Permeable Reactive Barrier Feasibility Assessment at Goldcorp's Red Lake Gold Mines: Hydrogeological, Geochemical and Geotechnical Design Considerations

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Abstract

Goldcorp is assessing the feasibility of using permeable reactive barriers (PRBs) to intercept and treat tailings-derived seepage in a discontinuously confined sand and gravel aquifer down-gradient from the Campbell Complex Tailings Management Area (Ontario, Canada). Uncertainty in hydrogeological, geochemical and geotechnical site conditions, and PRB matrix properties was managed using an iterative design process informed by staged site investigations, field-scale tracer migration studies, advanced hydrogeological and geotechnical laboratory testing, numerical groundwater flow modeling, and evaluation of removal rates for parameters of primary concern (As, Co, Fe) in laboratory-based geochemical flow-through column studies.

Keywords: PRB design, bioremediation, hydraulic residence time, iron, arsenic, cobalt

Introduction

Goldcorp is assessing the feasibility of using PRBs (Blowes et al. 2000) to intercept and treat groundwater affected by seepage from the Red Lake Gold Mines Campbell Complex Tailings Management Area (TMA). This paper, which presents hydrogeological, geochemical and geotechnical considerations driving PRB design, represents the third in a series of three papers relating to PRB feasibility at the Campbell Complex. The other two papers, presented as part of these proceedings, describe the groundwater plume distribution and contaminant behaviour (Martin et. al., 2018), and present the results of tracer testwork designed to confirm contamination flowpaths (Helsen *et al.*, 2018).

The Campbell Complex is located 7 km northeast of the Town of Red Lake in northwestern Ontario and has been the site of gold-ore mining and milling operations since 1949. Tailings have been discharged to the current TMA since 1983. A portion of the water that accumulates in the TMA infiltrates into the subsurface and travels along the "Red Lake Flow Path," a groundwater flow path that discharges to ditches draining a golf course (GC ditches), which in turn feed a downstream wetland and lake (Martin et al. 2018).

Seepage flows show tailings-related signatures reflecting mill process waters (SO_4, Cl, NH_3, CN, Cd, Co, Cu, Ni and Zn) and remobilization from tailings solids (Fe and As). As, Co and Fe represent the parameters of primary concern (POPCs) given exceedances of their site-specific groundwater targets in the TMA pond source water and down-gradient plume. Secondary target parameters include SO_4, NO_3, NO_2, Cd, Cu, Ni and Zn. Pilot study results indicated that primary and secondary parameters were amenable to treatment with a common PRB design (Bain and Blowes, 2005).

Assessments completed in support of feasibility design for the PRB include: 1) detailed site characterization of the physical and chemical hydrogeology (Martin *et al.* 2018); 2) advanced laboratory-based testwork to evaluate geotechnical and hydrogeologic properties of the aquifer and the PRB reactive matrix materials; 3) *in situ* tracer testwork to evaluate contaminant migration pathways (Helsen et al. 2018); 4) predictive numerical groundwater flow modeling; and, 5) evaluation of removal rates for POPCs in laboratory-based geochemical flow-through column studies.

Overview of Proposed PRB Design

Site investigations since 1990 have delineated a 200 m wide plume at the downstream toe of the West Dam of the TMA (Martin *et al.* 2018). Staged implementation of the PRB is proposed to optimize design and construction methods prior to placing the PRB across the full plume width. Initial emplacement of the PRB would be a 30 m long segment oriented parallel to the downstream toe of the West Dam and perpendicular to groundwater flow (Figure 1). Based on preliminary design results, the PRB width would be designed to achieve a hydraulic residence time (HRT) of 4 to 7 days. To maximize remedial benefit, it would be located to intercept the highest hydraulic conductivity (K) zones of the aquifer, which also exhibit the highest concentrations of POPCs. Results from a tracer migration study (Helsen et al. 2018) confirmed the selected location would treat TMA-affected groundwater that discharges to the downstream receiving environment.

The PRB would be placed to intersect the sand and gravel aquifer from competent bedrock (17 to 20 m below ground surface) to a nominal depth of 5 m below grade. A soil-cement-bentonite surface seal would serve as backfill from the top of the reactive matrix materials to ground surface. Seal and matrix materials were designed to equal or surpass strength and density characteristics of the native materials.

