golder experience, effective connected porosity
	Colluvium	Triangular	0.03, 0.07, 0.12		Johnson (1967) "Sandy clay" range; consistent with observed.
	Lower volcano sedimentary sequence	Triangular	0.02, 0.08, 0.14		Based on porosity estimates: Groundwater Baseline report (Golder 2014)
Infrastructure Geometry and Properties					
Area of HLF intersecting shallow aquifer	Phase 1	Single	323,554	m²	Based on "Phases 1-3 Leach Pad Layout and Ore Heap Plan, Drawing 6", GRE, April 2014 and estimated extent of shallow aquifer.
	Phase 2	Single	134,920	m²	
	Phase 3	Single	8,993	m²	
Area of HLF intersecting deep aquifer	Phase 1	Single	156,956	m²	
	Phase 2	Single	142,030	m²	
	Phase 3	Single	337,627	m²	
Active Area	All phases	Single	278,400	m²	Total active area, active area overlying each phases calculated by scaling of proportional area. Total area of Phase 2 is less than the active area, therefore 100% of area of Phase 2 taken as active during operation.
Area of PSP		Single	21,470	m²	Amulsar Site 28 HLF Water Balance Calculations Memo, G.R.E., 01-05-14
Area of Storm Pond 1		Single	14,784	m²	Amulsar Site 28 HLF Water Balance Calculations Memo, G.R.E., 01-05-14
Liquid depth on liner	HLP - active operational	Single	0.1	m	Design specification (GRE 2014a) and based on maximum head on the liner calculated using the Dupuit Equation and based on infiltration rates of 0.01 m3/hr/m2, 485.49 mm/year and 10 mm/yr (operational, uncapped and post-closure), 7 m drain spacing, and clogged drainage media permeability 10-3 m/s.
	HLP - inactive, open (uncapped)	Single	0.04	m	
	HLP - Post-Closure	Single	0.01	m	
	PSP	Single	10	m	Maximum possible depth of liquid in PSP; Based on "Phases 1-3 Leach Pad Layout and Ore Heap Plan, Drawing 6", GRE, April 2014.
Ore heap height		Single	112.7	m	Average maximum heap height across all Phases; Based on "Phases 1-3 Leach Pad Layout and Ore Heap Plan, Drawing 6", GRE, April 2014.
Ore heap field capacity		single	10	%	Amulsar Site 28 HLF Water Balance Calculations Memo, G.R.E., 01-05-14
Operational period	Total	Single	10.5	years	Amulsar Site 28 HLF Water Balance Calculations Memo, G.R.E., 01-05-14
	Phase 1	Single	27	months	
	Phase 2	Single	43	months	
	Phase 3	Single	55	months	
Rinsing period		Single	1	years	Based on instructions received from Marc Leduc (Lydian) in email "Heap closure concepts - to be used for the EIA closure plan", 03-07-2014
Capping period		Single	1.5	years	Based on instructions received from Marc Leduc (Lydian) in email "Heap closure concepts - to be used for the EIA closure plan", 03-07-2014
Managed closure period		Single	5	years	Based on instructions received from Marc Leduc (Lydian) in email "Heap closure concepts - to be used for the EIA closure plan", 03-07-2014
Uncapped infiltration rate		Single	485.49	mm/yr	Calculated from values presented in: Amulsar Site 28 HLF Water Balance Calculations Memo, G.R.E., dated 01-05-14
Post-closure infiltration rate		Single	20	mm/yr	Conservative estimate based on climatic conditions, see report text.
Dilution width	HLF, Phase 1 (shallow aquifer)	Single	800	m	Average width; Based on "Phases 1-3 Leach Pad Layout and Ore Heap Plan, Drawing 6", GRE, April 2014.
	HLF, Phase 2 (shallow aquifer)	Single	551	m	
	HLF, Phase 3 (shallow aquifer)	Single	98	m	
	HLF, Phase 1 (deep aquifer)	Single	676	m	
	HLF, Phase 2 (deep aquifer)	Single	400	m	
	HLF, Phase 3 (deep aquifer)	Single	400	m	
Longest flowpath across pond base	PSP	Single	210	m	Flow path across full diagonal of base to sump in opposing corner; Based on "Phases 1-3 Leach Pad Layout and Ore Heap Plan, Drawing 6", GRE, April 2014.
Liner					

