Prediction of Seepage from a Platinum-Group Metals Tailings Storage Facility

Koovila Naicker and Keretia Lupankwa
Golder Associates, South Africa

ABSTRACT

The Platreef mineralized belt is located in the Northern Limb of the Bushveld Igneous Complex (BIC) in South Africa's Limpopo Province and hosts the highest concentration of Platinum Group Elements (PGE) and gold in Africa. The BIC comprises of the mafic-ultramafic Rustenburg Layered Suite (RLS) that is separable into five distinct compartments one of which is the Northern or Potgietersrus limb (length of 110km and a width of 15 km). The Critical Zone of the RLS is dominated by pyroxenite, anorthosite, norite and olivine- rich rocks and is characterized by regular layering of chromite and PGE-mineralization. The Platreef is correlated to the Upper Critical Zone with chromitites and PGE rich zones being direct correlates of the Upper Group 2 and Merensky Reefs. Sulphide minerals: Pyrrhotite [Fe_7S_8], pentlandite [$(Ni,Fe)_9S_8$], chalcopyrite [$CuFeS_2$], millerite [NiS], troilite [FeS], pyrite [FeS_2] and cubanite [$CuFe_2S_3$] occur in the BIC.

Geochemical characterisation conducted on the Upper Critical Zone lithologies involved static and kinetic testwork (by use of humidity cells) for ore, wall rock, waste rock and tailings material. The geochemical characterisation data was use to assess groundwater impacts from the proposed Tailings Storage Facility (TSF) from the Project.

Selected ore, hanging wall and footwall units or 28% of samples representing the underground mine unit classified as likely (sulphide sulphur >0.3% and Net Potential Ratio <1) acid generation potential. The Platreef Rougher tailings material was found to be non-acid generating due to low sulphide-sulphur content (0.015%). Humidity cell tests (HCT) results indicated low metal loading rates for tailings and rock samples after two weeks. Seepage mass load ranges were modeled as a function of tailings material properties, Goldsim water balance and HCT results and used as source-term input in the solute-transport model to assess impacts to the groundwater regime.

Keywords: Bushveld Igneous Complex, platinum tailings, humidity cell, source-term; groundwater

INTRODUCTION

A geochemistry prefeasibility study was conducted to assess the risk of Acid Rock Drainage (ARD) and Metal Leaching (ML) associated with a PGE project, as part of the Environmental and Social Impact Assessment. The proposed Tailings Storage Facility (TSF) presents unique specific water quality risks during operational and post closure phases of the TSF, partly associated with the ARD/ML potential of the tailings material. The geochemistry study aimed to quantify these risks based on the Goldsim TSF water balance, static and kinetic (humidity cell test - HCT) results from laboratory generated tailings material. The source-term developed for the proposed TSF was used as inputs in the Feflow solute transport model.

BACKGROUND

The Project includes a recently discovered underground deposit of thick PGE-nickel-copper-gold mineralization, in the Northern Limb of the Bushveld Igneous Complex (BIC). The PGE deposit will be extracted using conventional underground mining methods over a period of 30 years. Tailings material and residue (from the water treatment plant) will be produced at a rate of 3.81 million (dry) tpa.

Geology

Archaean rocks belonging to the western end of the Pietersburg Greenstone Belt and associated granitoid gneisses constitute the oldest rocks (3.6 -2.5 Ga) in the area surrounding the Project and include:

- Goudplaats- Hout River Gneiss Suite: banded migmatitic gneiss with leucocratic to dark-grey granites and pegmatites;

- Turfloop Granite: Fine to medium grained, grey and pink granodioritic /monzogranitic;

- Lunsklip Granite: Medium to coarse grained or porphyritic pink to grey syenogranite; and

- Uitloop Granite: Medium grained to porphyritic reddish alkali granite.

