SITE GROUNDWATER MANAGEMENT STRATEGIES:
GROUNDWATER METAL REMEDIATION USING PERMEABLE REACTIVE BARRIERS

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ABSTRACT
Permeable reactive barriers (PRBs) can be a successful site management tool for groundwater impacted by Metal Leaching and Acid Rock Drainage (ML/ARD). Using a sustainable biological and chemical treatment approach, they intercept and passively treat dissolved metal contaminant plumes, thereby reducing risks to the receiving environment and downstream receptors. Drawing on previous experience with PRBs containing an innovative mixture of organic leaf compost, limestone and zero valent iron, we will discuss strategies for remediation of metal contaminant plumes.

PRBs are flexible and can be adapted to site conditions. PRB design considers contaminant concentrations and plume morphology; then optimizes PRB physical configurations and media composition to best match target treatment performance requirements. Tandem treatment walls can be designed to intercept high dissolved metal concentrations. Principals for design and installation in tidally influenced foreshore environments are also considered including the placement of targeted media mixes. Installation techniques successfully applied to date have included a slurry-assisted continuous trenching method through sand and gravels and rejuvenation of existing walls using a caisson method to sustainably extend the life of PRB sections.

A review of PRB geochemical performance has demonstrated successful reduction of metal concentrations through bacterially mediated sulphate reduction with formation of sulphide minerals, formation of mineral oxyhydroxides, and adsorption and co-precipitation with iron oxyhydroxides. Removal rates have been typically greater than 99% (for example, copper and zinc reductions from magnitudes of 10’s mg/L to <0.001 mg/L). Mineralogical analysis of media cores indicated the formation of sulphides, secondary precipitates, and oxyhydroxides.

PRBs provide a site-specific, flexible and effective approach to address management of groundwater ML/ARD in a variety of mine site applications; therefore, reducing potential impacts to the environment. In the presentation, we will explore potential design and installation strategies for PRBs and their remediation performance.

Key Words: passive treatment, sulphate reducing bacteria, biological treatment design
PRB PASSIVE TREATMENT TECHNOLOGY

Permeable reactive barriers (PRBs) are included in a family of passive treatment technologies that can remediate metal contamination in water (Skousen et al., 2005). Open Limestone Drains, Anoxic Limestone Drains, Constructed Wetlands (aerobic and anaerobic), and Sulfate-Reducing Bioreactors are all examples of passive treatment, which may be defined as the removal of contaminants by applying naturally occurring biochemical or chemical reactions, materials, and/or water gradients (including gravity).

The principle treatment strategy for a PRB is to intercept contaminated groundwater in-situ (hence the term “barrier”) with a reactive media, which then reacts or adsorbs contaminants as the groundwater flows under natural or induced gradients (Blowes et al., 2000). Note that different reactive materials can be used in PRBs to treat a wide variety of metal contaminants (Table 1).

Table 1. Examples of Reactive Media used in PRBs for Metal Remediation

<table>
<thead>
<tr>
<th>Principal Reaction Mechanism</th>
<th>Reactive Media</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (Eh)</td>
<td>Zero valent iron (ZVI), iron slag, Ferrous hydroxide, Ferrous carbonate, Ferrous sulphide</td>
</tr>
<tr>
<td>Precipitation (pH)</td>
<td>Limestone</td>
</tr>
<tr>
<td>Precipitation (biochemical)</td>
<td>Organic matter (leaf detritus, compost, wood mulch, sawdust, manure, hay, sludge)</td>
</tr>
<tr>
<td>Adsorption</td>
<td>Peat, Lignite (Brown coal), Fly ash, Organic matter (leaf detritus, compost, wood mulch, sawdust, manure, hay, sludge), Aluminosilicates (Zeolite), Activated Alumina, Phosphates (Apatite), Activated Carbon, Exchange Resins</td>
</tr>
</tbody>
</table>

Notes:
(1) PRBs can also treat organic hydrocarbons and chlorinated solvents. Their principal reaction mechanisms would include chemical destruction, biodegradation and adsorption using similar reactive media.