Amulsar Gold Project
Hydrogeological Risk Assessment

Appendix B
Model Inputs and Justifications

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Parameter	Species/Material	Distribution	Input	Unit	Justification
Permeability	Low K soil liner	Log Uniform	1.00E-08	m/s	Design specification of 1x10^{-8} m/s (GRE, 2014).
	drainage layer	Uniform	1.15e-3,3,3e-3	m/s	Calculated based on specifications for ABG Deckdrain 600S at 100 kPa
Thickness	Low K soil liner	Single	0.3	m	Design specification (GRE, 2014)
	drainage layer	Single	5.8	mm	Thickness based on specification for ABG Deckdrain 600S drainage geocomposite
Number of pinholes, excellent CQA	All stages and areas	Triangular	0,0,8	ha-1	England and Wales Environment Agency (2004), defect frequencies end of Stage 2
Number of hole, excellent CQA	All stages and areas	Triangular	0,0,3	ha-1	England and Wales Environment Agency (2004), defect frequencies end of Stage 2
Number of tears, excellent CQA	All stages and areas	Triangular	0,0,2	ha-1	England and Wales Environment Agency (2004), defect frequencies end of Stage 2
area of pinhole	All stages and areas	Single	2.55	mm2	Midpoint of range, England and Wales Environment Agency (2004)
area of hole	All stages and areas	Single	52.5	mm2	Midpoint of range, England and Wales Environment Agency (2004)
area of tear	All stages and areas	Single	5050	mm2	Midpoint of range, England and Wales Environment Agency (2004)
time of onset of FML degradation	All stages and areas	Single	238	years	Anti-oxidant depletion plus induction time at 20 degC (Koerner et al, 2011).
Unsaturated Zone Properties					
Permeability	Colluvium	Log Triangular	5e-8, 1e-7, 5e-7	m/s	Range based on lithological description of the Colluvium (silty sandy clay).
	Lower volcano sedimentary sequence	Uniform	3.8e-7, 1.9e-6, 9.5e-6	m/s	Range based on hydraulic testing of the Lower Volcanics, HLF site (Geometric mean of 19 tests, plus/minus half an order of magnitude for variation of mean conductivity of the entire pathway from the estimated mean)
Saturation	Colluvium	Uniform	0.67		Fraction of total rock volume; Golder experience
Moisture content	Lower volcano sedimentary sequence	Uniform	0.024		30% of porosity; Golder experience
Total Unsaturated Pathway length	HLF, Phase 1 (shallow aquifer)	Uniform	6, 14	m	Range calculated from existing site investigation data.
	HLF, Phase 2 (shallow aquifer)	Uniform	14, 16.5	m	Range calculated from existing site investigation data.
	HLF, Phase 3 (shallow aquifer)	Uniform	16.5, 20	m	Range calculated from existing site investigation data.
	PSP and Storm Pond 1 (shallow aquifer)	Uniform	1, 6	m	Estimated from groundwater contours (ESIA Chapter 4.8)
	HLF, Phase 1 (deep aquifer)	Triangular	5, 20, 35	m	Estimated from groundwater contours (ESIA Chapter 4.8)
	HLF, Phase 2 (deep aquifer)	Triangular	3, 32.5, 80	m	Estimated from groundwater contours (ESIA Chapter 4.8)
	HLF, Phase 3 (deep aquifer)	Triangular	3, 40, 104.5	m	Estimated from groundwater contours (ESIA Chapter 4.8)
Pathway length, Colluvium	HLF, Phase 1 (shallow aquifer)	Single	pathway length	m	Assumed that all of unsaturated zone is assigned the properties of Colluvium.
	HLF, Phase 2 (shallow aquifer)	Single	pathway length	m	
	HLF, Phase 3 (shallow aquifer)	Single	pathway length	m	
	PSP and Storm Pond 1 (shallow aquifer)	Single	Equal to unsaturated pathway length	m	
	HLF, All Phases (deep aquifer)	Single	3	m	Typical thickness of unsaturated Colluvium above Deep aquifer.
Saturated Pathway Properties					
Permeability	Colluvium	Log Triangular	5e-8, 1e-7, 5e-7	m/s	Range based on lithological description of the Colluvium (silty sandy clay).
	Lower volcano sedimentary sequence	Uniform	3.8e-7, 1.9e-6, 9.5e-6	m/s	Range based on hydraulic testing of the Lower Volcanics, HLF site (Geometric mean of 19 tests, plus/minus half an order of magnitude for variation of mean conductivity of the entire pathway from the estimated mean)
Thickness	Colluvium	Single	5	m	Assumed thickness of saturated Colluvium in Shallow aquifer, see text.
	Lower volcano sedimentary sequence	Single	100	m	Golder experience, and hydraulic testing. The Lower Volcanics are highly anistotropic, most flow is likely to occur in the upper 100 m.
Total Saturated Pathway Length	HLF (shallow aquifer)	Single	2053	m	In direction of groundwater flow to discharge point in stream or Arpa River;
	HLF (deep aquifer)	Single	2965	m	Based on "Phases 1-3 Leach Pad Layout and Ore Heap Plan, Drawing 6", GRE, April 2014
	PSP (shallow aquifer)	Single	132	m	
	Storm Pond 1 (shallow aquifer)	Single	132	m	
Saturated pathway width, Colluvium	HLF, Phase 1 (shallow aquifer)	Single	526	m	Based on "Phases 1-3 Leach Pad Layout and Ore Heap Plan, Drawing 6", GRE, April 2014 and estimated extent of shallow aquifer.
	HLF, Phase 2 (shallow aquifer)	Single	474	m	
	HLF, Phase 3 (shallow aquifer)	Single	105	m	
Saturated pathway width, Lower volcano sedimentary sequence	HLF, Phase 1 (deep aquifer)	Single	894	m	Based on "Phases 1-3 Leach Pad Layout and Ore Heap Plan, Drawing 6", GRE, April 2014
	HLF, Phase 2 (deep aquifer)	Single	947	m	
	HLF, Phase 3 (deep aquifer)	Single	657	m	
	Total dilution width (deep aquifer)	Single	1040	m	
Hydraulic Gradient	Shallow Aquifer	Single	0.08		Calculated from existing site investigation data.
	Deep Aquifer	Single	0.11		
Receiving Watercourses					
Low flow in receiving water	River Arpa	Triangular	2, 2.5, 3	m3/s	Based on estimated 5%ile low flow, Amulsar ESIA surface water baseline
Width of discharge zone	HLF	Single	900	m	Based on "Phases 1-3 Leach Pad Layout and Ore Heap Plan, Drawing 6",

APPENDIX C
Model Results

GoldSim model outputs showing impacts on surface water quality in the pathways assessed. Graphs show concentrations in the Arpa River calculated by the GoldSim model and at the point of discharge to the stream southwest of the HLF.

