TECHNICAL MEMORANDUM

DATE January 28, 2019 **Project No.** 1788500.002 TM02 Rev1

TO Ms Vicky Peacey, Resolution Copper Mining

CC Greg Ghidotti, Matt Wickham, RT G&I

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RESOLUTION COPPER MINING – ALTERNATIVE 5

PEG LEG WATER BALANCE – ADDITIONAL BADCT TECHNOLOGIES TO REDUCE SEEPAGE

1.0 INTRODUCTION

A draft EIS site-wide water balance (SWWB) model was developed for the Peg Leg Tailings Storage Facility (TSF) in Appendix G of the Peg Leg Alternative 5 Report (Golder 2018). The water balance was for the 41-year planned operating life of the Peg Leg TSF under steady-state conditions. The water balance in Golder's June 2018 report incorporated Level 1 seepage controls and largely used pump back wells to collect seepage water in excess of what could be transmitted by the expected aquifer characteristics. This technical memorandum describes an evaluation of the GoldSIM model seepage results incorporating additional seepage controls and Best Available Demonstrated Control Technologies (BADCT) such as "thin lift" deposition. The additional BADCT controls include modifying the conventional thickened tailings deposition to thin lift deposition when sufficient surface area becomes available for this method of tailings deposition to function.

In addition, this technical memorandum presents supplemental modeling to quantify long-term post-closure seepage (drain down seepage estimates) based on analytical models presented by McWhorter and Nelson (M&N) (1978, 1979, and 1980). The closure model includes the addition of store and release closure covers on the non-potentially acid-generating (NPAG) and potentially acid-generating (PAG) facilities and a drain down estimate to quantify the number of years after operations to expect drain down flows to occur.

2.0 ALLOWABLE SEEPAGE BASED ON WATER QUALITY

Montgomery and Associates (M&A) estimated the maximum allowable seepage rate at Peg Leg based on water quality/geochemistry considerations (M&A 2018). Their estimate allows about 261 acre-feet per year (acre-ft/yr) of seepage based on meeting selenium concentrations (Se) and 355 acre-ft/yr based on allowable nickel (Ni) concentrations. The allowable operating and closure values from M&A are summarized in Table 1.

Table 1: Preliminary Estimates of Maximum Allowable Uncollected TSF Seepage: Years 0–245 after Start of Mine (after M&A, December 20, 2018)

Limiting Constituent	Alternative 2 Near West (af/yr[3])		Alternative 3 Near West (af/yr)		Alternative 4 Silver King (af/yr)		Alternative 5 Peg Leg (af/yr)		Alternative 6 Skunk Camp (af/yr)	
	Groundwater	Surface Water	Groundwater	Surface Water	Groundwater	Surface Water	Groundwater	Surface Water	Groundwater	Surface Water
First	160 (Se)	3 (Se)	133 (Se)	3 (Se)	146 (Se)	6 (Se)	261 (Se)	370 (Se)	413 (Se)	329 (Se)
Second	413 (Cd)	66 (Cu)	394 (Tl)	71 (Cu)	270 (Sb)	83 (Zn)	355 (Ni)	682 (Cu)	873 (Tl)	1643 (Cu)

Notes:
[1] Allowable groundwater seepage assumes groundwater concentrations at downgradient aquifer monitoring location will not exceed Arizona Department of Environmental Quality Numeric Aquifer Water Quality Standards (Arizona Administrative Code - Title 18, Ch. 11, Art. 4, Sup. 16-4, 2016)
[2] Allowable surface water seepage assumes surface water concentrations at downgradient surface water monitoring location will not exceed half of available concentration between current background concentrations and Arizona Department of Environmental Quality Water Quality Standard for "Aquatic and wildlife warm" (A&ww) water with chronic exposure (Arizona Administrative Code - Title 18, Ch. 11, Sup. 16-4, 2016)
[3] af/yr = acre-feet per year

Maximum allowable seepage to comply with Arizona Department of Environmental Quality (ADEQ) water quality standards

It is noted that the allowable water quality seepage is considerably lower than the aquifer conveyance capacity of 1,337 acre-ft/yr restriction used in Golder's original water balance.

3.0 SEEPAGE MODELS

To estimate the operation and closure seepage, Golder used a combination of the previously developed GoldSIM model, an analytic drain down solution presented by M&N, and added a constant cover infiltration value during closure.

- At closure for both conventional and thin lift deposition, Golder added the infiltration values from the M&A (2008) cover seepage estimates (see Section 3.1).
- For conventional deposition described in Golder's June 2018 report, we used the previously developed GoldSIM model and estimated the drain down time period based on M&N.
- For thin lift deposition, Golder modified the previously developed GoldSIM model during operations and adjusted the drain down time period based on M&N.

The following sections present the model assumptions, changes, and results.

3.1 Cover Seepage Estimate

The cover infiltration was estimated by M&A based on a March 2016 cover study by KCB (2016). Infiltration values through a store and release cover are as listed below. The remaining precipitation is either evaporated, used by vegetation, or contributes to runoff.

- PAG impoundment: infiltration = 1% of precipitation (17 acre-ft/yr)
- NPAG impoundment: infiltration = 2% of precipitation (121 acre-ft/yr)
- All NPAG dams: infiltration = 7% of precipitation (30 acre-ft/yr for PAG dam and 66 acre-ft/yr for NPAG dam)

For Peg Leg, the total cover infiltration is estimated to be 234 acre-ft/yr. Comparison of this value to the allowable values estimated by M&A indicates that the maximum allowable drain down is 27 acre-ft/yr, indicating that drain down would need to be practically complete before seepage recovery wells could be turned off.

3.2 Application of M&N drain down model

The analytical solutions developed by M&N (1978, 1979, 1980) were used to estimate the time period required for the various stages of tailings drainage described in the three companion papers by M&N. The stages of TSF seepage, as outlined in the M&N papers, are summarized as follows (quotations are from M&N 1979, 1980, and 1978, respectively):

- Stage 1: “During this stage a wetting front advances downward through the partially saturated underlying foundation material. Above the wetting front, the material may or may not be saturated.” If the unsaturated zone in the foundation is 34 feet thick and has a low moisture content, Golder’s estimate for this period based on the M&N approach for conventional deposition is about 13 years. Stage 1 would extend at least 31 years for the thin lift alternative.
- Stage 2: “When the wetting front contacts either an impervious stratum or the phreatic surface of the aquifer, a groundwater mound will develop and rise toward the Impoundment. Stage II represents the time interval during which the mound is developing.” Based on the M&N approach, Golder’s estimate for conventional deposition is that Stage 2 will require from year 13 to year 28 to occur. For thin lift deposition, the mound would continue to rise during operations, but not be complete.
- Stage 3: “After the groundwater model establishes contact with the impoundment, saturated seepage occurs through a mound whose height is defined by the elevation of the impoundment.” Stage 3 involves the lateral spreading of the groundwater mound. Golder’s M&N calculations indicate that for conventional deposition Stage 3 begins at about year 28 and will continue through the remaining operating life of the impoundment (through year 41) with varying seepage rates based on changing permeabilities. Golder notes that the M&N approach does not adjust for the increasing area of the facility and is therefore a simplification.
- Stage 4: “Stage IV begins with the termination of tailings disposal in the impoundment. It is assumed that no more water from any source accumulates in the impoundment during this stage. Thus, seepage during Stage IV causes the impoundment to drain (McWhorter and Nelson, 1978).” Stage 4 is based on vertical seepage only and Golder notes that this assumption is incongruous with the Stage 3 lateral spreading. Based on historic observations of drain down of existing tailings facilities, Golder considers that Stage 4 will begin shortly after operations cease deposition. However, analytically, the M&N solutions indicate that there is a lag time before Stage 4 begins after cessation of operations. A drain down curve is presented in Attachment 1 and summarized in Figures 1 and 2. Golder considers that year 0 of the drain down curve corresponds to year 41 (end of operations).