The reactive media and treatment mechanisms shown above are not mutually exclusive. For example, organic matter based PRBs (the focus of this paper) can be mixed with limestone and ZVI, thereby enhancing precipitation (biochemical) of metal sulfides, while also creating a stable precipitation environment (Eh, pH) for metal oxyhydroxides and adsorption to organic matter.

ORGANIC MATTER, LIMESTONE AND ZVI PRBs

For organic based PRBs, biochemical treatment relies on the biologically mediated anoxic reduction of sulphate to sulfide by creating conditions favourable for sulphate-reducing bacteria species such as desulfovibrio, hence harnessing their natural metabolic processes (Equation 1).

\[
2CH_2O_{(s)} + SO_4^{2-}_{(aq)} + 2H^+_{(aq)} \rightarrow H_2S_{(aq)} + 2CO_2_{(aq)} + H_2O_{(l)} \quad (1)
\]
Where: CH$_2$O(s) = Organic substrate

The short-lived hydrogen sulfide anion quickly reacts with dissolved metal cations to form insoluble precipitates (Equation 2).

$$Me^{2+}_{(aq)} + H_2S_{(aq)} \rightarrow MeS_{(s)} + 2H^+ \quad (2)$$

Where: MeS$_{(s)}$ = Metal precipitate

Other reactions also occur in combined organic matter/ZVI PRBs, depending on the type and content of the reactive media and geochemical environment. For example, as ZVI iron dissolves into an anaerobic solution to form oxyhydroxides (Equation 3), divalent metal contaminants can be captured through subsequent co-precipitation (Equation 4) and secondary precipitation (Equation 5) mechanisms.

$$Fe^0_{(s)} + 2H_2O \rightarrow Fe^{2+}_{(aq)} + H_2(g) + 2OH^-_{(aq)} \quad (3)$$

$$Fe^{2+}_{(aq)} + Me^{2+}_{(aq)} + 3H_2O \rightarrow FeMeO(OH)_{2(s)} + 4H^+_{(aq)} \quad (4)$$

$$Me^{2+}_{(aq)} + 2OH^-_{(aq)} \rightarrow Me(OH)_{2(s)} \quad (5)$$

Where: Fe$^0_{(s)}$ = Zero Valent Iron

Note that biologically mediated sulphate to sulfide reduction by sulphate reducing bacteria and ZVI chemical reactions mutually occur in anoxic environments. Maintaining an anaerobic, low Eh, neutral pH environment is essential for promoting growth of sulphate-reducing bacteria and proper functioning of organic matter/ZVI PRBs.

Adsorption of metals to organic surfaces also occurs, although these include weak physical attachments (i.e. Van der Waals forces) that allow remobilization with changes in geochemistry such as increases in Eh or reductions in pH. However, adsorbed metals can be transformed through the precipitation reactions above, or through ion exchange reactions occurring on the surfaces of the organic matter.

**PRB DESIGN**

To work effectively PRBs require contaminated water to flow through the reactive media; hence design of the barrier is important. A principle aspect of PRB design is the balance between four design factors: media reactivity, longevity, structure, and permeability. Regarding PRB permeability, reactive media should have a higher hydraulic conductivity than the surrounding soils to prevent changes in groundwater flow (i.e. underflow beneath the PRB). However, permeability must be balanced with the desire to maximize reactive media densities in the PRB to provide effective treatment. Likewise, while effective treatment (and reduced residence time) occurs with materials with higher reactivity, this must be balanced by media longevity. Longevity can be considered a temporal design factor which unites the three other design factors. In summary, all four design factors are interdependent and require careful planning to properly unite with site-specific conditions (Table 2) to develop a successful PRB.
An iterative approach can be applied to balance the technical requirements (and cost efficacy) for the PRB design. First, individual design and site factors are assessed for technical feasibility and cost. Critical design factors are then ranked and input into a decision matrix which then identifies those combinations of design elements to be shortlisted and studied in depth.