PRB design followed typical engineering work flow: 1) pilot study to demonstrate treatment efficacy; 2) preliminary design to identify preferred construction methodologies and inform subsequent investigation and study; and, 3) feasibility level design. The feasibility study focused on improving cost evaluations and assessing geotechnical, hydrogeological and geochemical design considerations identified during preliminary stages (Table 1).

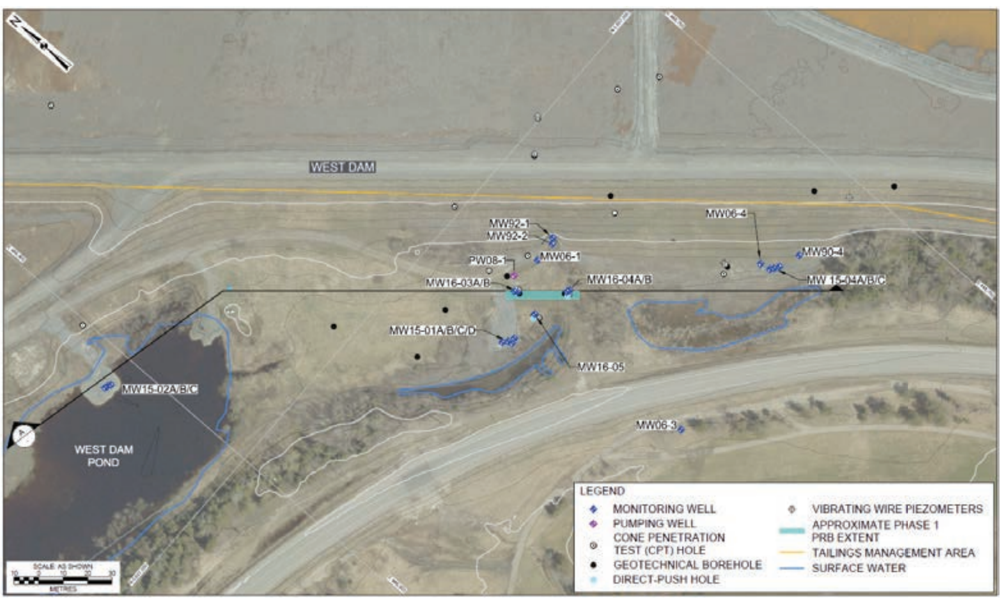

Figure 1. Location of proposed PRB, downstream toe of West Dam of the Campbell Complex TMA.

Geotechnical Design Considerations

Geotechnical challenges related to PRB design included emplacement at the toe of an upstream, compacted clay core, zoned-earthfill embankment (West Dam) and soft glaciolacustrine silts and clays confining an artesian, fining-upwards, glaciofluvial sand and gravel aquifer. Interpretation of cone penetration test (CPT) results also indicated the presence of potentially liquefiable sands and silts within the footprint of the proposed PRB.

Prior to CPT liquefaction screening, preliminary design of the PRB considered a 30 m long, 18 m deep, up to 3 m wide reactive matrix emplaced using a biopolymer- or guar-slurry-supported trenching method. 2-D limit equilibrium analyses were conducted to evaluate stability of the adjacent West Dam and Hwy 125, including required trench setback distances. Trench stability analyses, including 3-D limit equilibrium, were also conducted to assess slurry head and trench panel requirements to prevent trench collapse during construction. However, to mitigate the potential for static liquefaction, secant-pile-type construction was considered as a preferred alternative to trenching, with overlapping large-diameter holes and temporary casing using caissons. This method permits additional flexibility and tooling to be used in the event boulders are encountered at the aquifer-bedrock interface during construction (Table 1).

Piping or clogging of the PRB were also considered; anticipated hydraulic head gradients from predictive numerical modeling, combined with continuous erosion filter (CEF) tests, indicated that piping failure is unlikely. The secant-pile construction method further reduces this risk as the overlapping of bores minimizes potential for through-going seams of segregated PRB materials.

