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Design of Passive Treatment Systems for Mine Drainage Waters

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ABSTRACT

Passive treatment systems are commonly used for remediation of mine drainage waters because they do not require continuous chemical inputs and operation. In this study, the selection and design criteria for such systems were evaluated, particularly the two most commonly used ones, i.e., permeable reactive barriers (PRBs) and vertical flow biological reactors (VFBRs). PRBs and VFBRs are operated on the same principles in terms of biochemical reaction mechanisms, whereas differences relate to configuration, engineering, and water management. In this study, each of these systems were described with respect to key design variables, such as metal removal mechanisms and removal rates, effectiveness and longevity, general design and construction, flow capacity, and cost. The information provided from this study could be used as a design guideline when a passive treatment option is considered for potential remediation of a mine site.

Key words : Passive treatment system, Mine drainage water, Permeable reactive barrier, Vertical flow biological reactor, Design

1. Introduction

In mine-impacted areas, passive treatment systems are often designed to neutralize acidity and remove metals in drainage waters (Jung et al., 2014; Underwood et al., 2014). Such systems do not require continuous chemical inputs because they are sustained by naturally occurring chemical and biological processes (Hedin et al., 1994; Hengen et al., 2014). In general, passive treatment systems are best suited for the treatment of waters with low acidity (< 800 mg $CaCO_3$/L), low flow rates (< 50 L/s), and therefore low acidity loads, where the key chemical outcomes are low metal concentrations and circumneutral pH. Over the past decade, a variety of passive treatment systems have been developed, and a large body of literature now exists with respect to the effectiveness of those systems for the treatment of acidic and neutral-pH mine drainage (e.g., Watzlaf et al., 2004; Johnson and Hallberg, 2005; Rose, 2010). Although a majority of the literature addresses the treatment of coal mine drainages, the data are also relevant for the treatment of drainages for metal mines (Gusek and Figueroa, 2009).

Considerations for the utility of passive treatment at a typical remediation project are based on three fundamental criteria: 1) availability of proven and demonstrable techniques for effluent treatment, 2) robustness and longevity, and 3) ability to operate with minimal intervention over the long term. Based on the literature, the two most popular passive treatment systems that have been considered for mine drainage waters are permeable reactive barriers (PRBs) and vertical flow biological reactors (VFBRs) (Jeen and Mattson, 2016).

Passive treatment systems are designed to provide a sequence of chemical reactions or biological processes that convert mobilized metals and complexes contained in the leachate into immobile or inert compounds. In this regard, passive treatment systems require consideration of several variables, including influent water chemistry, flow rate, volumetrics of the treatment cells, anticipated residence times, and effluent water quality targets.

The purpose of this study was to provide selection and design criteria from which to assess the potential applicability of PRBs and VFBRs at a particular remediation project.

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It is expected that from the criteria, primarily derived from the experiences in Canadian and U.S. sites, general guidelines for remediation of mine-impacted sites, including Korean sites, could be drawn. In this paper, each of the passive treatment systems are described with respect to key variables, such as metal removal mechanisms and removal rates, effectiveness and longevity, general design and construction, flow capacity, and cost.

2. Passive Treatment Options

2.1. Permeable reactive barriers (PRBs)

In the mining sector, PRBs are typically designed to intercept plumes of mine-influenced groundwater that show elevated concentrations of trace elements and, often, low pH (Fig. 1). The use of PRBs involves installing an appropriate reactive material into the aquifer so that contaminated water flows through the reactive zone. The reactive material induces chemical transformations that remove the contaminants through physical, chemical, or biological processes (ITRC, 2005). In particular, PRBs containing organic carbon (e.g., sawdust, spent brewing grain, compost, and peat) promote the removal of dissolved constituents in mine drainages under natural groundwater flow conditions by creating conditions suitable for microbially mediated sulfate reduction (Eq. 1) and the subsequent precipitation of metal sulfide minerals (Eq. 2) (Benner et al., 1997; Blowes et al., 2000; Guha and Bhargava, 2005):