M&N calculations are summarized in Attachment 1, which provides the supporting calculations along with confirmation that the analytical solution generates the results presented in the referenced M&N papers. Golder notes that the M&N models estimate these theoretical seepage stages for an idealized symmetrical tailings facility located on flat topography, with a constant footprint and ideally with a centralized reclaim pond. The Peg Leg site is not symmetrical, is situated on gradually sloping topography, and its footprint increases with time. Therefore, the M&N approach presents approximate, yet reasonable, results.

3.3 Conventional Deposition (Golder, June 2018 report)

No changes to the previously developed GoldSIM operating model were made under this scenario. Changes to Golder’s GoldSIM model for closure include the addition of a closure cover on the embankments and impoundment areas. With the cover in place, runoff from the closure cover on the embankments is discharged in addition to the runoff from the NPAG impoundment area. The PAG cells also include a store and release cover where the water either infiltrates or evaporates.

Golder had not completed water balance simulations for closure in our June 2018 report, but rather presented a conceptual closure design in Appendix H. The changes listed below address the post-closure water balance.

- Runoff from NPAG beach areas would be conveyed off the NPAG facility and therefore leaves the water balance model. The runoff coefficient from the closed beach area is increased to 0.35 (versus 0.15 during operations and which contributed directly to the TSF reclaim pond).
- The runoff coefficient for the closed embankment would be increased to 0.5 in closure (compared to 0.05 during operations). Runoff is classified as non-contact water and is also discharged from the facility.
- The percent of wet beach is decreased from 70% during operations to 10% at start of closure.
- Closure areas are based on footprint areas presented in Appendix E of the June 2018 report. (Golder notes that dust management areas in Appendix G are at times larger than footprint areas due to the correction for slope areas versus footprint areas and some incremental areas being covered by subsequent tailings construction [thereby the incremental dust management areas are not additive.])
- The difference between the precipitation minus the infiltration and runoff is assumed to be temporary storage within the cover and evaporation.
- We estimated the post-closure drain down time using M&N.

To be consistent with Golder’s June 2018 report, we the NOAA data referenced in our report, which is based on an annual precipitation of 18.7 inches corresponding to the Superior, Arizona, climate station USC00028349. For seepage calculations, this value is conservative compared to the PRISM data used by M&A in their site wide water balance calculations, which indicates a precipitation of about 14 inches per year.

3.4 BADCT Approach – Thin lift deposition

Golder’s June 2018 Peg Leg report identified the potential of using “thin lift” deposition to reduce saturation of the tailings, thereby reducing deposited tailings water content and seepage (see Appendix G, Attachment 3). The thin lift scenario was not quantified in Golder’s previous water balance. Thin lift deposition uses the high evaporation rates in the Arizona desert to reduce the placed water content of the tailings. The drier tailings are also subject to lower permeability and less seepage. Several criteria need to be present for thin lift deposition to be applicable, including sufficiently large areas allowing for slow rates of rise of the tailings surface, high evaporation rates, and low precipitation. Golder’s initial assessment found that the benefits of thin lift deposition occur as early as year 3 and can be implemented after year 15 because sufficient area is available for evaporation. In the modified water balance model, Golder assumed thin lift deposition could be implemented at year 7.

To quantify the potential reduction in seepage rates, Golder incorporated additional BADCT seepage controls into the GoldSIM model for the thin lift deposition, as follows:

- NPAG:
  - Added a year “switch” in GoldSIM to change to thin lift deposition in year 7. The footprint is about 1,195 acres at the time of this changeover.

- Added NPAG_K_{sat}_thin_lift = 9.5 x 10^{-7} cm/sec for seepage calculation after changing to thin lift deposition. The seepage demand equals the NPAG wet beach area x NPAG K_{sat} (the conventional approach used K_{sat} for impounded NPAG tailings = 5 x 10^{-5} cm/sec and a cyclone underflow liner below the NPAG pond = 1 x 10^{-6} cm/sec).
- Prior to the year changeover to thin lift deposition, the footprint for the NPAG facility is lined with either HDPE or a tailings overflow liner with an equivalent K_{sat} = 1 x10^{-8} cm/sec.
- Similar to the conventional model, Golder allows no seepage of standing water against the native subgrade and assume any such area is lined with high-density polyethylene (HDPE).
- Golder modified the pump back assumption to include pumping back all water exceeding the allowable water quality criteria of 261 acre-ft/yr (versus the aquifer capacity of 1337 acre-ft/yr).

- PAG:
  - Included an HDPE or asphaltic membrane liner below the PAG tailings and upstream slopes of the embankments: K_{sat} = 1 x 10^{-8} cm/sec (the conventional approach used 1.8 x 10^{-7} cm/s under tailings and 1 x 10^{-6} cm/sec under pool on top of slime seal).
  - Included bedrock under PAG dam, K_{sat} = 1 x 10^{-7} cm/sec (previously used K_{sat} for compacted and surface amendments under embankment equal to 1 x 10^{-5} cm/sec).

Golder notes that due to the smaller PAG operating cell footprint, lower embankment heights, and lower permeability of the PAG tailings, the overall contribution of PAG seepage to the water balance is small compared to the NPAG facility.

4.0 RESULTS

The results of the water balance model and drain down analysis are summarized in this section. Seepage occurs from the locations shown in Figure 1.

- NPAG cyclone sand embankments
- NPAG impoundment footprint
- PAG cyclone sand embankments
- PAG impoundment footprint

In the conventional GoldSIM model, flows exceeding the aquifer capacity are recovered in closely spaced seepage pump back wells. In the thin lift models, flows exceeding the water quality limitation are recovered by a reduced number of wells. Golder assumes the seepage from the closed facilities will also not exceed either the aquifer or water quality capacity, and therefore limits the drain down flows.

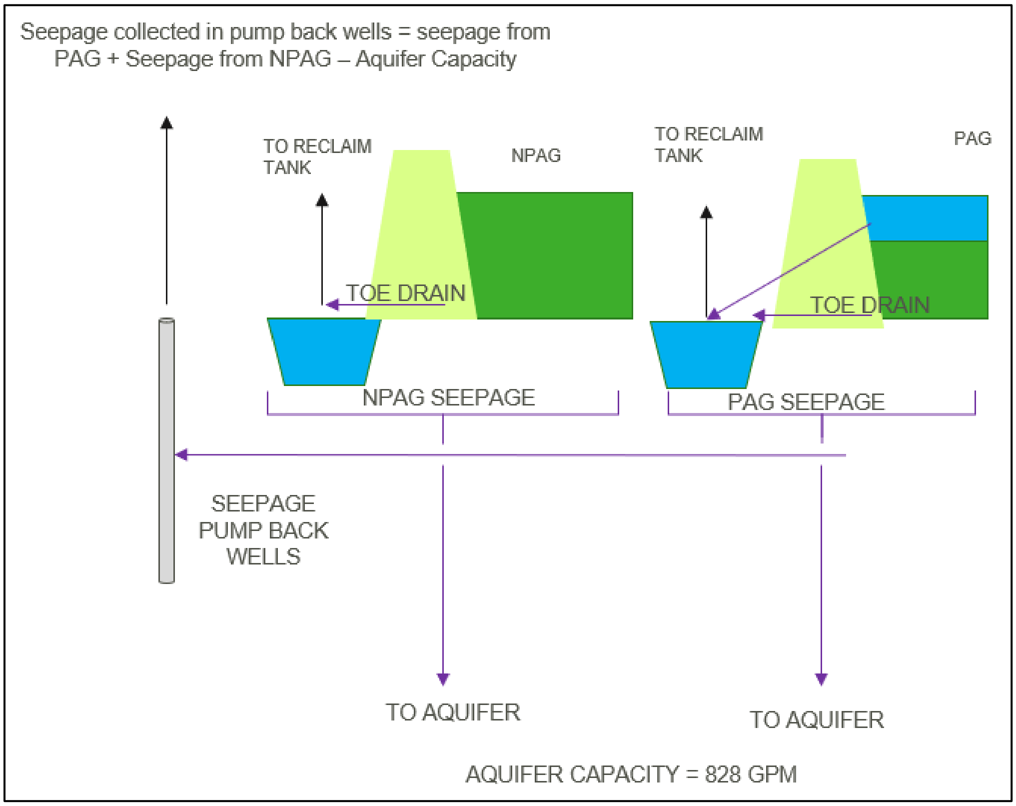

Figure 1 – Seepage Line Diagram

4.1 Conventional Deposition Results

Table 2 provides a summary of GoldSIM results for conventional tailings deposition.