The Transvaal sequence overlies the Archaean basement greenstones and granitoids to the east. The BIC intrudes the Transvaal Supergroup and is the world's largest mafic layered intrusion (Cawthorn and Boerst , 2006). The BIC is subdivided into three suites namely, the mafic-ultramafic Rustenburg Layered Suite (RLS), the Lebowa Granite Suite and the Rashoop Granophyre Suite (Figure 1). According to (Cawthorn and Boerst, 2006), the RLS typically consists of the following zones from bottom to top:

- The Marginal Zone: Comprised of generally finer grained rocks and contains abundant xenoliths of country rocks. The main rock type is norite. This unit is not always present.

- Lower Zone: Dominated by pyroxenite and harzburgite. Completely absent in some areas.

- Critical Zone: Dominated by pyroxenite, anorthosite, norite and olivine- rich rocks. It is characterized by regular rhythmic layering of cumulus chromite and PGE mineralization.

- Main Zone: Consists of norite and gabbronorite, minor mottled anorthosite and pyroxenite.

- Upper Zone: consists of magnetite gabbronorite, olivine-magnetite gabbronorite and olivine-apatite diorite. It is characterized by vanadium mineralization.

The RLS is separable into five distinct compartments known as the Western Limb, the far- Western Limb, the Eastern Limb, the Northern or Potgietersrus limb and the Southern Limb. The northern limb is a slightly sinous, north-west striking sequence of igneous rocks (dip 40° to 45° W) with a length of 110km and a width of 15 km (Kinnard, 2004).

The RLS hosts major deposits of PGEs, chromite ($FeCr_2O_4$), vanadium (V) and nickel (Ni), with minor copper (Cu), gold (Au) and silver (Ag) mineralization. The PGEs (mainly platinum [Pt] and palladium [Pd]) are hosted in three major mineralized horizons, namely: Upper Group 2 (UG2) chromitite and Merensky reef in the Critical Zone of the western and eastern limbs; and the Platreef of the northern limb (Cawthorn and Boerst 1999).

Six separate mineralized zones occur throughout the Upper Critical Zone of the Project. Cyclic units T1M and T2 are the best developed and show good continuity. The other mineralized zones contain erratic mineralization and disrupted continuity. Much thicker than the normal Merensky Reef, the Turfspruit T1M and T2 ore zones are much less affected by contamination from sedimentary xenoliths than most of the other units in the footwall. The Pseudo and UG2 Reefs found stratigraphically below the TCU usually are less continuous, being disrupted by sedimentary xenoliths and associated contamination/alteration. Sulphide minerals that occur in the BIC include, Pyrrhotite [Fe_7S_8], pentlandite [$(Ni,Fe)_9S_8$], chalcopyrite [$CuFeS_2$], millerite [NiS], troilite [FeS], pyrite [FeS_2] and cubanite [$CuFe_2S_3$] Schouwstra and Kinloch, 2000.
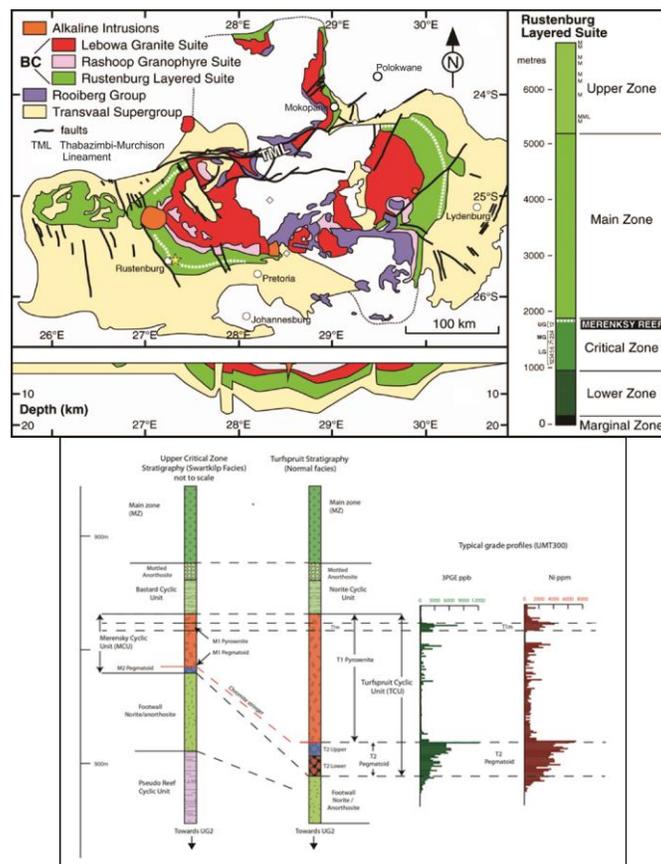
Figure 1 a) Simplified geological map of the BIC showing RLS b) Revised stratigraphy for the Project area