$$SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2HCO_3^- \quad (1)$$

$$Me^{2+} + H_2S \rightarrow MeS + 2H^+ \quad (2)$$

where CH_2O represents an organic carbon substrate, Me^{2+} is a divalent metal (such as Fe, Cd, or Zn), and MeS is a sparingly soluble amorphous metal sulfide (e.g., FeS_2, CdS, or ZnS). Because sulfate reduction generally occurs in excess compared to the amount of metal sulfide precipitation that occurs, and given that sulfate reduction liberates bicarbonate at neutral pH, the net result is generally a decrease in the overall acidity of the treated water. Metal removal by adsorption onto organic carbon and by metal hydroxide/carbonate precipitation may also be enhanced because of alkaline conditions in the PRB (Gibert et al., 2005). In most

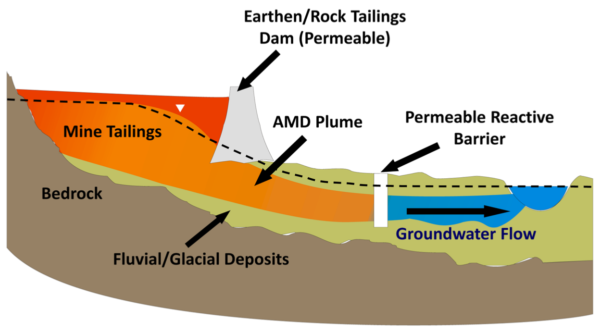

Fig. 1. Schematic of a PRB. Note that AMD represents acid mine drainage.

cases, sulfate reduction and subsequent metal sulfide precipitation should provide sufficient attenuation to achieve water quality targets for elements. Sulfate removal rates strongly depend on the organic carbon source, but for most forms of organic carbon, the sulfate removal rate is typically 100 mg/L per day of residence time.

As an example of actual treatment cases, a full-scale PRB for the removal of mine-related contaminants was installed at the Nickel Rim Mine near Sudbury, Ontario (Benner et al., 1997, 1999). The PRB was successful in treating mine-influenced water with slightly acidic pH ($5 < pH < 6$) and elevated concentrations of sulfate (1000-4000 mg/L), Fe (200-1000 mg/L), and Ni (up to 30 mg/L) over a period of 5 years. A pilot-scale PRB was installed in Vancouver, British Columbia to remediate sulfate-rich groundwater containing elevated levels of Cu, Ni, Zn, Cd, and Co (Ludwig et al., 2002). The reactive material was compost based and installed in a guar gum slurry trench. The trench was 10 m wide, 6.7 m deep, and approximately 2.5 m thick in the general direction of groundwater flow. Cd concentrations decreased from 15.3 μg/L to 0.2 μg/L, and Zn concentrations decreased from values in excess of 2 mg/L to < 0.1 mg/L. Groundwater velocity estimates were as high as 1 m/day (total flow ≅ 0.3 L/s), and the input concentration of sulfate was approximately 1000 mg/L. A full-scale PRB was constructed at the same site between November 2000 and February 2001. It is the largest organic-based PRB yet installed and is approximately 400 m in width, as much as 15 m in depth, and 2.5 m to 5 m in thickness (Mountjoy and Blowes, 2002).

Recently, PRBs containing organic carbon and granular zero-valent iron (ZVI) have gained attention (Lindsay et al., 2008; Guo and Blowes, 2009; Jeen et al., 2014). ZVI is a strong reductant and, when mixed with organic carbon, sustains conditions suitable for the growth and activity of sulfate-reducing bacteria (SRB). This is partly due to the acid-consuming nature of the reduction of water during anaerobic corrosion of ZVI, which can generate neutral or alkaline conditions (preferred by SRB). Eq. 3 describes the anaerobic corrosion of ZVI.