Table 2. Summary of Design Tenets for PRBs

<table>
<thead>
<tr>
<th>Design Factors</th>
<th>Site-Specific Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactivity</strong></td>
<td></td>
</tr>
<tr>
<td>Reactive media type</td>
<td>Water chemistry</td>
</tr>
<tr>
<td>- Identify reactive media/mix appropriate for contaminants</td>
<td>- Seasonal variations</td>
</tr>
<tr>
<td>- Bench/pilot scale to determine media reaction kinetics using site water</td>
<td>- Contaminant concentration maximums (and future changes)</td>
</tr>
<tr>
<td>- Reactivity safety factors</td>
<td>- Biological, anion/cation competition for reactive media (passivation, wall face fouling)</td>
</tr>
<tr>
<td>Site-specific conditions</td>
<td>Site-specific treatment criteria</td>
</tr>
<tr>
<td><strong>Permeability</strong></td>
<td></td>
</tr>
<tr>
<td>Permeability safety factors</td>
<td>Site hydrogeology</td>
</tr>
<tr>
<td>- Permeability modeling to prevent reduced flow or underflow</td>
<td>- Seasonal variations</td>
</tr>
<tr>
<td>- Reactive media passivation and wall face fouling</td>
<td>- Soil stratigraphy</td>
</tr>
<tr>
<td>- Reactive media passivation and wall face fouling</td>
<td>- Heterogeneous flow (lateral or vertical)</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
<td></td>
</tr>
<tr>
<td>Barrier morphology</td>
<td>Plume morphology</td>
</tr>
<tr>
<td>- Tailor media/mix (residence time and PRB thickness) for higher contaminant flux zones</td>
<td>- Variations in concentration spatially (lateral and vertical features)</td>
</tr>
<tr>
<td>- Oxygen ingress (use different media mix near surface to reduce permeability or cap with water table/surface barrier)</td>
<td>Site morphology</td>
</tr>
<tr>
<td>- Flow capture (i.e. funnel and gate, sheet pile walls)</td>
<td>- Available space for PRB</td>
</tr>
<tr>
<td>- Designs to address chemistry, permeability, site or equipment limitations</td>
<td>- Bedrock topology or confining layers to key into</td>
</tr>
<tr>
<td>Installation methods</td>
<td>Installations methods</td>
</tr>
<tr>
<td>- Wall dimensions</td>
<td>- Surface flows (avoid oxygenated water infiltrating into PRB)</td>
</tr>
<tr>
<td>- Scale of work</td>
<td>- Terrain and site accessibility</td>
</tr>
<tr>
<td>- Available installation equipment and their advantages and limitations on use</td>
<td>Installation methods</td>
</tr>
<tr>
<td>Notes: Longevity can be considered a temporal design factor based on media reactivity, structure and permeability considerations.</td>
<td></td>
</tr>
</tbody>
</table>

**REACTIVITY**

PRBs are designed to passively intercept contaminants flowing through a reactive media. A thorough understanding of site water chemistry (i.e. not just contaminants) is required to determine an appropriate
reactive media type or media mix (e.g. organic matter, limestone and ZVI). This includes understanding potential future changes in groundwater chemistry where site water quality continues to evolve (i.e. due to changes in contaminant source or ML/ARD uncertainties). Seasonal and other groundwater variations are also important in determining contaminant maximum concentrations and flux.

As with any water treatment approach, bench-scale column testing is conducted to verify reaction kinetics of different media types/mixes, and hence establish residence times required to achieve site-specific treatment criteria. Reactive media candidates shortlisted for full scale use and site contaminant groundwater maximum concentrations are tested to realistically determine reaction kinetics. Uncertainties in the column test kinetics, seasonal variations and/or future concentrations can be reduced by incorporating design safety factors.