The stratigraphic sequence in the Project area have been revised following a recent discovery of a cyclic magmatic (Figure 1b) sequence consists of apparently uncontaminated pyroxenite, harzburgite, and dunite in the upper part of the Platreef (Grobler et al., 2012). This sequence has been termed Turfspruit Cyclic Unit (TCU) and correlated to the Upper Critical Zone of the Western and Eastern Limbs. Mineralization in the TCU shows generally good continuity and is confined to pegmatoidal orthopyroxenite and harzburgite.

In the project area, sulphides occur typically as disseminated grains, varying in size from a 5 μm to 2 cm blebs. The blebs occur mainly in serpentinized peridotite and calc-silicate rocks. The base metal sulphides also occur in places as intergrowth with secondary silicates (alteration assemblages dominated by talc, tremolite and serpentine) and in secondary hydrothermal veins traversing primary or secondary silicates.

Climate

The project area is situated in the Central Bushveld bioregion in the South Africa, with an altitude of approximately 1100 m above mean sea level. The project area lies within a water scarce region. The available information indicates only 10.5 years of combined rainfall data from weather stations in the area. The area falls in a summer rainfall climate region with the peak rainfall period from November to February when the area receives ~70% of the annual average rainfall (Figure 1). The annual minimum and maximum temperatures are 13.0 °C and 26.3 °C (average temperature is 19.7 °C). The area falls in evaporation zone 1C (Midgely et al, 1990). The mean annual S-pan evaporation is 1 700 - 2 000 mm/a.
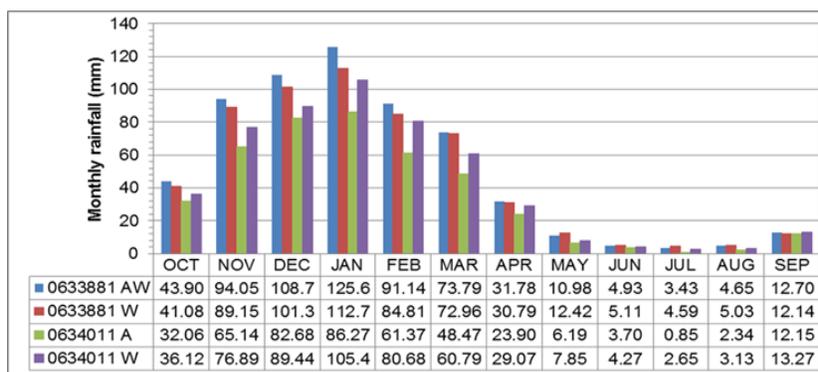

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
0633881 AW	43.90	94.05	108.7	125.6	91.14	73.79	31.78	10.98	4.93	3.43	4.65	12.70
0633881 W	41.08	89.15	101.3	112.7	84.81	72.96	30.79	12.42	5.11	4.59	5.03	12.14
0634011 A	32.06	65.14	82.68	86.27	61.37	48.47	23.90	6.19	3.70	0.85	2.34	12.15
0634011 W	36.12	76.89	89.44	105.4	80.68	60.79	29.07	7.85	4.27	2.65	3.13	13.27

Figure 2 Average monthly rainfall for rainfall stations in study area

Water Balance

A water balance model for the proposed TSF was constructed in Goldsim on a daily time step. Gauge number 0633881 (MAP=572 mm) was used. Runoff factors were informed by average runoff for the quaternary catchment (Middleton et al., 2009). Design criteria for the TSF, used in the water balance modeling are summarized in Table 1. The simulated water balance results are provided in Figure 3 and that water balance is a deficit water balance.