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

The hydrogen gas released in this reaction may be used by SRB in addition to organic carbon as an electron donor (Lovley and Goodwin, 1988). The surfaces of commercially produced granular iron materials are moderately corroded. These iron oxide surfaces are well suited for the adsorption of metals from mine waters (Wilkin and McNeil, 2003). Dissolved metals may also precipitate or co-precipitate with corrosion products that form on the surfaces of the ZVI. Because of these properties, mixtures of organic carbon and ZVI may offer improved removal of dissolved metals from water over use of organic carbon alone.

The economics of PRBs are tied to the longevity of the media and long-term hydraulic capture in the system. Longevity of reactive barriers may be limited by the chemical characteristics of the barrier, including the total mass of reactive material and the rate of reaction within the barrier. Potential processes leading to decreased reaction rates include consumption of reactive material, declining reactive surface area resulting from the precipitation of secondary minerals on reactive surfaces, clogging, and development of preferential flow paths (Blowes et al., 2000). Barrier life may also be limited by physical changes to the barrier, including decreases in porosity and permeability. In general, the longevity of PRBs is anticipated to be 15-20 years (ITRC, 2011). Given that PRBs are contained within the subsurface environment, they are minimally influenced by atmospheric temperature and have been shown to function well in cold climates (e.g., Benner et al., 1997).

2.2. Vertical flow biological reactors (VFBRs)

VFBRs are operated on the same basic principles as PRBs in terms of biochemical reaction mechanisms (Neculita et al., 2011). Differences relate to configuration, engineering, and water management (Fig. 2). A VFBR is a particular design of a general class of passive treatment systems similar to vertical flow wetlands (VFWs) or reducing and alkalinity producing systems (RAPSs). A VFBR is constructed in a geomembrane-lined facility, typically with the following structure, from the bottom upward in the direction of flow: 1) foundation, which may include excavation into natural substrates; 2) geo-membrane liner to provide containment and minimize downward seepage; 3) influent distribution system (perforated pipe), laid in gravel matrix; 4) reactive substrate layer, comprising a permeable matrix with reactive amendment (e.g., sawdust, spent brewing grain, compost, peat, and ZVI); 5) effluent collection system, consisting of perforated pipe; and 6) vegetative soil cover.

Post-aeration prior to discharge to the receiving environment may also be required to oxygenate the effluent and oxidize parameters that may be elevated in the suboxic outlet flow (e.g., ammonia, ferrous iron, and hydrogen sulfide). This can be achieved via the draining of treated effluents by gravity to an aerobic leach field (Fig. 2).

In a VFBR system, influent waters are forced upward through a permeable reactive matrix where reactions, identical to those described above for PRBs, take place. In this manner, a primary difference between VFBRs and PRBs is the nature of the hydraulic gradient. For PRBs, natural

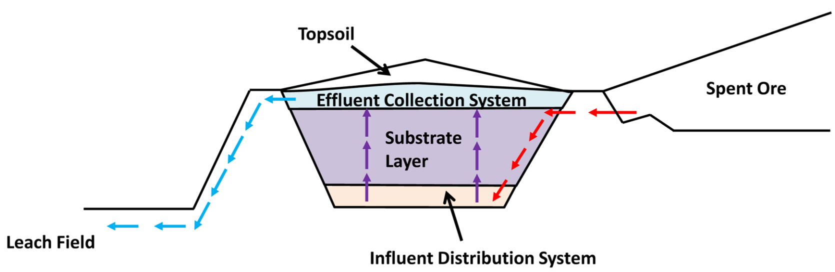

Fig. 2. Schematic cross section of a VFBR.

groundwater flow paths dictate the gradient and flow direction. For VFBRs, the upward flow path is afforded by containment (lined system) and water pressure. Given the imposed hydraulic containment of VFBRs, they are less dependent on natural substrate features in comparison to PRBs, which operate most effectively for well-constrained groundwater flow paths. This affords increased flexibility regarding VFBR placement.