Table 2 – Conventional Deposition Seepage Summary Results (GoldSIM results)

Area	PAG Impoundment Seepage	PAG Dam Seepage	NPAG Impoundment Seepage	NPAG Dam Seepage	Max Aquifer Capacity	Seepage Pump Back Wells	Seepage Lost to Aquifer
Unit (per year)	ac-ft	ac-ft	ac-ft	ac-ft	ac-ft	ac-ft	ac-ft
Operations Min (YR 1-41)	26	311	43	251	1,337	-	826
Operations Avg (YR 1-41)	130	1,080	1,697	842	1,337	2,429	1,317
Operations Max (YR 1-41)	223	1,502	2,617	951	1,337	3,946	1,337
Initial Closure Seepage	17	30	914	66	1,337	0	1027

The post-closure drain down time was estimated using the M&N calculations for the NPAG and PAG facility. As mentioned above, the quantity of water during drain down cannot exceed the aquifer capacity; therefore, if the calculated flow exceeds the aquifer capacity, the maximum aquifer capacity is reported. The time to drain down the NPAG facilities is shown in Figure 2. The graph is exclusive of the cover infiltration.

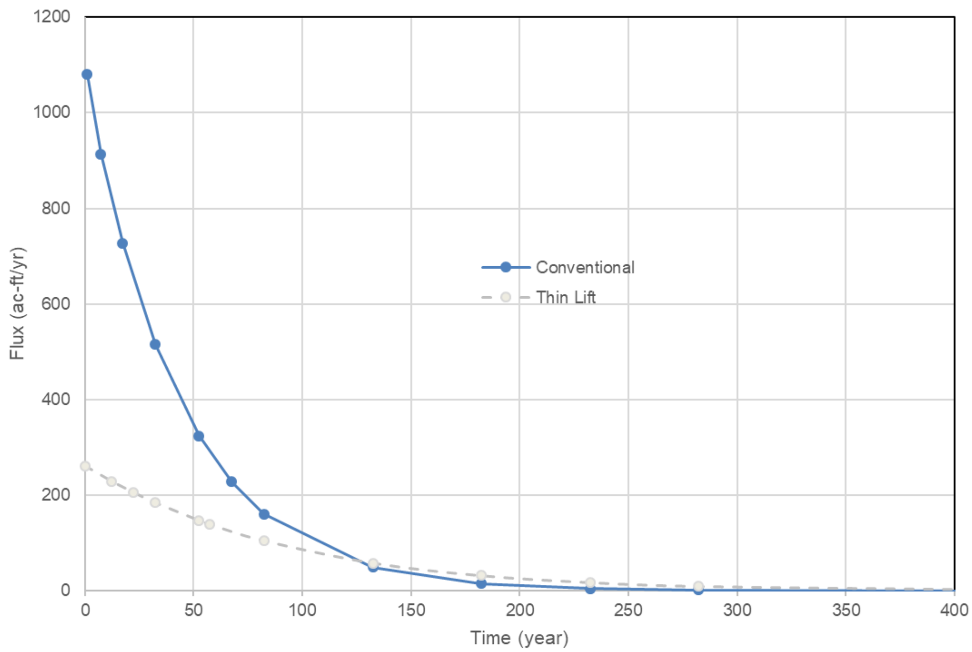

Figure 2: Estimated Stage 4 M&N Drain Down Time for Conventional Deposition

The maximum allowable post-closure seepage rate at Peg Leg is about 261 acre-ft/yr based on selenium concentrations (Se). However, the expected cover infiltration of 234 acre-ft/yr reduces the allowable seepage to 27 acre-ft/yr. To meet these criteria post-closure, the present analyses indicate that the pump well system would need to be operated for at least 150 years post closure. More detailed analysis along with subsurface investigations are warranted and necessary to refine this estimate.

4.2 Thin Lift Deposition Results

The result of the thin lift deposition analyses are presented in Table 3. The results show about a 50% reduction in seepage from the NPAG facility and 98% reduction from the PAG facility. The majority of seepage reduction from the PAG facility occurred from reducing seepage from the dam footprint and reducing the seepage from the PAG pond by including the liner.

Table 3 – Thin Lift Deposition – Seepage Summary Results

Area	PAG Impoundment Seepage	PAG Dam Seepage	NPAG Impoundment Seepage	NPAG Dam Seepage	Max Allowable Aquifer Capacity	Seepage Pump Back Wells	Seepage Lost to Aquifer
Unit (per year)	ac-ft	ac-ft	ac-ft	ac-ft	ac-ft	ac-ft	ac-ft
Operations Min (YR 1-41)	0	10	1	251	261	195	261
Operations Avg (YR 1-41)	7	19	799	842	261	1,404	261
Operations Max (YR 1-41)	12	29	1,497	951	261	2,227	261
Initial Closure Seepage	11	25	399	66	261	240	261

The conceptual differences in closure seepage rates versus time for thin lift deposition is depicted in Figure 3. It is noted that seepage rates during operations are significantly higher for a conventional thickened tailings deposition than for thin-lift deposition. However, during closure the drain down period is about the same for either deposition approach given the simplifications of the analyses. This is because infiltration through the cover would be similar, and although the driving head for conventional deposition is higher initially, the permeability is also higher, allowing for better drainage.

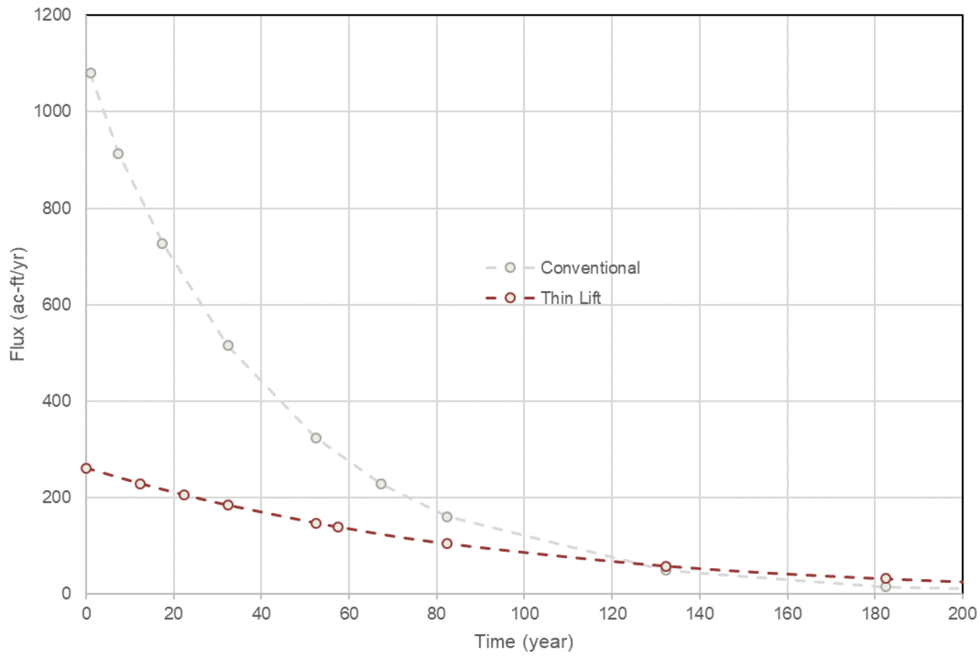

Figure 3: Estimated Stage 4 M&N Drain Down Time for Thin Lift Deposition

Drain down findings

- Thin lift deposition is expected to reduce NPAG seepage quantities by about 50% overall.
- Pump back wells are required to meet the water quality considerations. The average pump back well during operations is 1,404 acre-ft/yr or about 871 gallons per minute.
- For a one order (10X) reduction in the thin lift K_{unsat}, drain down times for thin lift deposition are about the same as conventional deposition.