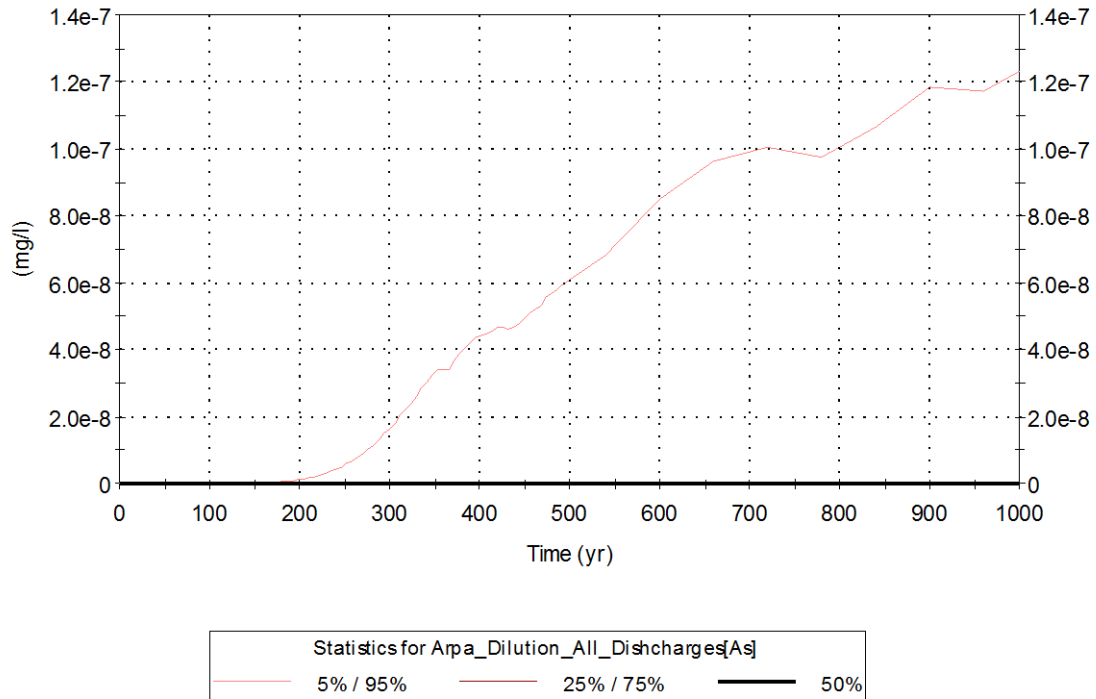## Concentrations in Surface Water after Discharge to the Arpa River

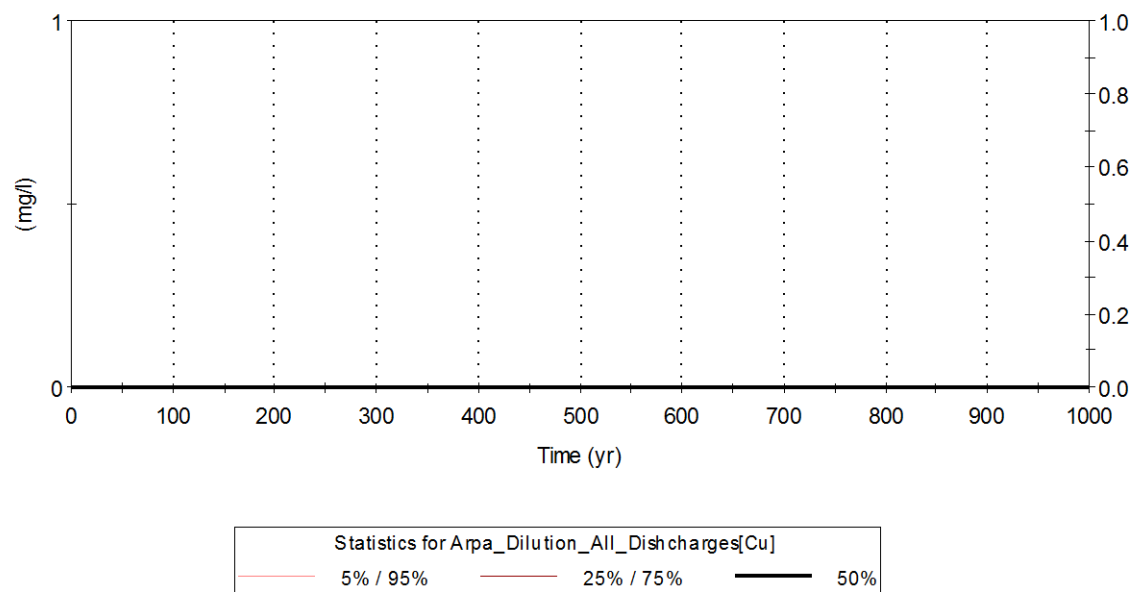*Figure 1: Arsenic Concentration, Discharge to the Arpa River Scenario 2*