Table 1 Design criteria for proposed TSF

Parameter	Design Specifications
Total storage capacity	135 000 000 tonnes (over 36.5 years)
Deposition rate	3 800 000 dry tonnes/annum
Footprint area	250 ha (Basin area 203 hectare)
Slurry density	50% solids by mass
Tailings SG	3.13
Deposition method	Spigot
Decant method	Barge

Figure 3 TSF water balance diagram

TAILINGS MATERIAL CHARACTERISATION

Rougher tailings material was received from a scoping study batch test done on a composite sample representing the current LOM blend: 15%T1; 42.5%T2U and 42.5%T2L. The Rougher tailings sample comprised 90-95% of the final tailings material. Metallurgical lock cycle test results for the final tailings indicated; particle size distribution of 80% passing 75µm and total S (0.25%), Cu (0.06%) and Ni (0.14%) concentration. The assay results for the Rougher tailings (open circuit) sample decreased by half for S, Cu and Ni. The assumption that the Rougher tailings sample tested is representative of the final tailings that will be produced is unknown and represented a limitation of the geochemical prefeasibility assessment.

Static Results

Acid base Accounting

Acid Base Accounting (ABA) results for the Rougher tailings sample is provided in Table 2. The circum-neutral paste pH (6.8) indicates the short-term pH of pore fluid in the sample and correlates with the low sulphide-sulphur (0.015%) concentration recorded.

Table 2 ABA results for Rougher Tailings

Parameter	Unit	Value
Paste pH	-	6.8
Total C	%C	0.16
Total S	%S	0.10
Sulphide-S	%S	0.015
Sulphate-S	%S	0.020
Neutralization Potential (NP)	kg CaCO$_3$eqv/t kg	5.99
Sulphide Acid Potential (SAP)	kg CaCO$_3$eqv/t kg	1.56
Sulphide Neutralizing Potential Ratio (SNPR)	ratio	3.84

X-Ray diffraction

Table 3 summarizes the mineralogical composition of the Rougher tailings. Silicate minerals dominate the tailings mineralogy and is consistent with the Platreef geology which is mainly mafic-ultramafic rocks, consisting of > 90% mafic minerals (enstatite, diopside, augite, actinolite, lizardite, biotite, chlorite) and anorthosite, which is felsic. Pyrite and/or pyrrhotite were not detected due to the limit of detection (<0.5%)

Table 3 Mineralogical composition (wt%) results of Rougher tailings material

Weathering Rate[1]	Mineral Name	Formula	Rougher Tailings (%)
Fast Weathering	Biotite	$KMg_{2.5}Fe^{2+}_{0.5}AlSi_3O_{10}(OH)_{1.75}F_{0.25}$	12
	Chlorite	$(Mg,Fe2+)5Al(Si3Al)O10(OH)8$	6.7
	Diopside	$CaMgSi_2O_6$	6.2
Intermediate Weathering	Enstatite	$Mg_2Si_2O_6$	45
	Actinolite	$Ca2(Mg,Fe2+)5(Si8O22)(OH)2$	5.3
Slow weathering	Lizardite	$Mg_3(Si_2O_5)(OH)_4$	3.6
	Talc	$H_2Mg_3(SiO_3)_4$	13
	Plagioclase	$Na,Ca)(Si,Al)_4O_8$	7.8
Resistant	Quartz	SiO_2	0.93

[1] *after SRK, 1989; Sverdrup, 1990; SRK, 1998*

Whole rock analysis

The extent of element enrichment in Rougher tailings was assessed with the aid of the geochemical abundance index (GAI), which compares the measured concentration of a particular element with the estimated median crustal abundance (INAP, 2010). Elements with a GAI value ≥ 3 (12 to 24 times the median crustal abundance) included Cr, Pt, Mo and Te and are of potential contaminants of concern (PCOC) in the tailings material.