For organic matter, limestone and ZVI based PRBs, a variety of organic materials can be incorporated into the design. For example, organic matter (ideally sustainably sourced at or near the site) can include compost, wood chips, hay, or manure (Waybrant et al., 1998, Waybrant et al., 2002, Figueroa et al., 2004). Microbes preferentially metabolize organic matter from easiest to more difficult; from simple sugars and acids to larger organic matter such as cellulose. It is recognized that PRBs are dynamic environments, where microbes play a key role in reaction kinetics for PRBs (Logan et al., 2005). Complex microbial communities including sulphate-reducing bacteria are reliant on the “supplied” PRB organic materials and each other to degrade organic matter and share nutrients. Hence, considering a variety of different organic materials (quality not just quantity), and understanding the evolution and succession of microbial communities as a PRB matures is important to maximize PRB design and longevity.

As part of preliminary design, site water quality is assessed for potential reactive media competition or fouling by other contaminants, cations or anions. Reactive media competition and oxygen ingress are sources of unintended PRB degradation. For example, ZVI can be fouled by calcium carbonates, sulphates, and silicates which can coat (passivate) iron surfaces, reducing both reaction rates and porosity (hence permeability) of the PRB (ITRC, 2005, 2011). Oxygen ingress (a key concern in bioreactors) can also cause excessive degradation of ZVI through formation of oxyhydroxides, causing both passivation of surfaces and permeability reductions. Regardless, as a PRB matures, both unintended and intended precipitates that are formed (including Reactions 1 to 5 above) begin to accumulate in the front face of the wall (wall face fouling), causing permeability to decline.

Field observations of cores from a mature PRB (composed of pea gravel, leaf compost, limestone, and ZVI) indicated the presence of wall face fouling and spatially erratic cementation similar to solely ZVI PRBs (Philips et al., 2010). It is likely that heterogeneous groundwater flow and/or contaminant flux and/or subtle density variations in the reactive media may have aggravated or contributed to the formation of preferential flow paths (such as macropores) through the PRB media.

PRB design can account for this performance concern through a) residence time safety factors (i.e. decrease media density and increase thickness) in combination with b) permeability safety factors (see
Permeability below), and/or c) structural improvements (see Structure below) creating transition zones or surface capping to limit oxygen ingress (Li et al., 2005, 2010).

**PERMEABILITY**

Like any site remediation process, a thorough understanding of site groundwater hydrogeology and geology provides a strong foundation for PRB permeability design.

PRB design can account for variations in soil permeability and heterogeneous or preferential flow paths (Hemsi et al., 2006). For example, a sand and gravel soil stratigraphic layer within a sand unit will likely convey a larger proportion of groundwater flow and hence contaminant flux. An appropriate PRB design would consider implications of the highly conductive sand and gravel unit on media residence time, permeability requirements, and wall structure. Depending on the complexity and scale of groundwater contamination, and site geologic and hydrogeological features, different PRB media mixes can then be customized to account for areas of higher or lower contamination.

For sites with complex subsurface hydrogeology and groundwater contamination, modeling of site groundwater flow and solute transport is beneficial in understanding site flow regimes, potential changes to flow paths once the PRB is installed into the ground, and supporting decision making for rejuvenation by assessing future changes in PRB longevity (such as gradual permeability reduction).

Again, note that permeability is balanced with the desire to increase the density of reactive media to promote an effective treatment environment (i.e. low Eh for organic matter/ZVI walls), and for cost effectiveness of handling and installing smaller media volumes. To avoid significant changes in groundwater flow patterns, the hydraulic conductivity of the PRB media should be higher than that of the surrounding soil. Accounting for permeability safety factors (and depending on site-specific conditions), reactive media conductivities could be expected to be several times higher than the surrounding soils. Previously installed PRBs included conductivity design targets approximately one order of magnitude higher than site soils (Ludwig et al., 2002), where design and installation was in highly conductive sand and gravel soils.