Similar to PRBs, VFBRs operate by producing reducing conditions that promote metal removal via sulfide precipitation. In addition, the organic component provides sites for metal adsorption. In some cases, effluent pH can be expected to decrease as a result of acidity generated through the oxidation of Fe(II) and precipitation of Fe(III) hydroxides. If required, circumneutral surface water and groundwater collecting in the outer perimeter of the VFBR can be introduced into the effluent drain to contribute sufficient alkalinity to promote circumneutral pH conditions.

An example VFBR system is the one constructed at a closed cyanide heap leach facility at the Santa Fe Mine in Mineral County, Nevada (Cellan et al., 1997). The system was designed for a minimum 20 days residence time and a peak flow rate of 2.8 L/s to treat weak acid dissociable (WAD) cyanide (CN), sulfate (SO_4), nitrate (NO_3), mercury (Hg), and selenium (Se). Monitoring results indicated that all the contaminants of concern were removed sufficiently from the effluent to meet mandated discharge criteria. A similar but downward-flow vertical biochemical reactor (BCR) was operated between September 2008 and October 2009 at a gravel pit adjacent to the Colorado River in western Grand Junction, Colorado (Walker and Golder, 2010). A single 124 m^3 pilot-scale BCR was constructed to afford a flow rate of 0.13-1.5 L/s to treat selenium-contaminated surface water. The pilot BCR achieved maximum selenium removal rates of 98% with a hydraulic retention time of 2.4 days and a minimum effluent Se concentration of 0.0005 mg/L from the average influent concentration of 0.034 mg/L.

Given the nature of the effluent collection and distribution system, VFBRs are potentially more susceptible to atmospheric influences (e.g., temperature) compared to PRBs; therefore, care must be taken in the design of VFBRs intended for use in cold climates. Like PRBs, VFBRs may require maintenance and rehabilitation during their life, although maintenance requirements for the latter may be

Table 1. Comparison of PRBs and VFBRs

Variable	PRBs	VFBRs
Parameters treated	Acidity, SO_4, NO_3, As, Cd, Co, Cu, Fe, Ni, Pb, Se, Zn	Acidity, SO_4, NO_3, As, Cd, Co, Cu, Fe, Ni, Pb, Se, Zn
Effectiveness	Proven effective	Effective, but requires more performance data
Flow capacity	0.025-0.05 L/s/m (up to 10 L/s)[a]	~9 L/s/ha
Longevity	15-20 years	10-20 years
Proven at full scale	Multiple examples	Few examples
Materials	Coarse granular material, reactive amendment	Coarse granular material, reactive amendment
Liner	Not required	Required
Site characterization requirements	High	Moderate
Water management infrastructure requirements	Low	Moderate (distribution/collection systems)
Requirement for secondary treatment	No	In some cases, post-aerobic treatment is required
Flexibility with regards to placement location[b]	Low	High
Maintenance requirements	Low	Moderate (water management infrastructure)
Likelihood of success	High	Moderate to high
Cost	High installation cost, low maintenance cost	Moderately high installation cost, relatively low maintenance cost

[a]10 L/s represents the highest flow for the largest PRB currently in use, but higher flows are feasible.
[b]Location for a PRB is dictated by the location of a tailings storage facility and underlying hydrostratigraphy. Greater flexibility is afforded for the location of VFBRs.

more onerous given the nature of the distribution and collection systems. With improper design, VFBRs are susceptible to clogging by suspended sediments. Elevated total suspended solids (TSS) in influent waters can result from poor design of the influent collection and distribution system or from the oxidation and precipitation of Fe and Mn within the aerobic portions of the VFBR. In general, TSS levels should be reduced to < 50 mg/L in the influent to maximize performance and life span of the system. Like PRBs, accumulation of Fe and/or Al precipitates can lead to short circuiting and reduced rates of reaction (Rose, 2010). Saturated conditions must be maintained for VFBRs to be effective. In this regard, water elevation within the VFBR must be controlled to minimize the potential for reoxidation of reduced species (e.g., metal sulfides). A general comparison of PRB and VFBR systems is summarized in Table 1.