Comparisons in drain down time between conventional deposition and thin lift deposition are presented in Figures 2 and 3.

The total seepage loss from the impoundment for conventional and thin lift deposition without the benefit of pump back wells is compared in Figure 4. Figure 4 includes the cover infiltration estimate discussed previously and not included in Figures 2 and 3. Figure 4 indicates that using thin lift deposition will reduce the total seepage outflows by over 50% compared to conventional, thickened tailings deposition.

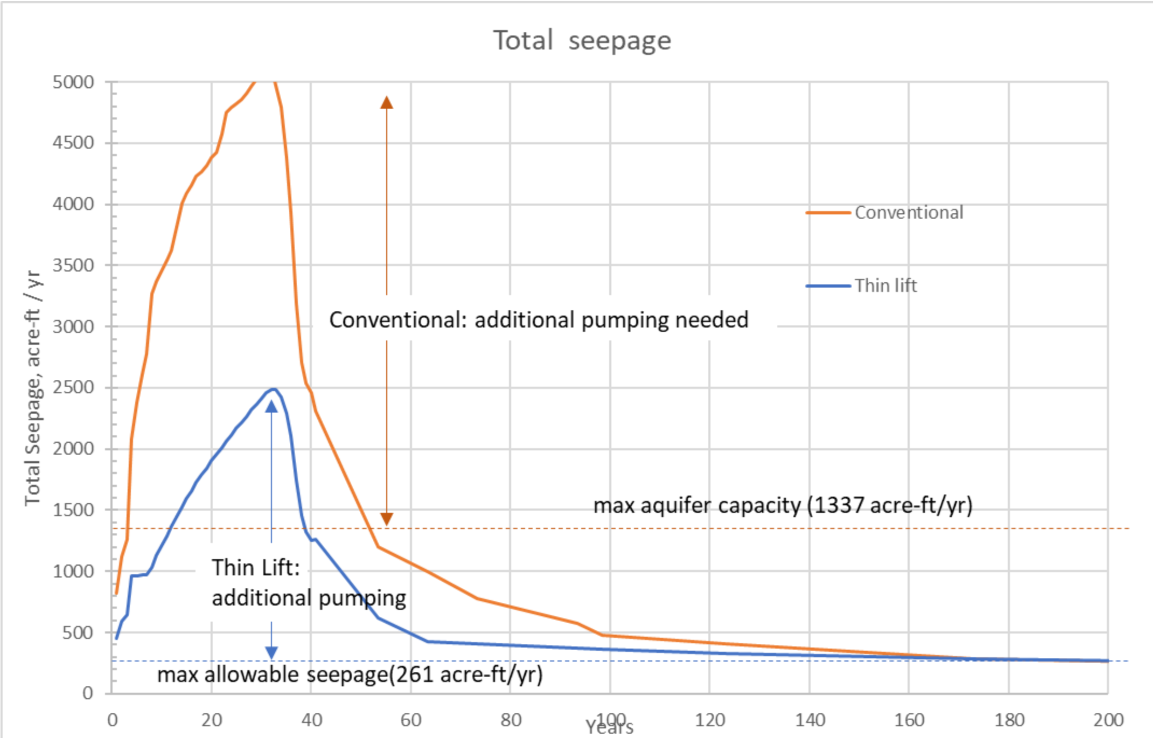

Figure 4 – Comparison of Total Seepage Loss Quantities without Pump Back Wells

Figure 5 shows the required pump back quantities to meet the aquifer capacity or allowable seepage limit, as follows:

- For conventional, thickened tailings deposition:
  - The site would need to pump back a maximum of 3,950 acre-ft/yr to meet the aquifer capacity limitation, and another 1,076 acre-ft/yr to meet the maximum allowable seepage value for a total maximum of 5,026 acre-ft/yr.
  - The average pump back requirement during operations is 2,430 acre-ft/yr to meet the aquifer capacity limitation and 3,506 acre-ft/yr to meet the allowable seepage rate.
- For thin lift deposition:
  - the site would need to pump back a maximum of 2,050 acre-ft/yr and average 1,404 acre-ft/yr to meet the allowable water quality criteria.
- Both conventional and thin lift deposition require operating pump back wells to either restrict exceeding the aquifer capacity or meet the water quality constraint. However, with thin lift deposition the maximum allowable seepage rate can be achieved under a more reasonable pump back scenario.
- Both conventional and thin lift deposition requires operating the wells into closure. As drain down occurs, the seepage rates become asymptotic to the allowable seepage value. The one-dimensional M&N analysis is not sufficiently accurate to predict exact length of operation, although the analysis indicates that wells may need to be operated from 100 to 150 years.

- In general, with thin lift deposition the pump back requirements are 40% of conventional deposition to meet the water quality constraint.

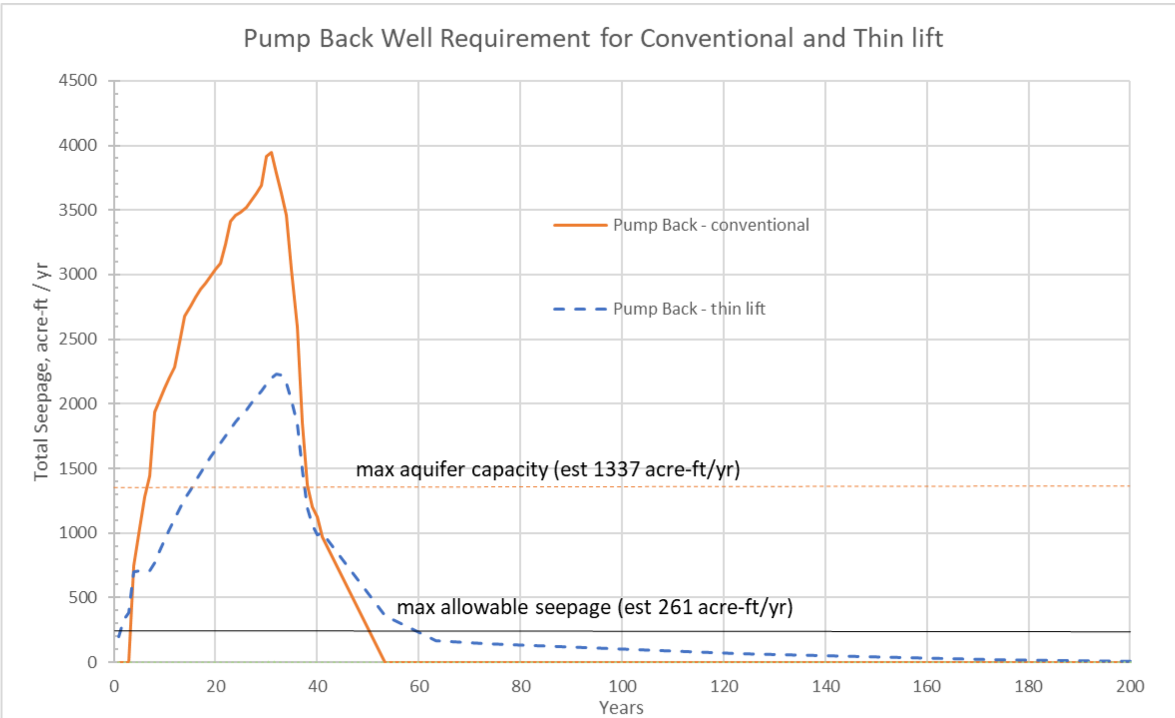

Figure 5: Estimated Pump Back Requirement for Conventional and Thin Lift Deposition

For comparison, the above values are summarized in Table 4 in both acre-ft/yr and gpm.