Figure 2: Copper Concentration, Discharge to the Arpa River Scenario 2
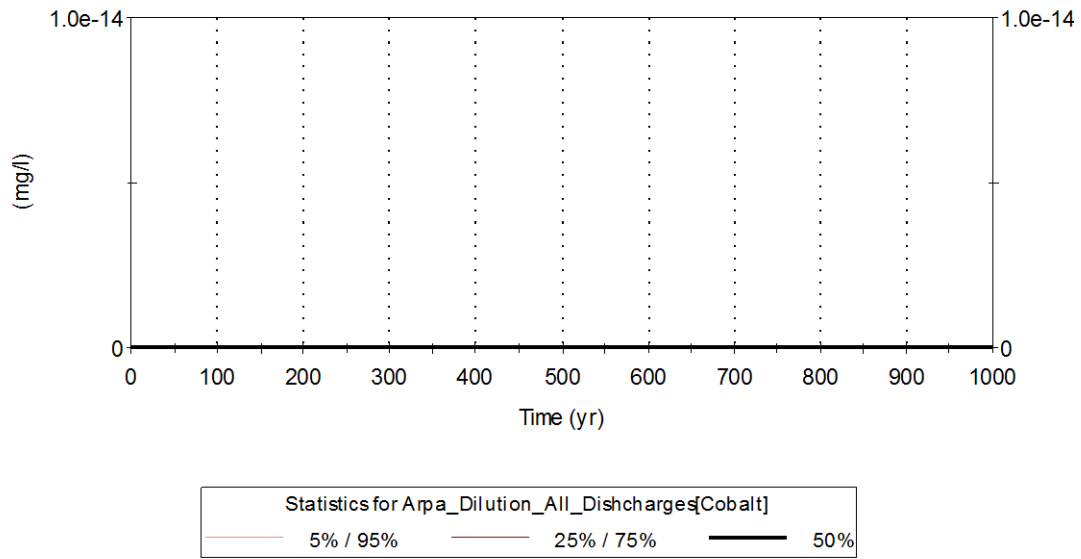
Figure 3: Cobalt Concentration, Discharge to the Arpa River Scenario 2
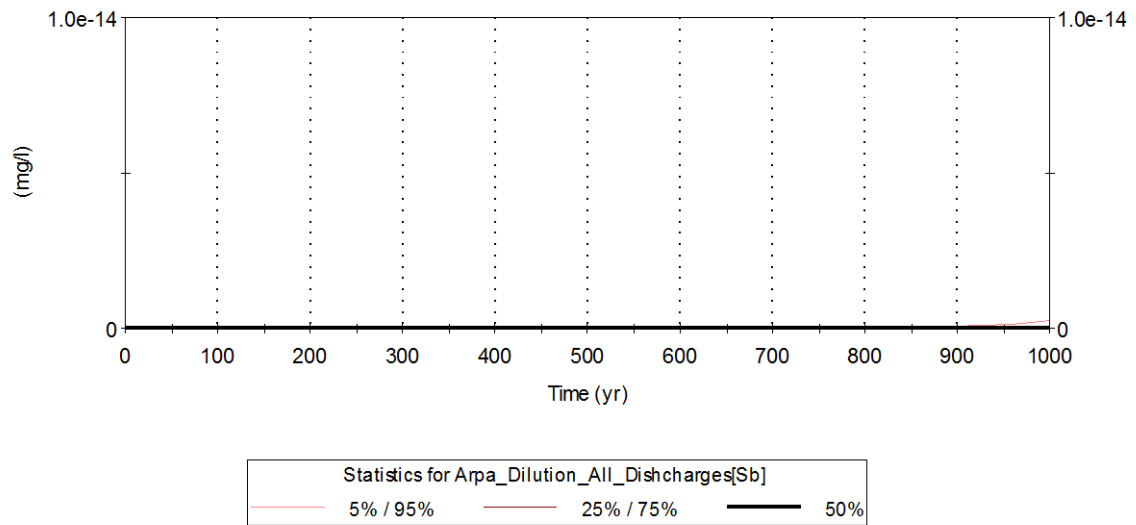
Figure 4: Antimony Concentration, Discharge to the Arpa River Scenario 2
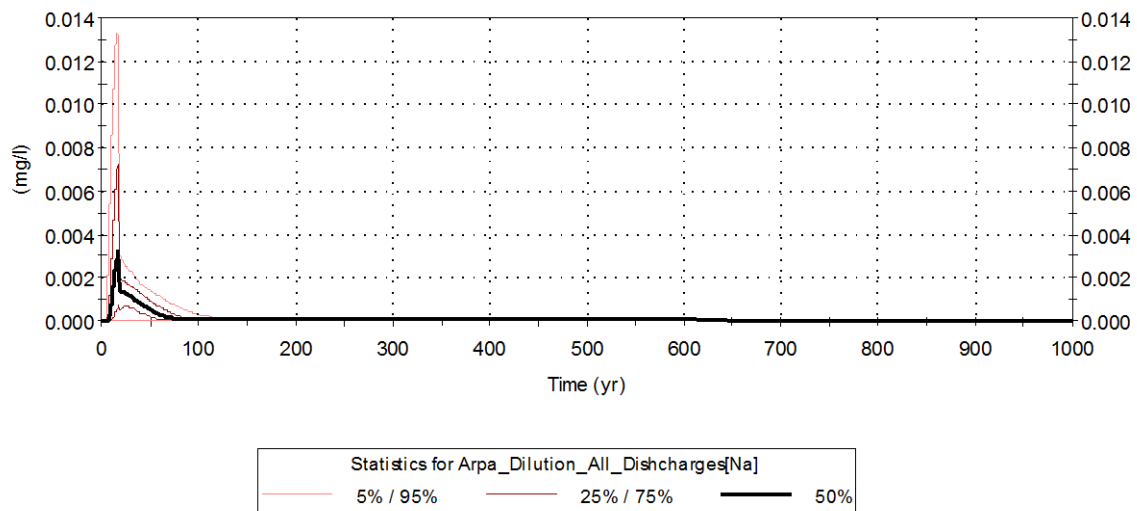
Figure 5: Sodium Concentration, Discharge to the Arpa River Scenario 2
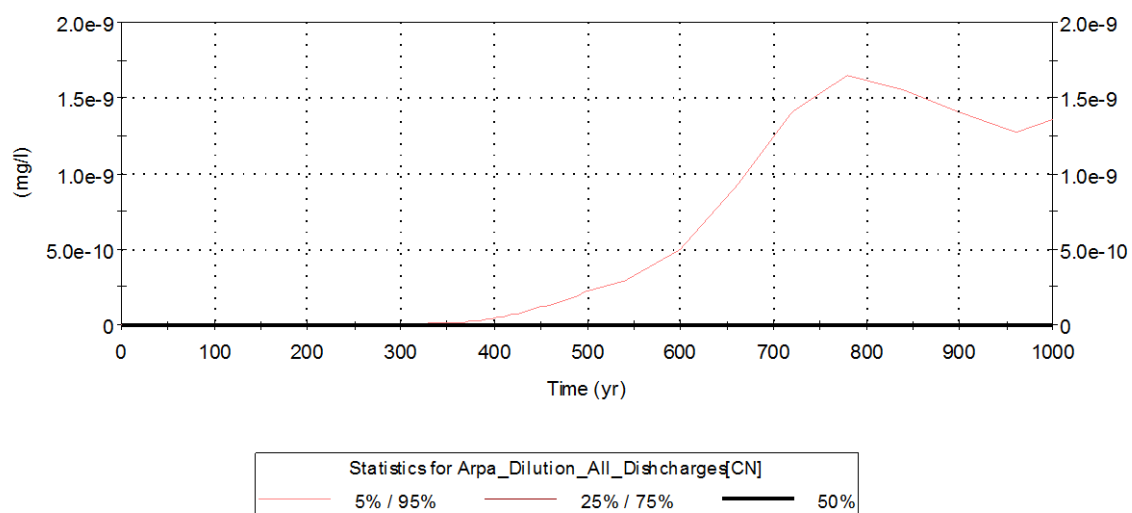
Figure 6: Cyanide Concentration, Discharge to the Arpa River Scenario 2
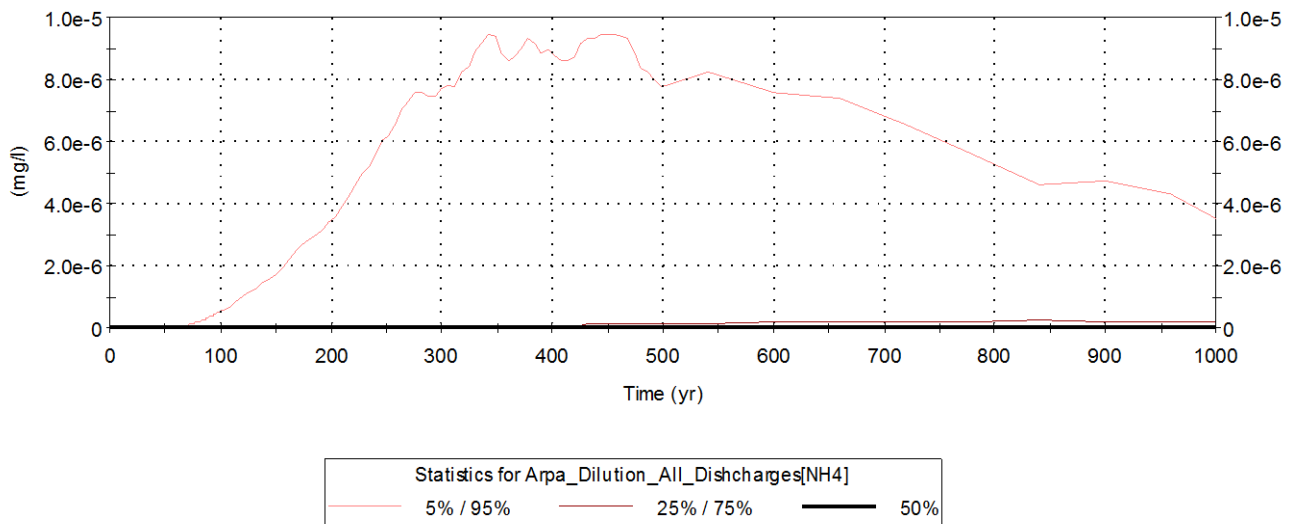
Figure 7: Ammonium Concentration, Discharge to the Arpa River Scenario 2
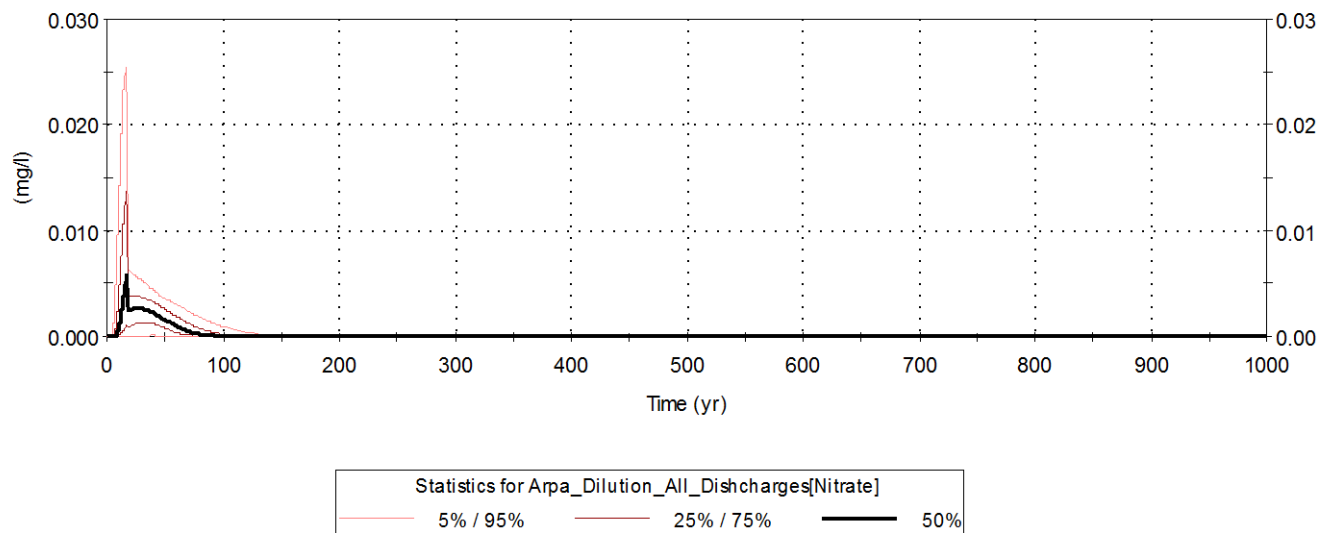
Figure 8: Nitrate Concentration, Discharge to the Arpa River Scenario 2