3. Design and Construction

The design of subsurface passive treatment systems depends on several variables, including topography, hydrology, hydrogeology, influent water quality, and desired effluent water quality. Specifically, residence time, flow rate, and depth of flow are critical considerations in the design stage. Required residence time depends upon contaminant types, removal rates, and treatment goals. Site conditions must also be evaluated to assess the suitability and potential effectiveness of the proposed system. In general, site-specific data requirements include water balance information, influent characteristics (major ions, TSS, trace elements, etc.), treatment targets, and site suitability features. Site suitability features include hydrogeologic conditions, available area, site topography, soil data and depth to the bedrock, availability of construction materials, availability of reactive media, climatic conditions, and presence of sensitive downstream environments. Based on these general characteristics of passive treatment systems, specific considerations for PRBs and VFBRs are as follows.

3.1. Permeable reactive barriers (PRBs)

Construction of PRBs involves digging a trench or pit in the flow path of the contaminated groundwater plume, filling the void with reactive materials (e.g., a mixture of organic solids, ZVI, and possibly limestone gravel) that are sufficiently permeable to allow the unimpeded flow of groundwater, and finally landscaping the disturbed surface.

The site characterization data needed for PRB design are extensive. In particular, data gathering on a smaller scale is necessary for placement of a PRB, including the complete vertical and horizontal delineation of the groundwater plume and characterization of the hydrogeologic, geochemical, geotechnical, and microbiological conditions. Work associated with PRB design includes treatability studies (e.g., lab-based column test work) and groundwater modeling.

The most common PRB design is the continuous PRB configuration. In such a system, the reactive media is distributed across the width and vertical extent of the groundwater contaminant plume. Continuous PRBs have minimal impact on natural groundwater flow when properly designed and constructed. Theoretically, PRBs do not need to be keyed into a low-permeability layer, as long as the permeability of the PRB is the same as or greater than that of the aquifer. However, it is good practice to key the PRB into an underlying low-permeability layer (e.g., bedrock or clay-rich till) if one is present or to a sufficient depth to ensure complete plume capture and as a safeguard in the event the permeability of the PRB is compromised. Ensuring sufficient permeability of the reactive matrix is one of the design considerations for PRBs. Installation methods include unsupported excavation, supported excavation, continuous trenching, and biopolymer trenching.

The flow capacity of PRBs depends on parameter concentrations of the influent water, metal removal rates of the reactive materials, and associated residence time. The highest flow rate for which a PRB can be applied is up to about one pore volume a week (i.e., 7 days of residence time). The largest PRB currently in use globally (i.e., 400 m wide, 15 m deep, and 2.5 m thick; Mountjoy and Blowes, 2002) operates at a flow rate of ~10 L/s. Theoretically, if land and resources are available, a bigger PRB, capable of treating higher flow rates, is feasible. This is illustrated in Fig. 3, which shows flow rate as a function of PRB thickness, assuming residence times of 7 days and 14 days. In Fig. 3, the flow rate of a PRB was calculated using Eqs. 4 and 5:

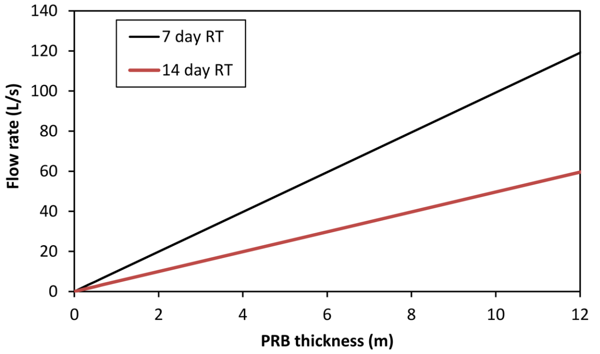

Fig. 3. Flow capacity for PRBs as a function of thickness, assuming residence time (RT) of 7 days and 14 days. A 1000 m width and 15 m depth of the barrier and an active pore volume of 40% were assumed.