Table 4: Summary of Maximum and Average Pump Back Quantities

	Meet Aquifer Capacity	Meet Water Quality	Meet Aquifer Capacity	Meet Water Quality
	Acre-ft/yr		Gallons per Minute (gpm)	
Conventional Deposition				
maximum	3950	5,026	2,449	3,116
average	2430	3,506	1,507	2,174
Thin Lift deposition				
maximum		2050		1,271
average		1404		871

These conclusions are intended for the draft EIS stage of analysis. Results will need to be validated with foundation investigations, tailings properties, and assumptions regarding thin lift deposition.

5.0 CLOSING

The analyses, conclusions, and recommendations presented in this technical memorandum were prepared in accordance with generally accepted standards of practice and standards of care for professional geotechnical engineering at the time this document was prepared. Golder's observations were completed based on the assumptions stated in this technical memorandum and the information in the references cited. As additional information and site characterization becomes available that may vary from that described herein and where different assumptions are more appropriate, Golder should be requested to re-evaluate our findings and conclusions.

This technical memorandum was prepared for the exclusive use of Resolution Copper Mining. Golder's technical memorandum may be provided to appropriate government agencies and/or used for internal purposes; however, Golder's technical memorandum, conclusions, and interpretations should not be construed as a warranty of actual conditions.

Golder appreciates the opportunity to support Resolution Copper in selection of a preferred tailings alternative. If you have questions or comments regarding the information contained herein, please contact Golder at (801) 312 9320, (801) 232-3315 (mobile), or via email at either JPilz@golder.com or DKidd@golder.com.

Joergen Pilz, PE
Senior Consultant

David A. Kidd, PE
Sr. Program Leader/Principal

6.0 REFERENCES

Golder Associates Inc (Golder). 2018. DRAFT EIS Design, Peg Leg Alternative 5. Project 1788500-1000-1600-16-R-0, including Appendix E – Embankment Staging Results and Appendix G – Water Balance. June 20, 2018.

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McWhorter, D.B., and J.D. Nelson. 1979. Unsaturated flow beneath tailing impoundments. Journal of Geotechnical and Geoenvironmental Engineering, 105(ASCE 14999).

McWhorter, D.B., and J.D. Nelson. 1980. Seepage in the partially saturated zone beneath tailings impoundments. Mining Engineering, 32(4), 432-439.

Montgomery and Associates (M&A). 2018. Technical Memorandum – Estimated Maximum Allowable Seepage from TSF Alternative Sites, Dec 20, 2018.

Attachments: Attachment 1 – McWhorter and Nelson Drain Down Analysis

https://golderassociates.sharepoint.com/sites/101376/deliverables/final/tm02/rev1/1788500.002tm02_resolution_badct_seepage_rev1_28jan19.docx

ATTACHMENT 1

McWhorter and Nelson Drain Down Analysis

CALCULATIONS

DATE	January 29, 2019	**PREPARED BY**	Gordan Gjerapic
DOCUMENT NO.	1788500-002, TM02, Rev. 1 Peg Leg TSF Drain Down Analytical Estimates	**CHECKED BY**	Joergen Pilz
		REVIEWED BY	Joergen Pilz
SITE NAME	Resolution Copper Mining		

PEG LEG TSF – DRAIN DOWN ESTIMATES USING MCWHORTER AND NELSON APPROACH

1.0 INTRODUCTION

This calculation brief has been prepared by Golder Associates Inc. (Golder) to present analytical drain-down estimates based on the approach proposed by McWhorter and Nelson (1978). Inputs for the analyses were developed from information for the draft EIS TSF design at the Peg Leg site (Golder 2018) and assuming implementation of seepage control measures and operational practices to minimize seepage as represented by model parameters summarized in Attachment 1.

2.0 RESULTS

Staged calculations based on the McWhorter and Nelson (1978) methodology resulted in the seepage estimates presented in Table 1.

Stage 1 and 4 calculations are based on excel spreadsheet calculations. Stage 4 uses a Visual Basic (VBA) implementation of the McWhorter and Nelson code. Stage 2 and 3 calculations are based on the attached coding implemented in the Software Program, “Mathematica,” which solves the complex equations directly (this is not possible in excel). The M&N solution indicates that Stage 3 will continue beyond the final operating year. However, field observations at Kennecott and other Arizona operations indicate that tailings drainage begins shortly after cessation of operations. To proceed from Stage 3 to Stage 4, we match the seepage quantity estimate (m/sec) from stage 3 as input into stage 4 to obtain the height of the saturated tailings and reset the time period as beginning at closure.

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Table 1: Peg Leg Seepage Estimates - McWhorter and Nelson (1978) Approach

Stage	Time (yr)	Seepage Rate (cm/sec)
1	0 to 13.12	4.70×10^{-7}
2	13.12 to 27.75	5.50×10^{-7}
3	27.75	7.25×10^{-7}
3	30	4.37×10^{-7}
3	35	2.94×10^{-7}
3	41	2.34×10^{-7}
4	41 - 500	See Figure 1

Figure 1 presents the estimated drain down for conventional tailings deposition.

Attachment 2 presents the drain down calculations.

Attachment 3 includes validation examples demonstrating that our implementation results in the solutions presented in the McWhorter and Nelson papers.

3.0 REFERENCES

Golder Associates Inc. (Golder). 2018. Order of Magnitude Design - Peg Leg Alternative 5, report submitted to Resolution Copper Mining LLC. Ref. No. CCC.0.-81600-EB-REP-00002, Project No. 178-8500, August 6, 2018.

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McWhorter, D. B., & Nelson, J. D. 1979 . Unsaturated flow beneath tailing impoundments. Journal of Geotechnical and Geoenvironmental Engineering, 105(ASCE 14999)

McWhorter, D. B., & Nelson, J. D. 1980. Seepage in the partially saturated zone beneath tailings impoundments. Mining Engineering, 32(4), 432-439.

Attachments: 1 – Figures
2 – Peg Leg Drain-Down Calculations
3 – McWhorter and Nelson (1978, 1980) – Validation Examples