Table 1. *Geotechnical, Hydrogeological and Geochemical Design Considerations for a PRB on the Red Lake Flow Path, Campbell Complex TMA, Ontario, Canada.*

Category	Risk/Consideration	Design Approach/Mitigation
Geotechnical		
Local stability of trench	Trench collapse	2-D then 3-D limit equilibrium stability analyses
TMA West Dam & HWY 125 stability	Slope failure	2-D limit equilibrium stability analyses
	Soft foundation soils	Advanced laboratory testing
	Static Liquefaction	Critical-state soil mechanics analyses
Piping failure	PRB clogging	Filter relationships screening
	Ground loss	Continuous erosion filter (CEF) tests
Boulders	Plume bypass	Construction contingency
Hydrogeological		
Aquifer hydraulic properties	Heterogeneity	"Point-" and "Aquifer-scale" testing for K, S
	Anisotropy	3-D numerical groundwater flow modeling
		"High" and "Average" value design scenarios
PRB materials	Properties not quantified	Advanced laboratory testing
	Segregation when placed	
Hydraulic head gradients	Seasonal variation	Continuous monitoring + consistent survey
	Measurement accuracy	High and Average condition design scenarios
Plume bypass	Poor initial location	*In situ* tracer study (Helsen *et al*. 2018)
	Bypass around PRB	3-D numerical groundwater flow modeling
Geochemical		
POPCs	Treatability	Pilot study results assessed by flow-through column study (Martin et al. 2018)
Products of reaction	Harmful concentrations	Literature review
		Monitoring trigger response action plan
Reaction rates	HRT	Flow-through column study
PRB matrix composition	Cost of ZVI	Flow-through column study evaluated ZVI composition of 10% and 25% by volume
Other		
TMA dam raise	Higher head gradient	3-D numerical groundwater flow modeling
TMA closure	Lower head gradient	3-D numerical groundwater flow modeling

1. K – hydraulic conductivity; S – storage properties; HRT – hydraulic residence time; ZVI – zero valent iron

Hydrogeological Design Considerations

Hydrogeological considerations for the design are associated with heterogeneity and anisotropy in hydraulic properties of the aquifer (Martin *et al*. 2018) and the unquantified hydraulic properties of the PRB materials. Seasonal variation in hydraulic head gradients, the magnitude of the gradients and the accuracy of groundwater levels also introduce uncertainty. Horizontal hydraulic conductivity (KH) of the sand and gravel aquifer near the Phase 1 PRB ranges from 1 x 10^{7} m/s to 3×10^{3} m/s (Figure 2) and spans 5 to 6 orders of magnitude in the till unit at depth (Martin et al. 2018). Aquifer effective porosity (n_{eff}) ranges from 0.2 to 0.4 while horizontal hydraulic head gradients (i_H) in the PRB area range from 0.01 to 0.001 with an average of 0.007(Martin *et al*. 2018).

A custom-built large laboratory flow-through cell (0.6 m wide × 0.6 m high × 1.20 m long) and large permeameter test cells (0.30 m dia. accommodating lengths of 0.10 and 0.30 m) were used to evaluate hydrogeologic parameters for proposed PRB materials. K_H was 3×10^{-3} and 6×10^{-3} m/s with an anisotropy ratio (K_H/K_V) of 5 to 10.

The potential for hydraulic bypass of the plume around or under the PRB, as well as "short-circuiting" through the PRB at locations where higher K aquifer materials are present was evaluated using a 3-dimensional (3-D) numerical groundwater flow model (MODFLOW-SURFACT model developed in Groundwater Vistas, ESI 2011). The model was calibrated to steady-state hydraulic heads, average discharge rates to the GC ditches, and a 3-day pumping test completed in PW08-01 (Figure 1). The PRB was implemented in the model as a 1.2 m wide zone with lengths from 30 to 200 m to evaluate HRT, bypass potential, changes in flow to the GC ditches and hydraulic head changes under the TMA. Effects from increasing the TMA pond level (i.e., TMA dam raise) and post-closure conditions (i.e., no operating pond) were also simulated.