Supernatant Analysis

The supernatant (process) water of the Rougher Tailings sample was separated from the tailings solid for analysis. The supernatant was found to have alkaline pH (8.52) and TDS of 202 mg/l. Chemical constituents contributing to the dissolved salt load included Cl, Alkalinity, NO_3, SO_4, Ca, Mg, Na, K and Si. Trace metals that are likely PCOC are B, Ba and Mo (concentrations > 0.1 mg/l). The dissolved Mo concentration (0.25 mg/l) observed for the tailings supernatant was in the same order as the distilled water leach (0.13 mg/l) and acid leach Mo (0.66 mg/l) concentration.

Kinetic Results by humidity cell method

The ASTM D 5744-96 method (Standard test method for accelerated weathering of solid material using a modified humidity cell) covers the procedure that accelerates the natural weathering rate of geologic materials. For the initial (week 0) flush 750 ml of distilled water was used according to MEND (2009) HCT method. The HCT (week 0) TDS was recorded as 423 mg/l (Figure 4a) and decreases in first two weeks due to the flushing of historically oxidized ARD and weathering products. Loading rates of major and trace metals followed the same trend and thereafter varied slightly with small changes in pH, due to solubility changes. An increase in the week 12 Ni loading (Figure 4b) can be expected as Ni is released as pentlandite is oxidized/weathered.
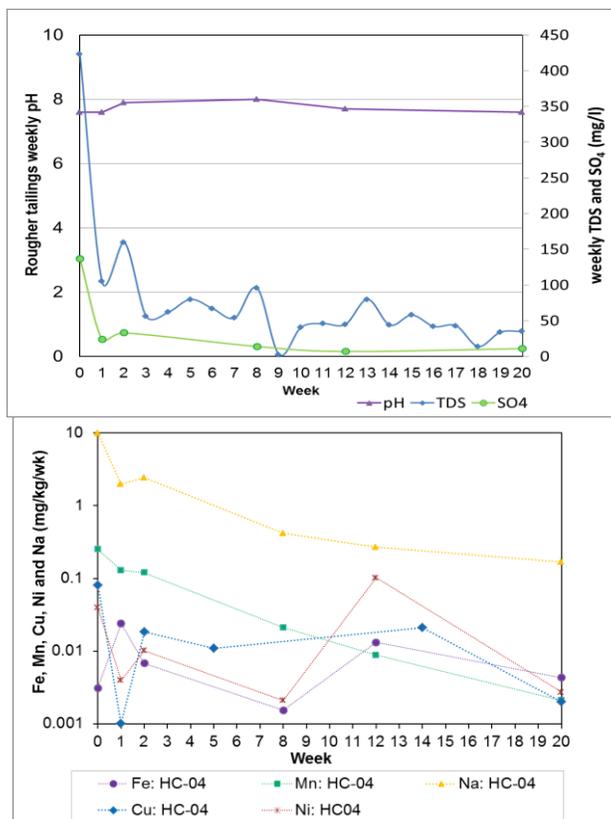
Figure 4   Rougher tailings HCT results: a) Variation of pH, TDS and SO₄ b) Weekly loadings Fe, Mn, Cu, Ni and Na

TSF SOURCE-TERM DEVELOPMENT

The TSF source-term model consisted of two key components: a flow module and a geochemical module supported by the TSF water balance and humidity cell results.