ATTACHMENT 1

Figures

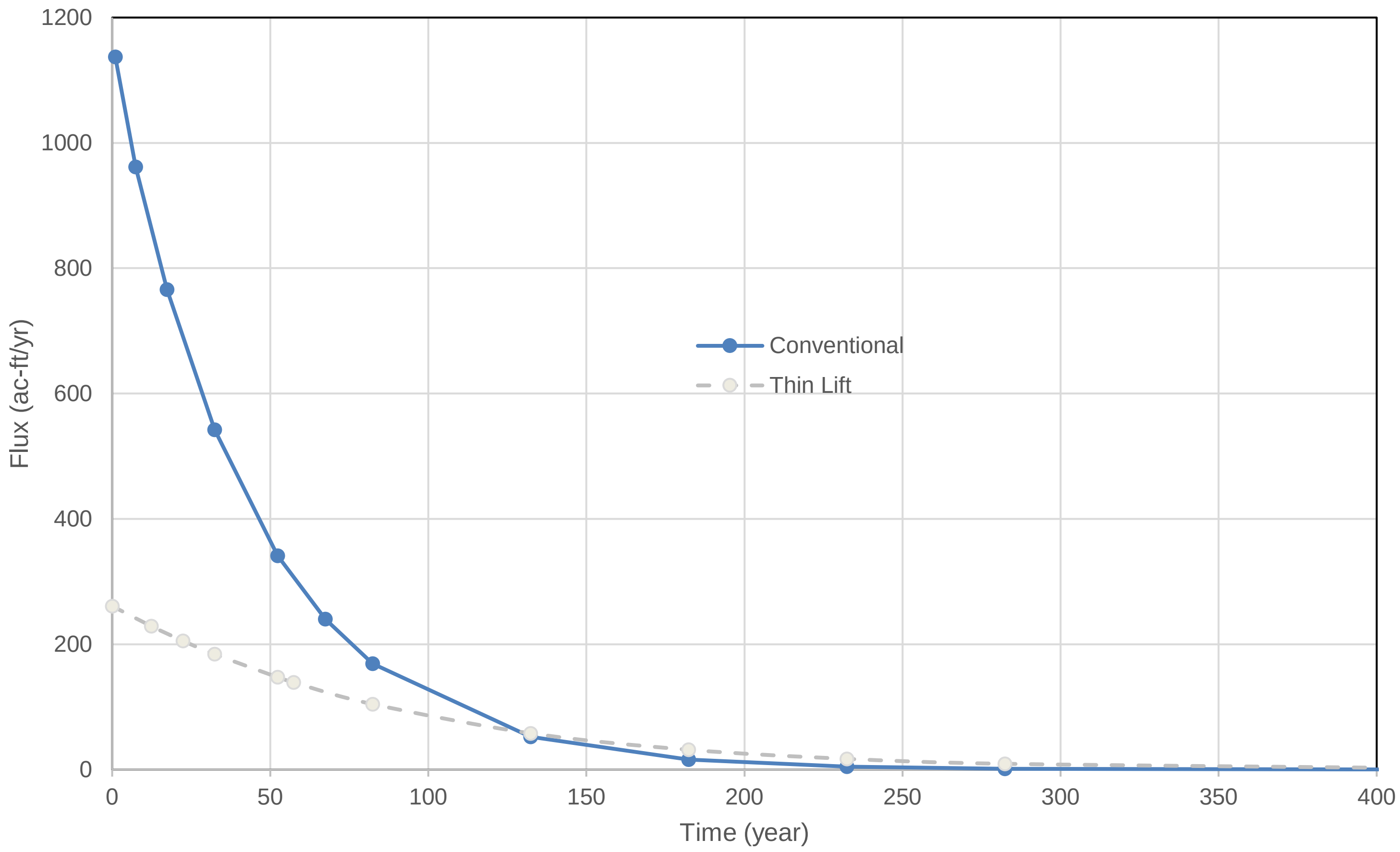

Figure 1

Peg Leg Post-Closure Drain-Down Based on McWhorter and Nelson (1978), Conventional

Peg Leg

Drain Down Estimates

Golder Associates

Final
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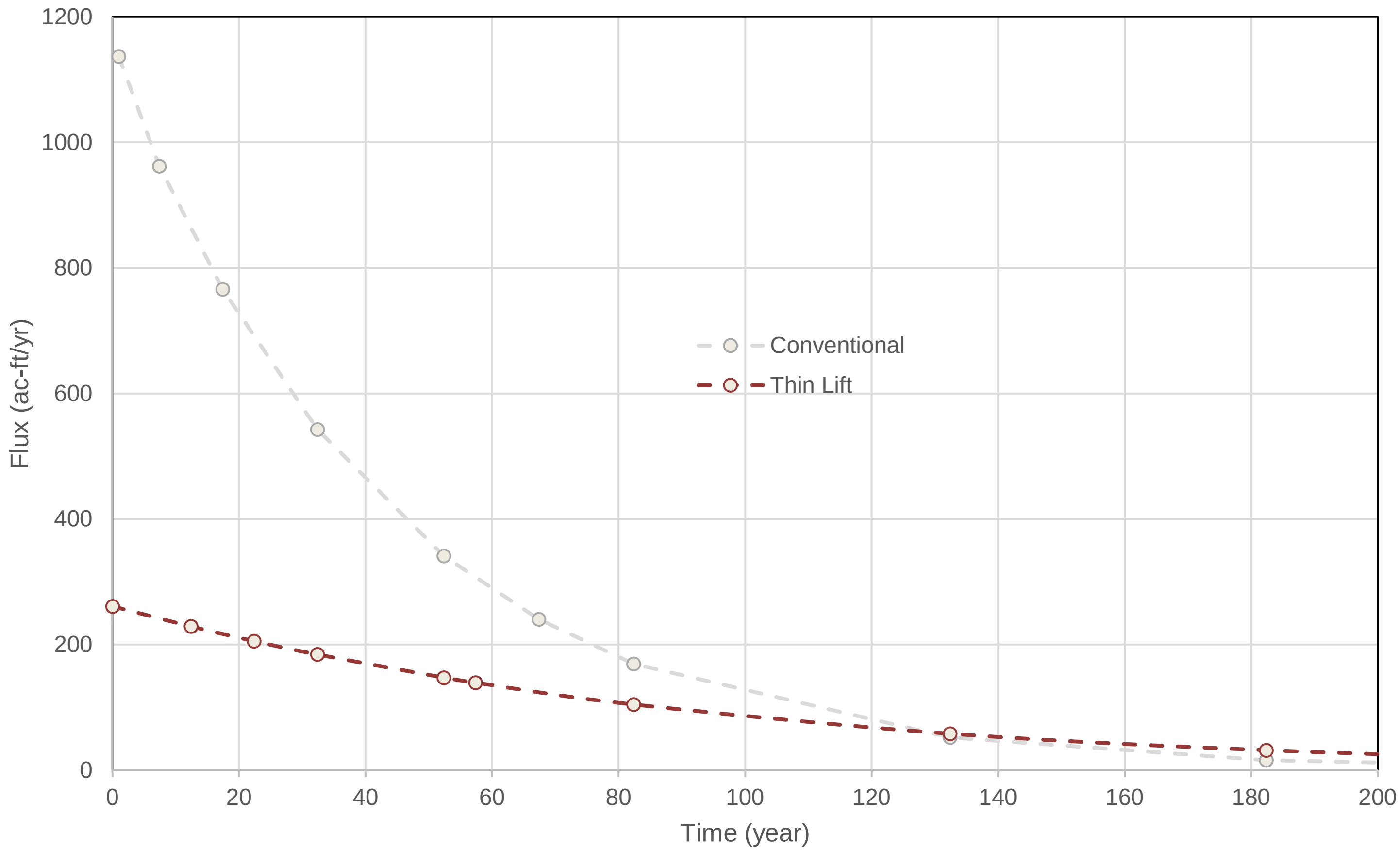

Figure 2

Peg Leg Post-Closure Drain-Down Based on McWhorter and Nelson (1978), Thin Lift

Peg Leg

Drain Down Estimates

Golder Associates

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ATTACHMENT 2

Peg Leg Drain-Down Calculations

Peg Leg Inputs for simplified draw-down analysis

Ha_max	1250	ft	Aquifer conveyance capacity			Aquifer initial conditions		
	381	m	q_max	1.85E+00	ft^3/sec	Gs	2.7	(est)
Gradient	3%			8.28E+02	gpm	w_initial	6%	(est)
Ka	1.00E-04	cm/sec		2.23993E-07	cm/sec	Void Ratio	6.67E-01	
TSF_length	15000	ft	NPAG	1.15E+09	ton	theta_init	9.72E-02	
	4572	m	PAG	2.20E+08	ton			
Total Area	5765	acre	Total	2.74E+12	lb	Unsat depth	34	ft
Area-yr7	1195	acre	Avg_Den	90	pcf		10.3632	m
Radius, R	8940.641	ft	Volume	3.05E+10	ft^3			
	2725.107	m	Avg_H	121.32	ft			
				36.98	m			