Concentrations in Discharge to the HLF Stream
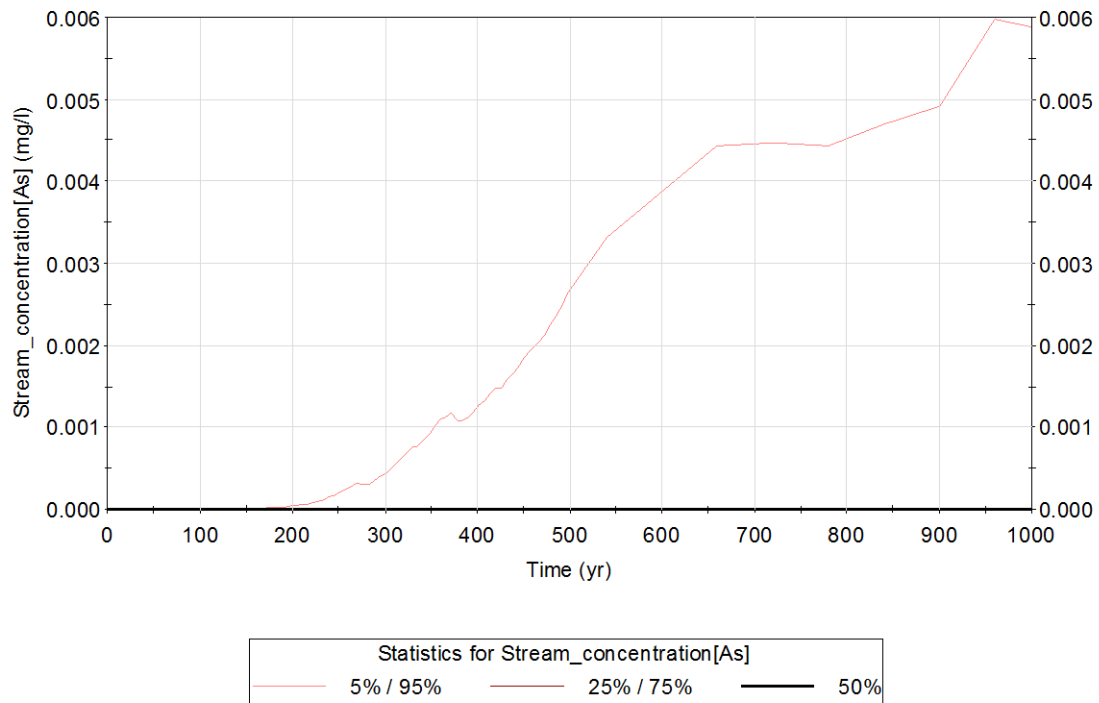
Figure 9: Arsenic Concentration, Discharge to HLF Stream
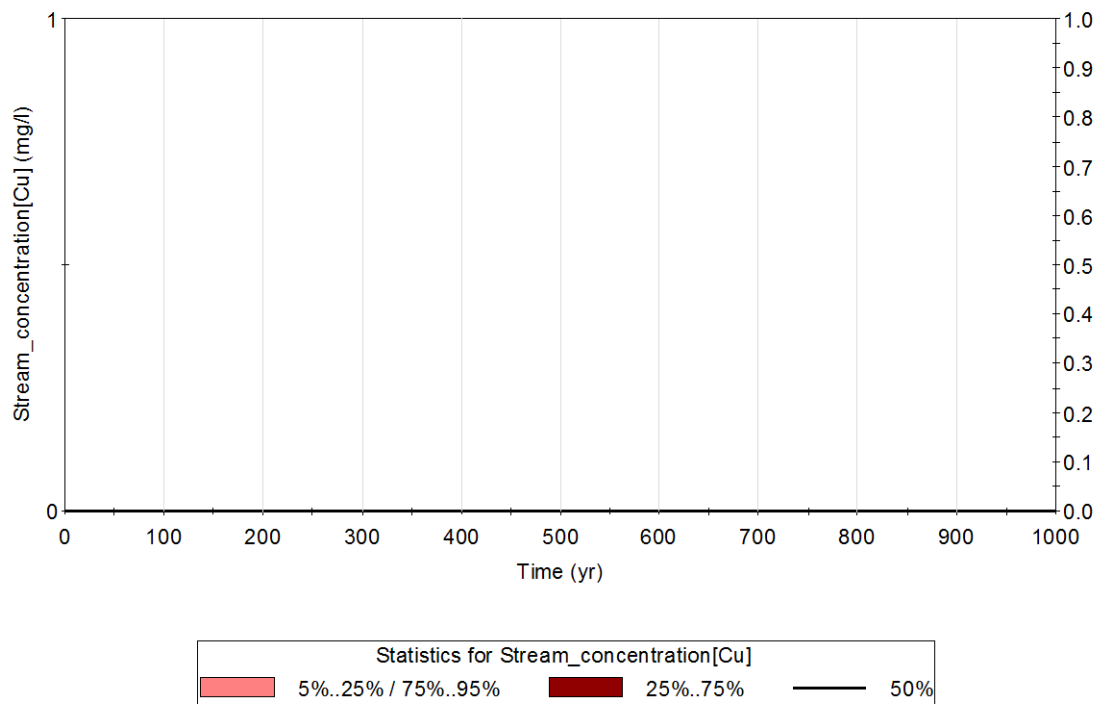
Figure 10: Copper Concentration, Discharge to HLF Stream