Flow Module

The water balance simulations of the average seepage to ground water (271 m³/day, Figure 3) provided guidance on the average vertical seepage emanating from the base of the proposed TSF. Staged development curves (tonnes/area)) for the proposed TSF was sourced from the TSF capacity design analysis. The pool and wet beach seepage volumes (low, likely and high case) were modeled dynamically; using the surface area at the time of calculation.

The modeled seepage volume from the TSF base and entering groundwater is provided in Figure 5a-b. The predicted seepage volumes under post-closure are significantly lower than during operational phase. Seepage from the TSF at post-closure is driven by rainfall infiltration (unsaturated flow processes) and evaporation. The following assumptions were made for the flow module:

- Dry conditions are expected for the dry beach and TSF wall resulting in runoff (only and no seepage flow contribution from these areas. The assumption is based on the water balance model that assumed that no deposition occurs on the dry beach;

- The saturated conditions at the pool section are associated with the permanent head of water at the pool and moist conditions associated with the wet beach. In practice, the wet beach moves as the deposition location changes resulting in higher infiltration losses and a gradual increase in return water followed by a sudden reduction;

- The pool (and wet beach) area varies from 2-5% (average case 2.4%) of the total area, after evaporation effects. Seepage from pool and wet beach was calculated by applying the Darcian equation with K= $1e^{-7}$ m/s (based on laboratory measurements on final tailings – fine fraction);

- The calibrated groundwater flow model provided the average recharge of 1% or $1.24e^{-05}$ m/d based on average low aquifer transmissivities ~1.0×10^{-3} m^2/d in the Turfloop Granite underlying the TSF site The contact zone between diabase dykes and the host Turfloop Granite rocks at the TSF site, are clayey and non-water bearing thus assumed not to be a conduit;

- It is assumed that approximately 95% of the vertical seepage is captured by the under drainage seepage collection system. and downstream cut--off drains.; and

- The recedence of the phreatic surface was assumed to be 10 years. For closure to post-closure phases, infiltration rates of 0.5-1.5% MAP (without cover) were assumed for the dry TSF.

Geochemical Module

Kinetic testing (HCT method) is not a direct indication of on-site drainage chemistry but simulates accelerated metal-mine waste material weathering rates. The difference between actual field conditions and HCT can differ by at least an order of magnitude. Liquid to solid ratios were used for field scaling evaporation in the project area is high.
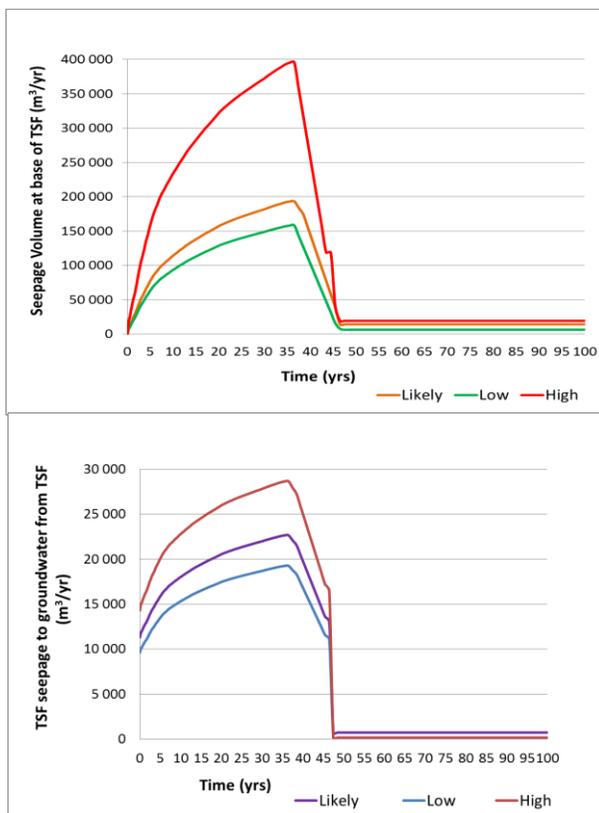
Figure 5   Modeled seepage flow volumes a) from the base of proposed TSF   b) entering groundwater