Key findings from the groundwater flow model include: 1) HRT in the PRB is largely controlled by K_H and i_H of the aquifer surrounding the treatment zone, provided K of the PRB is greater than K of the aquifer; 2) K of the PRB matrix should lie in the range from 10^{-6} to 10^{-3} m/s to avoid elevated heads beneath the West Dam of the TMA; 3) HRT

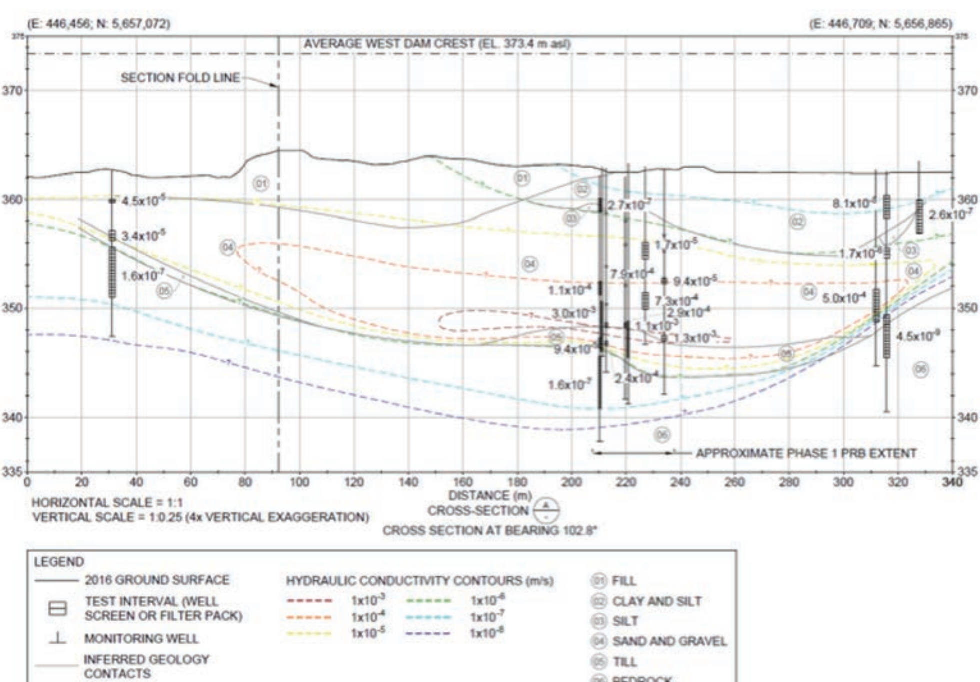

Figure 2 – Cross-section A showing geologic materials and interpreted K horizons along the PRB

Table 2. HRTs, hydrogeologic properties and calculated PRB design widths required to treat As, Fe and Co for High and Average design scenarios during Operations and Post-Closure.

Parameter	High Case		Average Case	
	Operations	Post-Closure	Operations	Post-Closure
HRT (days)[(1,2,3)]				
As	1.9		0.75	
Fe	11		7.1	
Co	16	24	34	14
Hydrogeologic Properties (units as shown)				
K [(4)]	3×10^{-3} m/s		5×10^{-4} m/s	
neff [(5)]	0.35		0.40	
iH [(6)]	0.003	0.0015	0.002	0.001
Required PRB treatment widths (m)				
As	4	2	.2	0.1
Fe	24	12	2	0.8
Co	13	27	8	2

1. High Operations scenario influent concentrations were set to maximum As, Co and Fe values recorded between 2006 and 2016 at monitoring wells immediately up-gradient (MW92-1, MW92-2, and MW06-1) and within the footprint (MW16 03A/B and MW16-04A/B) of the Phase 1 PRB (Figure 1). Average Operations scenario influent concentrations were set to highest 50th percentile As, Co and Fe values observed in the same wells over the same period.
2. As and Fe concentrations for the High and Average Post-Closure scenarios were assumed to remain unchanged since As and Fe are generated through the reductive dissolution of Fe-oxide phases in the tailings, and this process is anticipated to continue over decadal time scales.
3. The primary source of Co is mill effluent, and therefore Co concentrations are expected to decline at closure. Data from site wells were examined to establish High (0.1 mg/L) and Average (0.06 mg/L) Post-Closure influent values.
4. K for High Operations and Post-Closure scenarios is based on the highest values measured in the aquifer. K for Average Operations and Post-Closure scenarios is the geometric mean of test results from wells MW15-01B, MW16 03A/B, MW16 05, MW06-1, MW92-1, MW16-04B, MW06-4 screened inside the 10^{-5} m/s K contour (Figure 2).
5. neff of *in situ* PRB materials could not be evaluated by laboratory testwork; best estimates were based on total porosities of the individual PRB materials, experience and literature.
6. iH assigned to High Operations scenario was set to 0.003 to reflect the high end of the range measured in wells nearest to Phase 1 (0.001 to 0.004) during the period from August 2016 to April 2017; iH for the Average Operations scenario was set to 0.002, the average over the same period. iH for Post-Closure scenarios was set to 50% of Operations values based on groundwater flow modeling results.