To achieve a desired permeability target, clean sorted sand or gravel can be mixed with reactive media. Permeability testing of different mixture ratios is integrated as part of column testing to best harmonize reactivity and longevity requirements. Note that accurate measurement of mixture ratios is critical to understanding permeability relationships during bench scale comparison testing, and for selecting a mix for full scale installation. Barrier configuration can also be used in conjunction with barrier composition to achieve a long-term permeability targets (see Structure Section below).

As material sources are identified for testing, verifying their quality also becomes important. Accurate grain size distributions and consistent grades of materials will reduce uncertainties in permeability and kinetic column testing, and ensure testing is representative of potential full scale installation (see Installation below). For example, passivation and PRB wall face fouling (and associated permeability
losses) can be mitigated by specifying minimum particle sizes, and expected particle size distributions for individual media components (i.e. organic matter, limestone, ZVI).

**STRUCTURE**

An advantage of PRB technology is its flexibility in design, and direct in-situ placement of reactive media where it is needed to remediate contamination. As reactive media metrics such as media mix ratios and thickness (to achieve a residence time) are established, the structure (i.e. dimensions and features) of the PRB can be fit to conform to site topography such as a creek bank or over an undulating subsurface bedrock surface to intercept contamination.

As part of proper site management and where site terrain allows, groundwater is ideally intercepted near the source to avoid contaminant mixing and dispersion down gradient, therefore necessitating treatment of larger groundwater volumes by the PRB. For instance, anoxic seeps or adit discharge locations are ideal candidates for PRBs since media can be installed directly over the seep and buried in place.

Conceptually, PRBs can be installed as either a continuous wall or as a funnel and gate configuration. Funnel and gate PRBs include a hydraulic cutoff wall to redirect groundwater toward the PRB. While both have their merits and challenges; site conditions (plume morphology and hydrogeology) and costs for equipment will largely dictate which method will be employed. For example, remote sites without accessible power may only consider installation of a continuous PRB. Where contamination is shallow and spread over a large lateral distance, a funnel and gate may be feasible. Expected timing and cost for rejuvenation should also be considered as part of structural planning (i.e. cost advantages for media replenishment of a continuous wall versus funnel and gate PRB).

![Figure 1. Continuous Wall and Funnel and Gate PRB Designs](image)

As noted previously, variations in groundwater contamination are often present due to asymmetries in source contamination and heterogeneities in subsurface geology. As groundwater contamination is rarely uniform in depth or lateral extent, different media mixes can be emplaced as layers in a PRB (Figure 2), or in separate PRB wall sections.
Also note surface caps (Figure 2) can be used to reduce atmospheric oxygen ingress from ground surface and mitigate potential passivation and permeability issues. Where the groundwater table varies seasonally or due to tidal cycles, a top layer of less permeable media (to at least the permanently saturated groundwater table) can also be used to suppress oxygen ingress and maintain water saturation above the anaerobic zone of the PRB.

Figure 2. Layered PRB Design

For areas of highest groundwater contamination, tandem walls can be used to increase residence time and/or overcome geotechnical and equipment trenching width limitations. The media mix can be identical or of different types (Figure 3) and/or ratios. Additionally, for cost and efficiency, groundwater contamination toward the outer edges of the plume can either be intercepted using single PRBs, or cut-off walls (funnels) installed to redirect contaminated water to the tandem wall.
Figure 3. Tandem Wall PRB Configuration
For example, a laterally dispersed groundwater metal plume was identified in a highly permeable tidally-influenced aquifer. Higher contamination occurred at shallow depths, likely confined by the presence of a saltwater wedge and freshwater density differences. Two tandem walls were installed to differing depths; one wall intercepting solely the highest contamination and a deeper wall to intercept both shallow and deeper contamination.