Peg Leg Inputs - Draw-Down estimates

Project life (yr)	41
Area of impoundment (ha)	2333.013
Equivalent radius R (m)	2725.107
Liner thickness Dl (m)	0.3
Thickness of pond, y (m)	0
Average thickness rate slimes Ds/time (m/yr)	0.090192
Avg thickness of coarse tailings Dt/time (m/yr)	0.81173
Initial saturated aquifer thickness, Ha (m)	370.6368
Initial thickness of unsaturated zone Df (m)	10.3632
Permeability of coarse tailings, Kt (cm/sec)	1.00E-05
Permeabilty of slimes, Ks (cm/sec)	1.00E-06
Permeability of liner, Kl (cm/sec)	1.00E-08
Permeability of foundation Kf (cm/sec)	1.00E-04
Permeability of aquifer, Ka (cm/sec)	1.00E-04
Porosity of foundation, n (-)	0.400
Initial water content in foundation, theta_i	0.097
Residual water content in foundation, theta_r	0.100
Diplacement pressure in foundation, hd (m)	-1.00E-01

Stage 1

Time (years)	0	5	10	15	20	25	30	41
Dt (m)	0	4.058647913	8.117296	12.17594	16.234592	20.29324	24.35189	33.28091
Ds (m)	0	0.450960879	0.901922	1.352883	1.8038435	2.254804	2.705765	3.697879
q (cm/sec)	1.333E-08	1.591E-07	2.970E-07	4.277E-07	5.516E-07	6.693E-07	7.814E-07	1.010E-06

theta_f	1.60E-01	water content behind wetting front
Stage 1 duration	13.12	yrs

Stage 2

qm _average	5.495E-07	cm/sec
(n-theta_f)	2.40E-01	
(n-thet_r)/(n-thet_r)	8.01E-01	
Ha_bar	375.8184	
alpha1	1.56E-03	
Stage 2 duration	14.63	yrs

See "Mathematica" calculations for Stage 2 and Stage 3 analytical estimates

```
In[24]:= (* Stage 2 and Stage 3 estimates for McWhorter solution -
          Peg Leg option estimates based on McWhorter and Nelson (1980) *)
         qm = 5.495 * 10^(-9) ;
         (* (m/sec) - average recharge, i.e. average impoundment seepage *)
         R = 2725.1; (* (m) - average radius for the TSF footprint *)
         Ka = 1 * 10^(-6); (* (m/sec) - saturated aquifer permeability *)
         Ha = 370.637 ; (* (m) - saturated aquifer thickness *)
         Df = 10.363;
         (* (m) - initial thickness of unsaturated aquifer - depth to GWT *)
         HaBar = Ha + 0.5 * Df; (* adjusted aquifer thickness for Hantush solution *)
         thetaSat = 0.4; (* saturated volumetric moisture content - porosity *)
         thetaR = 0.1; (* residual volumetric moisture content - after drain-down *)
         thetaF = 0.16;
         (* volumetric moisture content behind the wetting front in Stage 1 *)
         thetaInit = 0.097; (* initial moisture content of the unsaturated aquifer,
         before wetting *)
         beta = ((thetaSat - thetaR) / (thetaSat - thetaF)) ^0.5;
         alpha1 = Ka * HaBar / (thetaSat - thetaF);

In[27]:=
         phi[x_, beta_] =
           BesselJ[1, x] * BesselY[0, beta * x] - beta * BesselJ[0, x] * BesselY[1, beta * x];
         psi[x_, beta_] = BesselJ[1, x] * BesselJ[0, beta * x] -
            beta * BesselJ[0, x] * BesselJ[1, beta * x];

In[30]:= s0[t_] := 4 * qm * R^2 / (Pi^2 * Ka * HaBar) * NIntegrate[(1 - Exp[-alpha1 / R^2 * x^2 * t]) *
             BesselJ[1, x] / (x^4 * (phi[x, beta]^2 + psi[x, beta]^2)), {x, 0, Infinity}]

         (* find amount of time required for
          the mound to reach the bottom of impoundment *)

In[31]:= res1 = FindRoot[s0[t] == Df, {t, Df * (thetaSat - thetaF) / qm}]

         General::stop : Further output of NIntegrate::inumr will be suppressed during this calculation. >>

Out[31]= {t → 4.61394 × 10^8}

In[32]:= Print["Time to finalize Stage 2 = ", (t /. res1) / (365 * 24 * 3600), " years"];

         Time to finalize Stage 2 = 14.6307 years

In[42]:= (* Stage 3 solution -
          seepage rate attenuation due to lateral resistance of the aquifer *)
         qStage2 = 7.25 * 10^(-9); (* (m/sec) -  flux at the end of Stage 2 *)
         qs3 = NDSolve[{(thetaSat - thetaInit) * R^2 / (4 * HaBar * Ka) *
               D[q[t] * (Exp[4 * Ka * HaBar * Df / (R^2 * q[t])] - 1), t] == q[t],
            q[0] == qStage2}, q, {t, 0, 15.0 * 365 * 24 * 3600}];

In[43]:= qStage3[t_] = N[Evaluate[q[t] /. qs3]][[1]];
```

Stage 4 calculations for Peg Leg option based on McWhorter and Nelson (1978)

Input parameters		Units	Empirical			
Dt	33.3	m	109.2	ft	Use VBA function	
Ds	3.69	m	12.1	ft	Time (yr)	qm (m/sec)
Dl	0.3	m	1.0	ft	0	9.82982E-09
Kt	1.00E-07	m/sec	1.0E-05	cm/sec	1	9.64247E-09
Ks	1.00E-08	m/sec	1.0E-06	cm/sec	2	9.45794E-09
Kl	1.00E-10	m/sec	1.0E-08	cm/sec	5	8.92112E-09
hb	-1.00E+00	m	-3.3	ft	10	8.08122E-09
hd	-1.00E-01	m	-0.3	ft	25	5.94711E-09
thetaSatTails	0.50	(-)			67.6	$\boxed{2.34788E-09}$
thetaRTails	0.10	(-)			75	1.98618E-09
tDrain	2.13E+09	sec	67.6	years	85	1.58146E-09
					100	1.12018E-09
Estimated avg. height of phreatic surface at the end of filling					120	7.04376E-10
Dtails_sat	4.935891518	m	16.2	ft	135	4.96328E-10
qm	$\boxed{2.34788E-09}$	m/sec			150	3.49297E-10
					200	1.07755E-10
					250	3.31301E-11
					300	1.01756E-11
					350	3.12433E-12
					500	9.04052E-14

Note: need to apply 67.6-yr offset for draw-down estimates as closure

In[44]:=
```
Print["Stage 3 Flux at 30 years = ",
  qStage3[(30 - 27.75) * 365 * 24 * 3600], " (m/sec)"];
```

Stage 3 Flux at 30 years = 4.37113×10^{-9} (m/sec)

In[45]:=
```
Print["Stage 3 Flux at 35 years = ",
  qStage3[(35 - 27.75) * 365 * 24 * 3600], " (m/sec)"];
```

Stage 3 Flux at 35 years = 2.93539×10^{-9} (m/sec)

In[46]:=
```
Print["Stage 3 Flux at 41.0 years = ",
  qStage3[(41 - 27.75) * 365 * 24 * 3600], " (m/sec)"];
```

Stage 3 Flux at 41.0 years = 2.34293×10^{-9} (m/sec)

ATTACHMENT 3

McWhorter and Nelson (1978, 1980) Validation Examples

Validation example from McWhorter and Nelson (1980)