$$1 \text{ PV of a PRB} = n \times \text{volume of a PRB (thickness} \times \text{width} \times \text{depth)} \quad (4)$$

$$\text{Flow rate} = 1 \text{ PV/RT} \quad (5)$$

where PV represents pore volume, n represents porosity (assumed as 40%), and RT represents residence time. The width and depth of a PRB were assumed 1000 m and 15 m, respectively. Based on a residence time ranging from 7 days to 14 days, a 1 m-thick PRB can afford flow rates of approximately 5 L/s to 10 L/s.

3.2. Vertical flow biological reactors (VFBRs)

There is not one uniform standard substrate design nor standard depth regarding the construction of VFBRs, but the general design includes the following specifications:

- Area/depth - Sizing of the facility is dependent on the range of flow volumes that will report to the system;
- Organic substrate - Combination of cellulosic (wood chips and hay) and organic waste (manure and peat) should have sufficient hydraulic conductivity to ensure that the system can handle design flows. Additions of organic materials may be required periodically to maintain treatment efficiency;
- Gravel/limestone - To maintain permeability (e.g., hydraulic conductivity of 10^{-3} to 10^{-4} m/s) and provide alkalinity, if necessary;
- Liner - Preferably, the base and sides of the vertical flow system will be constructed of compacted material with low hydraulic conductivity to prevent influent water from seeping through the sides and short-circuiting the treatment system; and
- Drains - The network configuration will be dependent on the actual configuration of the vertical flow system but should have sufficient coverage to encourage vertical flow through the entire vertical cross section.

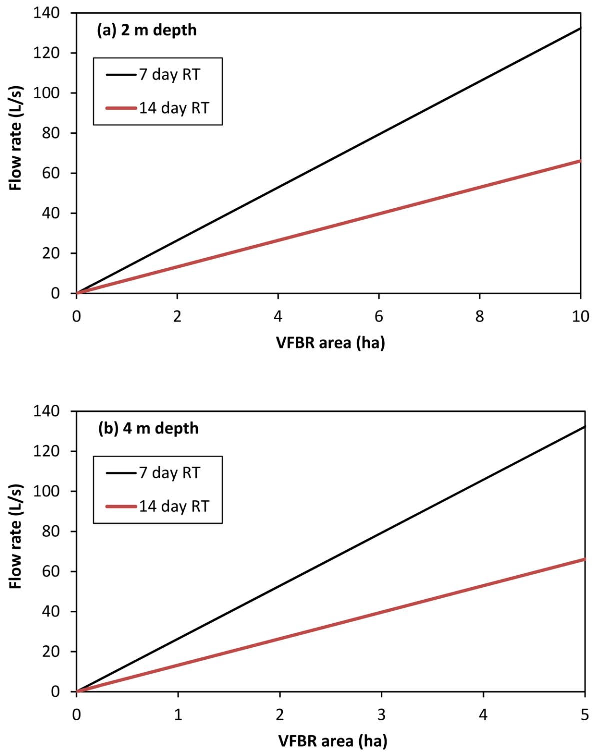

Fig. 4. Flow capacity for VFBRs as a function of surface area, assuming residence time (RT) of 7 days and 14 days. A (a) 2 m and (b) 4 m depth of the active vertical flow bed and an active pore volume of 40% were assumed. Note the difference in scale for the VFBR area between (a) and (b).