As noted previously, PRB design should consider the potential for permeability losses due to passivation and wall face fouling caused by precipitation. This can be addressed through structure by creating a transition wall in front of a main reactive wall. The transition wall intercepting groundwater would have a lower proportion of reactive media (or a different media type altogether as shown in Figure 3), hence dispersing precipitates over a larger media volume.

Although not proven, another transition wall approach may be to increase the wall face surface area. Instead of installing a lower proportion of reactive media, alternating layers of higher permeability materials such as pea gravel could be bedded with reactive media. This “layer cake” approach could maintain similar reactive media density in the transition wall as the main wall, but also create macropores that are more resistant to face fouling issues.

Figure 4. Tandem Wall PRB Configuration with Layer Cake Transition Wall

**INSTALLATION**

Installation will directly affect the reactivity, permeability and hence longevity of the PRB. Three factors are important to successful installation of a PRB – quality of materials, quality of process, and quality of installation method.
Careful control over material quality is essential to ensure adequate reactivity and permeability of the PRB. This includes consistency in particle size ranges and chemical quality of materials such as ZVI and organic material. Prior to and during installation, a materials quality management plan should be established.

Quality in process includes thorough reactive media mixing and careful placement of the media into the ground to avoid mix separation (through unintended gravity sorting) and densification (affecting permeability). Ironically, while thorough mixing is required to ensure consistent reaction kinetics and permeability throughout the PRB, organic materials, limestone and ZVI for PRBs should not be mixed aggressively to avoid pulverization of the reactive materials. To address this, media materials can be measured, placed into stockpiles, and then mixed in a set pattern with an excavator to maximize mixing while reducing unnecessary handling of the material. Gravimetric and permeameter analysis can then be used to verify mixing thoroughness.

Time is also essential for installation as ZVI will continue to undergo undesirable aerobic reactions with atmospheric oxygen and moisture until it can be placed into the ground. Cementation of stockpiles will become visually apparent as the mixed piles sit on the ground surface. While this cementation is usually broken up during handling for installation, it is preferred that mixing and emplacement occurs within days of each other (usually pending gravimetric and permeameter analysis of the pile) to avoid potential effects on material quality.

Decision factors in determining a suitable PRB installation method include the wall thickness (to achieve residence time), the depth for installation, availability (and costs) of specialized trenching equipment, and site specific geotechnical conditions (ITRC, 2005, 2011). PRB installation methods are diverse and are beginning overlap with pressure injection methods typically applied to source zone remediation. Current installation methods include sheet pile wall and backfill, slurry trenching (polymer slurry to stabilize trench walls), continuous trenching/backfill, deep soil mixing, caisson, pressure/jet grouting, and directional injection. Each has their advantages and limitations in achieving site-specific objectives.

For one example, the design of a PRB required installation depths greater than 15 meters through highly permeable, tidally influenced sand and gravels. The design also required a minimum wall thickness greater than 2 m. Slurry trenching using an excavator bucket (approximately 2 m wide) was identified as the most appropriate method. For installation, a large long-arm excavator and clamshell on a crawler crane were used to respectively excavate native soils and carefully place mixed media into a guar slurry trench.

REJUVENATION

While it can be assumed that reactivity, permeability and longevity design factors have largely been considered for the installation of the initial PRB, rejuvenation of PRBs should also consider enhancement “tweaks” for the new PRB. One critical additional component of rejuvenation becomes the consideration of geochemical stability of the spent media and its long term reactivity (due to new media addition,
mechanical agitation, oxygen ingress during reinstallation); and if removal is necessary, its management for disposal. During rejuvenation assessment for one PRB, some of the methods considered included:

- Slurry trenching – Potential geotechnical concerns associated with subsurface settlement of the existing PRB media and surrounding soils. Risks for wall failure were high. Could remove all spent media.
- Pressure/jet grouting or directional injection of new carbon and ZVI materials - Densification of soil was a concern. Potential uncertainties associated with subsurface injection control (differing conductivities of the permeable sand and gravel soils and the existing media), and adjacent utilities. Stability of spent media and its reactivity with new media was a concern.
- Deep soil mixing. Densification of soil was a concern. Potential uncertainties associated with quality control (complete mixing), and limitations given depths required. Stability of spent media and its reactivity with new media was a concern.
- Overlapping round caissons – Densification of soil was a concern. Required rehandling and wasting of new media in overlapping caissons. Could remove all spent media.
- Non-overlapping caissons – Densification of soil was a concern. Did not require rehandling of new media. Stability of spent media and its reactivity with new media was a concern.
- Box Caissons - Densification of soil a concern. Did not require rehandling of new media.

PERFORMANCE

PRB performance monitoring includes three basic components: geochemistry in transects across the PRB, hydraulic conductivity, and mineralogy. Geochemistry for compost, limestone, ZVI PRBs includes chemical analysis of target contaminants of concern, and key indicator parameters such as concentrations of other divalent metals sensitive to PRB geochemistry, pH, alkalinity, dissolved organic carbon, redox potential, and dissolved sulphide and sulphate (Sasaki et al., 2008). For example, organic and ZVI based PRBs require anoxic, reducing conditions. It would be expected that the redox potential would be low following installation and increase gradually over the lifetime of the PRB as treatment media is consumed. Overall, a firm understanding of the reactions taking place within the designed PRB will guide the selection of the geochemical indicators required for performance monitoring.

For the past decade, the chemical performance of PRBs has been proven at many sites (Skousen et al., 2005, Ludwig et al., 2009). Chemical removal rates for a PRB monitored over the past decade have typically remained greater than 99%, with reductions for several target divalent metal contaminants reduced by several orders of magnitude (10’s mg/L to <0.001 mg/L). Mass flux calculations and removal rates are also useful to determine the performance (ITRC, 2011) and potential longevity changes in the PRB.

Hydraulic conductivity testing for the PRB will vary depending on its size, complexity and age. Testing may include slug testing, estimation of hydraulic conductivity using continuous water level monitoring (Millham and Howes, 1995), pump testing, and tracer testing. Care should be taken not to induce migration of organic media caused by more aggressive mechanical water extraction methods (i.e. slug testing and pump testing).
As a PRB matures, organic carbon content decreases and ZVI surfaces degrade, while authigenic secondary mineral precipitates accumulate (i.e. wall face fouling). Collection of cores for gravimetric and mineralogical analysis can be useful in inferring the geochemical environment in which the minerals were formed, and contaminant mass flux treated/captured, and the quality and quantity of organic carbon materials remaining.

CONCLUSIONS

PRBs are a cost effective, site-specific, and sustainable treatment technology. The long-term performance of PRBs provide a sustainable solution to more active treatment technologies where remote site or source access may be difficult and point-of-use power may be cost prohibitive. Current state of the technology and life-cycle estimates (Higgins et al., 2009) indicates that PRB systems have low monitoring costs over their life-span (assuming at least ten years). The only long-term costs are routine compliance and monitoring costs (ITRC, 2011).

This is in contrast to active treatment systems which require energy for groundwater pumping, pipes and water treatment infrastructure, and imported chemicals. Although active treatment technologies are more reliable and definitive in their treatment capability - their capital and on-going costs can be considerably higher than a passive system.

PRBs offer a site-specific, sustainable solution to managing groundwater contamination at mine sites. A sustainable PRB design will ideally use locally sourced materials and structurally fit the PRB into site features to minimize disturbance. An advantage of this passive treatment method is that it provides in situ, on-site source and pathway removal of contaminants, which reduces risks to down gradient receptors. With careful planning and attention to quality, PRBs can offer significant cost savings compared to other technologies.

REFERENCES