Figure 11: Cobalt Concentration, Discharge to HLF Stream
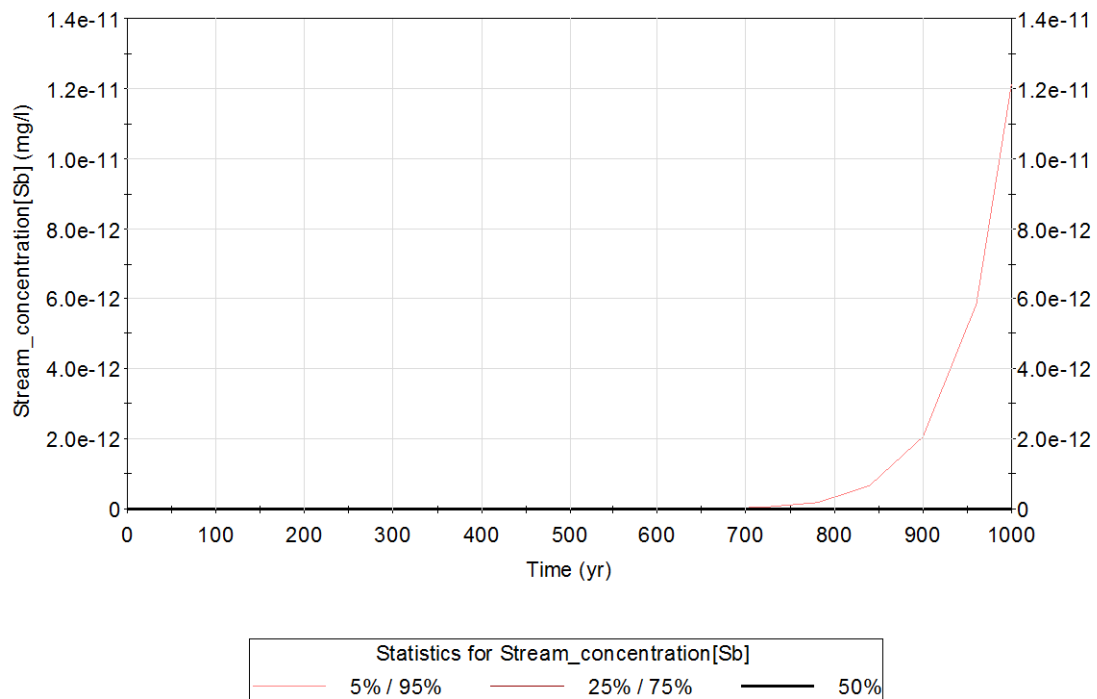
Figure 12: Antimony Concentration, Discharge to HLF Stream