Similar to PRBs, flow rate is critical when sizing VFBRs. Furthermore, VFBRs perform best over time when receiving influent at a consistent flow rate. Flow velocity should be low (less than 0.15 m/s) to provide sufficient contact time to attain target removal rates (Burton and Tchobanoglous, 1991). In general, a residence time of 7-14 days is recommended. Flow depths vary from system to system depending on these factors. Based on a residence time ranging from 7-14 days, a 2 m depth of the active vertical flow bed, and an active pore volume of 40%, flow rates of approximately 6.6 L/s per hectare to 13.2 L/s per hectare are achievable (or average of ~9 L/s/ha based on a residence time of ~10 days). This is illustrated in Fig. 4a, which shows flow as a function of surface area for water residence times of 7 days and 14 days. VFBRs can be constructed to support the upward flow of waters through a permeable reactive matrix that may be up to 4 m thick. Increased depth of the reactive bed allows for greater unit flow yields per area (Fig. 4b). In Fig. 4, the flow rate of a VFBR was calculated using equations similar to Eqs. 4 and 5; however, the volume of a VFBR was calculated as area × depth (assumed as either 2 m or 4 m). The flow rate was plotted as a function of area.

4. Cost

The main costs of PRBs are related to the site characterization, design, and construction. Whereas the initial installation cost may be substantial, there is little expense thereafter to maintain or operate the barrier (i.e., no active energy costs nor need for employees to monitor and maintain the system). Generally, the cost factors that should be evaluated for a PRB installation include the following: site characterization, design, construction, purchase and installation of reactive media, licensing fees, operation and maintenance (O&M) costs, annual monitoring and reporting costs, and media replacement/rejuvenation.

Capital and operating costs for PRBs vary from site to site depending on the size of the barrier, barrier design, reactive material used, and physical and chemical characteristics of the contaminated groundwater plume. Usually the capital costs are similar to a pump-and-treat system, but operating costs are much lower. Of the various costs, the media costs are generally the greatest. Sources of organic carbon are highly variable; thus, cost estimates rely heavily on treatability studies for design. Whereas limited information is available with regard to the construction costs of operational-scale PRBs, material and installation costs for the PRB at the Nickel Rim mine site (15 m long, 3.6 m deep, and 4 m wide) were approximately $42,600 (Benner et al., 1997). This includes the cost for construction, materials, and the reactive mixture, but does not include costs for design, operation, monitoring, and periodic maintenance. Approximately half of that cost was incurred for materials and the other half for installation. Based on this information, the unit capital cost for the Nickel Rim site was calculated as approximately $197 per cubic meter of PRB volume.

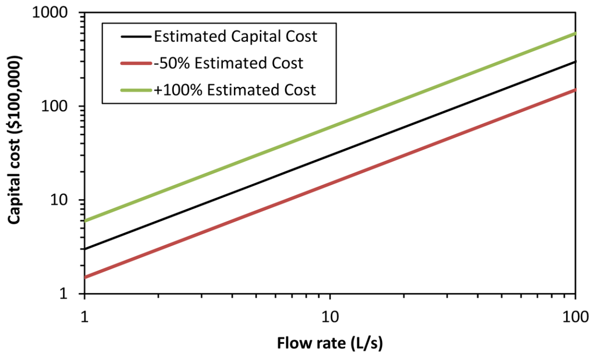

Fig. 5. Estimated capital cost for PRBs as a function of flow rate.

Using the unit capital cost approximated from the Nickel Rim site, capital costs for constructing PRBs were estimated assuming a residence time of 7 days (Fig. 5). Capital cost was calculated by multiplying a volume of PRB with the unit capital cost ($197/m^3 of a PRB). The capital cost was plotted as a function of a flow rate, which has a corresponding volume a PRB (using Eqs. 4 and 5). According to the estimation, capital costs for a PRB, with a volume of ~7,500 m^3 to handle a flow of ~5 L/s (residence time of 7 days), are estimated at $1,470,000 (range of $740,000 to ~$2,960,000; Fig. 5). The assumed -50% (×1/2) and +100% (×2) ranges represent uncertainties associated with the unit capital cost estimation. Annual monitoring and reporting costs are estimated as $27,000/year to $42,000/year (ITRC, 2011).