Project life (yr)	20
Area of impoundment (ha)	32
Equivalent radius R (m)	319.1538
Liner thickness Dl (m)	1
Thickness of pond, y (m)	0
Average thickness rate slimes Ds/time (m/yr)	0.15
Avg thickness of coarse tailings Dt/time (m/yr)	1.1
Initial saturated aquifer thickness, Ha (m)	25
Initial thickness of unsaturated zone Df (m)	20
Permeability of coarse tailings, Kt (cm/sec)	2.00E-03
Permeabilty of slimes, Ks (cm/sec)	1.50E-05
Permeability of liner, Kl (cm/sec)	1.00E-06
Permeability of foundation Kf (cm/sec)	1.00E-04
Permeability of aquifer, Ka (cm/sec)	8.00E-04
Porosity of foundation, n (-)	4.00E-01
Initial water content in foundation, theta_i	0.00E+00
Residual water content in foundation, theta_r	1.30E-01
Diplacement pressure in foundation, hd (m)	-2.30E+00

Stage 1

Note: Stage 1 ends after 3.2 years of TSF operation

Time (years)	0	1	2	3	4	5	6	7
Dt (m)	0	1.1	2.2	3.3	4.4	5.5	6.6	7.7
Ds (m)	0	0.15	0.3	0.45	0.6	0.75	0.9	1.05
q (cm/sec)	3.300E-06	4.502E-06	5.680E-06	6.834E-06	7.964E-06	9.071E-06	1.016E-05	1.122E-05

theta_f	2.58E-01	water content behind wetting front
Stage 1 duration	3.22370349	yrs

Stage 2

qm _average	9.0495E-06	cm/sec	(between years 4 and 7)
(n-theta_f)	1.42E-01		
(n-thet_r)/(n-thet_r)	5.25E-01		
Ha_bar	35		
alpha1	1.97E-03		

See "Mathematica" calculations for Stage 2 and Stage 3 analytical estimates

```
In[119]:= (* Stage 2 and Stage 3 estimates for McWhorter solution -
 example from McWhorter and Nelson (1980) *)
qm = 9.05 * 10^(-8) ;
(* (m/sec) - average recharge, i.e. average impoundment seepage *)
R = 320; (* (m) - average radius for the TSF footprint *)
Ka = 8 * 10^(-6); (* (m/sec) - saturated aquifer permeability *)
Ha = 25 ; (* (m) - saturated aquifer thickness *)
Df = 20; (* (m) - initial thickness of unsaturated aquifer - depth to GWT *)
HaBar = Ha + 0.5 * Df; (* adjusted aquifer thickness for Hantush solution *)
thetaSat = 0.4; (* saturated volumetric moisture content - porosity *)
thetaR = 0.13;  (* residual volumetric moisture content - after drain-down *)
thetaF = 0.26;
(* volumetric moisture content behind the wetting front in Stage 1 *)
thetaInit = 0.0; (* initial moisture content of the unsaturated aquifer,
before wetting *)
beta = ((thetaSat - thetaR) / (thetaSat - thetaF))^0.5;
alpha1 = Ka * HaBar / (thetaSat - thetaF);

In[106]:=
phi[x_, beta_] =
  BesselJ[1, x] * BesselY[0, beta * x] - beta * BesselJ[0, x] * BesselY[1, beta * x];
psi[x_, beta_] = BesselJ[1, x] * BesselJ[0, beta * x] -
   beta * BesselJ[0, x] * BesselJ[1, beta * x];

In[108]:= s0[t_] := 4 * qm * R^2 / (Pi^2 * Ka * HaBar) * NIntegrate[(1 - Exp[-alpha1 / R^2 * x^2 * t]) *
     BesselJ[1, x] / (x^4 * (phi[x, beta]^2 + psi[x, beta]^2)), {x, 0, Infinity}]

(* find amount of time required for
 the mound to reach the bottom of impoundment *)

In[109]:= res1 = FindRoot[s0[t] == Df, {t, Df * (thetaSat - thetaF) / qm}]

General::stop : Further output of NIntegrate::inumr will be suppressed during this calculation. >>

Out[109]= {t -> 1.22102 × 10^8}

In[110]:= Print["Time to finalize Stage 2 = ", (t /. res1) / (365 * 24 * 3600), " years"];

Time to finalize Stage 2 = 3.87182 years

(* Stage 3 solution -
 seepage rate attenuation due to lateral resistance of the aquifer *)
qStage2 = 1.12 * 10^(-7); (* (m/sec) -  flux at the end of Stage 2 *)
qs3 = NDSolve[{(thetaSat - thetaInit) * R^2 / (4 * HaBar * Ka) *
       D[q[t] * (Exp[4 * Ka * HaBar * Df / (R^2 * q[t])] - 1), t] == q[t],
    q[0] == qStage2}, q, {t, 0, 9.6 * 365 * 24 * 3600}];

In[115]:= qStage3[t_] = N[Evaluate[q[t] /. qs3]][[1]];
```

In[116]:=
```
Print["Stage 3 Flux at 7.75 years = ", qStage3[0.75 * 365 * 24 * 3600]];
```

Stage 3 Flux at 7.75 years = 1.039×10^{-7}

In[117]:=
```
Print["Stage 3 Flux at 9.8 years = ", qStage3[2.8 * 365 * 24 * 3600]];
```

Stage 3 Flux at 9.8 years = 9.07069×10^{-8}

In[118]:=
```
Print["Stage 3 Flux at 16.6 years = ", qStage3[9.6 * 365 * 24 * 3600]];
```

Stage 3 Flux at 16.6 years = 7.29012×10^{-8}

Validation of McWhorter and Nelson (1978) Stage 4 calculations
based on M&A input parameters for Alt 2 design

Input parameters		Units
Dt	109.39	m
Ds	20.5	m
Dl	1	m
Kt	1.00E-06	m/sec
Ks	5.00E-09	m/sec
Kl	1.00E-08	m/sec
hb	-8.10E-01	m
hd	-2.30E+00	m
thetaSatTails	2.00E-02	(-)
thetaRTails	0.00E+00	(-)
tDrain	1.18E+08	sec

Results after 3.74 years

Dtails_sat	10.04702487	m	OK
qm	7.84719E-09	m/sec	OK

Use VBA function

Time (yr)	qm (m/sec)
0	3.0719E-08
1	2.14695E-08
2	1.49186E-08
3	1.03241E-08
3.5	8.57862E-09
5	4.90596E-09
6	3.3738E-09
7	2.31791E-09
8	1.59142E-09
10	7.49256E-10
20	1.72118E-11
50	#VALUE!
100	#VALUE!
200	#VALUE!
250	#VALUE!
300	#VALUE!
350	#VALUE!
500	#VALUE!
100	#VALUE!

Victoria Boyne

From: ResolutionProjectRecord
Subject: FW: EXTERNAL:Action Items from Geochem Workgroup Meetings 11/13, 12/11
Attachments: M&A_Alt 2 and 3 Seepage _January2010.pdf; Golder_Alt5_BADCT_Seepage_JAN19.pdf; KCB_Alt4-DEIS_Seepage-January 2019.pdf; KCB_Alt6-DEIS_AppIV-SeepageAmendment-January 2019.pdf

From: Peacey, Victoria (RC) <Victoria.Peacey@riotinto.com>
Sent: Wednesday, January 30, 2019 4:32 PM
To: mcrasmussen@fs.fed.us
Cc: RCPermitting <RCPermitting@riotinto.com>; Donna Morey <dmorey@swca.com>; Ghidotti, Greg (G&I) <Gregory.Ghidotti@riotinto.com>; Morissette, Mary (RC) <Mary.Morissette@riotinto.com>; Chris Garrett <cgarrett@swca.com>
Subject: EXTERNAL:Action Items from Geochem Workgroup Meetings 11/13, 12/11

Hello Mary,

In response to action items from Geochm Workgroup meetings in November and December 2018, please see the attached technical reports from KCB, Golder and M&A with updated TSF seepage rates after consideration of additional seepage controls.

Due to file size constraints, I will send the updated GoldSim modeling report which compares seepage from all TSF alternatives (per the attached), in a separate submittal.

Thanks,

Vicky Peacey
Senior Manager – Environment, Permitting and Approvals

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