Figure 13: Sodium Concentration, Discharge to HLF Stream
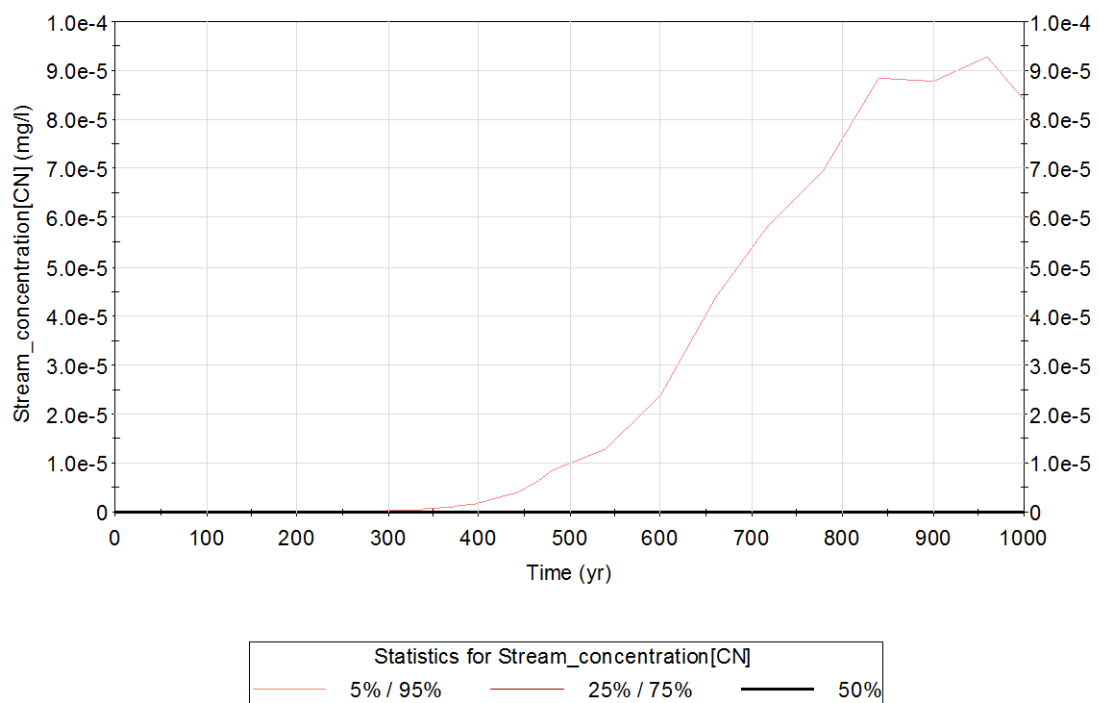
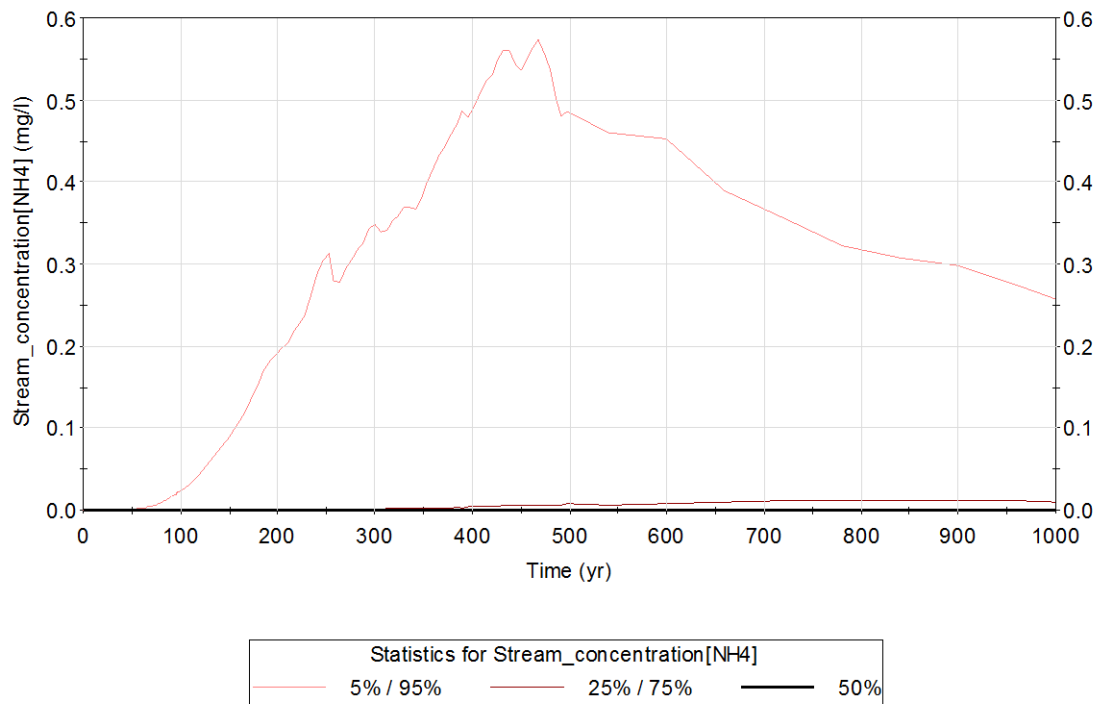*Figure 14: Cyanide Concentration, Discharge to HLF Stream*