in the range of 4 to 7 days for a 1.2 m wide PRB are unlikely adjacent to the most conductive zones of the plume during operating conditions; and, 4) under post-closure conditions, hydraulic head gradients decline such that targeted HRTs may be realized.

Geochemical Design Considerations

Flow-through column experiments using TMA-affected groundwater from the Red Lake Flow Path indicated a reactive matrix composed of 25% zero valent iron (ZVI), 30% organic materials and 45% sand and fine gravel (by volume) could achieve remedial targets for As, but not for Co or Fe (data not shown). Removal rates for Co were lower than anticipated, likely because non-labile Co complexes were present (Martin *et al.* 2018). Additionally, calculation of Fe removal rates from column studies were confounded by early-time release of dissolved Fe associated with reductive dissolution of ZVI corrosion products.

Performance of the PRB was evaluated by considering the HRT required to reduce concentrations of POPCs to acceptable levels (defined by site-specific targets). HRT was calculated as the quotient of the difference between influent POPC concentration and the target post-treatment concentration divided by mass removal rates derived from the geochemical flow-through column studies (data not shown). To account for temperature difference between laboratory columns (23°C) and aquifer groundwater (6°C) a factor of 3.0 was applied to derive a temperature-scaled HRT (Benner *et al.* 2002).

PRB treatment widths (W_{PRB}) required to achieve targeted post-treatment concentrations were calculated as the product of HRT for each of the POPCs and average linear groundwater velocity, calculated as $(K_H\ i_H)/n_{eff}$. Sources of uncertainty in hydrogeological and geochemical design variables were accounted for by considering four design scenarios (Table 2): a High case and an Average case for each of Operations and Post-Closure conditions.

Required treatment widths to achieve target remediation values for As, Co and Fe are shown in Table 2. HRTs and treatment widths for As (0.1 to 4 m) for all design scenarios are considered practical from the perspectives of construction methodology and working space. In contrast, HRTs and treatment widths required to treat Fe for the High Operations scenario (24 m) and High Post-Closure scenario (12 m) are considered impractical. However, HRTs and treatment widths for the Average Operations and Post-Closure scenarios are within practical ranges (HRT of 7 days, treatment widths of 0.8 to 2 m). HRTs and treatment widths required to support the removal of Co to concentrations less than the target values are impractical for all but the Average Post-Closure scenario.

Conclusions

Geotechnical concerns related to using a biopolymer- or guar-slurry-supported trenching method were managed by changing to a secant-pile-type construction method. Evaluation of HRTs and PRB treatment widths for the four design scenarios considered indicated that design and installation of the PRB will treat As but is not practical for full treatment of all POPCs. In particular, design of the PRB to treat current Co concentrations is not recommended given the uncertainty in treatment efficiency (owing to the prevalence of non-labile complexes generated during ore processing) and the likelihood that Co concentrations will decline once operations cease. Design of the PRB to treat Fe for the High Operations scenario is also not recommended due to the treatment width required and uncertainty in treatment efficacy.

Design of the PRB to treat Fe concentrations for the High Post-Closure scenario (i.e., treatment width of 12 m) as part of a long-term passive closure strategy may have merit. A lower bound on the design treatment width of 2 m was recommended to address Fe concentrations for the Average Operations scenario. This minimum treatment width would also reduce As concentrations for the High Post-Closure scenario to less than the target concentration.

The work completed emphasizes the critical need for robust characterization, detailed understanding of physical and chemical aspects of the flow system, and a phased design approach.

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