Equilibrium-speciation modeling assessed mineral solubility controls on the weekly HCT seepage under oxidizing conditions (pe 2-5) and gas equilibration). Ferrihydrite - $Fe(OH)_3$ and Gibbsite - $Al(OH)_3$) were found to control dissolved Fe and Al concentrations in the seepage. The following assumptions were made for the geochemical model and source-term development:

- Operational input seepage qualities were assumed to remain constant over time i.e. the measured supernatant TDS of 202 mg/l was used without considering evaporation and recirculation effects;

- Post-closure field capacity of 15-22% (average 20%) was assumed for scaling HCT data. The HCT utilized 500 ml deionized rinse water weekly (except week 0) for 1000 g Rougher tailings sample (1:2 liquid: solid ratio). Based in assumed field capacity the average weekly TDS concentration (77 mg/l, Figure 4a) was scaled up by factor 2.3, 2.5 and 3.3 for the low, likely and high case seepage TDS concentration;

- Salt depletion rate (~7%) was estimated from the week 0 (high case) TDS and 77 mg/l; and

- The TSF seepage quality interaction with the underlying weathered zone does not change the seepage quality that is reporting to the groundwater.

Seepage concentration and TSF source-term mass loading ranges to ground water is shown in Figure 6a-b. The sharp increase in the modeled post-closure high case TDS concentration (256 mg/l)

is based on the 15% m/m moisture content; and to a lesser extent from ARD products generated from trace sulphide minerals (0.015%) as phreatic surface recedes and the TSF dries out.

CONCLUSION

A source-term has been developed for platinum TSF by integrating; PFS engineering design, Goldsim model simulation results, and geochemical characterisation results. The source-term TDS concentration time series was input into the solute transport groundwater model to quantify impacts. Several assumptions were made during the geochemical assessment and source-term development; including limited representativeness of the final tailings, and need to be addressed in the feasibility assessment.
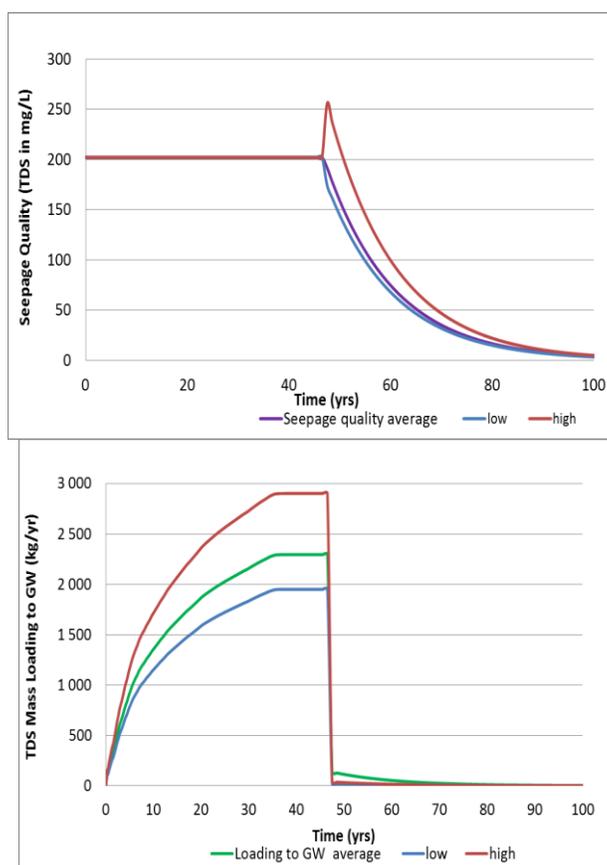

Figure 6 Proposed TSF source-term seepage a) TDS concentration and b) TDS mass loading ranges

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