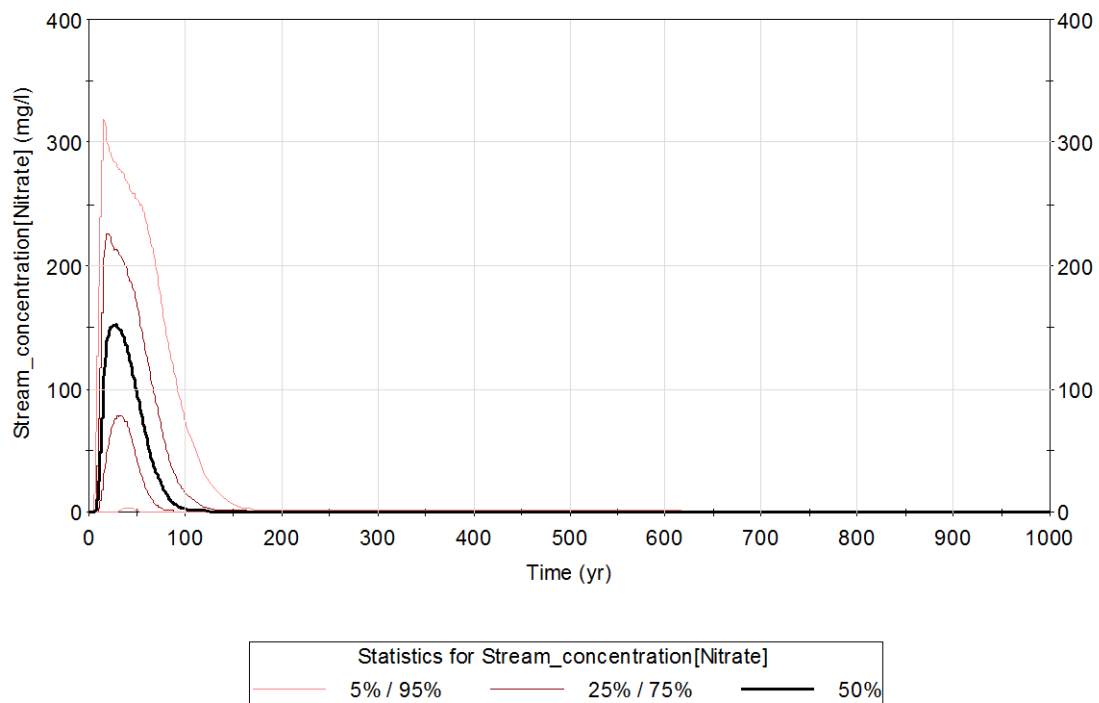*Figure 15: Ammonium Concentration, Discharge to HLF Stream*

Figure 16: Nitrate Concentration, Discharge to HLF Stream

APPENDIX D

Electronic Copies of GoldSim Models

As a global, employee-owned organisation with over 50 years of experience, Golder Associates is driven by our purpose to engineer earth's development while preserving earth's integrity. We deliver solutions that help our clients achieve their sustainable development goals by providing a wide range of independent consulting, design and construction services in our specialist areas of earth, environment and energy.

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