Factors that affect the costs of VFBRs include required land area, pretreatment requirements (e.g., TSS removal), water management infrastructure, topography, soil type, land use, and site complexity. In general, VFBRs are considered more expensive to construct than surface wetland systems because of the engineered media and the likely requirement for a liner. VFBRs require less land and plants, but more piping and a better control of flow. Other site-specific factors such as water chemistry, treatment goals, and source and availability of construction media can also influence the cost. Typical cost factors for VFBRs can be proportioned as follows: 1) land cost: 3%, 2) clearing and grubbing: 4-5%, 3) excavation and earthworks: 15-25%, 4) liner: 12-25%, 5) media: 50-55%, and 6) miscellaneous: 10-12%.

Similar to PRBs, the media costs are usually the greatest of these costs. The unit capital cost for VFBRs is estimated

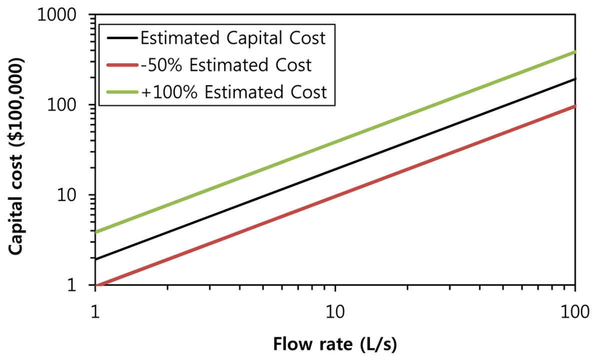

Fig. 6. Estimated capital cost for VFBRs as a function of flow rate.

at approximately $127 per cubic meter of VFBR volume (Jack Adams, University of Utah, personal communication). Capital cost for a VFBR (Fig. 6) was calculated using a method similar to the one used for a PRB, whereas in this case, the unit capital cost of $127/m^3 for a VFBR was used instead. Based on this, capital costs for a 1 ha system, with a volume of ~7,500 m^3 to handle a flow of ~5 L/s (residence time of 7 days), are estimated at $950,000 (range of $475,000 to ~$1,900,000; Fig. 6). Annual maintenance, monitoring, and operational costs are estimated at ~2.5% of the construction costs, or roughly $25,000 per hectare per year (U.S. EPA, 2000).

5. Conclusions

This study provides generic information about passive treatment systems that could be considered for treating seepage from a mine site. Passive treatment systems, such as PRBs and VFBRs, are designed to provide a sequence of chemical reactions or biological processes that convert mobilized metals contained in the mining-influenced water into immobile or inert compounds. The systems require consideration of several variables, including influent water chemistry, flow rate, volumetrics of the treatment cells, anticipated residence times, and effluent water quality targets.

From this study, it is suggested that actual design and installation of passive treatment systems should be determined based on site-specific conditions. Thus, accurate site characterization and water balance calculations should be conducted to determine feasibility and capacity of passive treatment systems that can afford the anticipated seepage from a tailings storage facility. The feasibility of passive treatment can be assessed through a combination of laboratory-scale testing, pilot-scale field verification, and hydrogeologic/geochemical modelling. It should also be noted that replenishment of the reactive materials or installation of additional reactive materials (e.g., in front of an existing PRB) may be required, as the reactivity and treatment potential of the passive treatment systems may decrease over time. The spent PRB reactive materials may be left in place if no significant changes in redox conditions are expected, whereas spent materials from VFBRs can be considered stable as long as they are stored under permanently saturated conditions. Overall, the selection and design criteria provided in this study could be used as a basis from which the potential applicability of passive treatment systems is assessed at a particular mine site.

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