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TECHNICAL ARTICLE

Economic Performance of Active and Passive AMD Treatment Systems Under Uncertainty: Case Studies from the Brunner Coal Measures in New Zealand

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Abstract
Acid mine drainage (AMD) often requires management long after mining operations have ceased. Cost-effective long-term passive treatment systems (PTS) are required for closure of mine sites. However, PTS research seldom defines well-constrained operational and financial parameters to enable confident decision making by mining companies. PTS are generally assumed to be a lower-cost alternative to active systems when used in favorable circumstances, but there is little objective information to define when they are more suitable than active treatment. Instead, general 'rules-of-thumb' for flow rates or acid loads are used to determine when PTS are best used. We used well-characterized AMD from multiple historic and active coal mine sites in New Zealand to test these rules-of-thumb from a financial perspective by modelling capital and operational costs over a 100 year timeframe. We present static and uncertainty-based cost assessments of a mussel shell reactor PTS compared to typical active AMD treatment systems at six mine drainage sources from the Brunner Coal Measures. We show that for expected AMD characteristics and duration of treatment, savings on operational costs with PTS can exceed the higher initial capital costs. In addition, the financial advantage of PTS over time may be achieved at flow rates and acidity loads that exceed the industry rules-of-thumb PTS limits. However, in some circumstances, cost projections for high up-front capital costs of purchasing all treatment media for the life span of the PTS is less favorable than discounted treatment media in active treatment systems over time. Understanding financial models of AMD treatment options during mine site design can help reduce the costs of operating and closing mine sites.

Keywords Passive treatment system · Active treatment · Cost-effectiveness · Closure · Geochemistry · Mussel shell reactor

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Introduction

Acid mine drainage (AMD) is common at active and abandoned mine sites around the world (INAP 2014). In New Zealand, AMD from Brunner Coal Measures is documented at active and abandoned opencast and underground mines (Alarcon 1997; Black et al. 2005; deJoux 2003; James 2003; Pope et al. 2010). These, and other New Zealand-based studies, provide a consistent and well characterized subset of AMD chemistry with low pH, moderate to high acidity, and elevated concentrations of Fe, Al, Mn, Ni, Zn, and sulphate compared to mine drainage chemistry from hard-rock mining operations in which different elements can be variably abundant in the drainage (e.g., Espana et al. 2005; Nordstrom and Alpers 1999; Rose and Cravotta 1998).

Treatment of AMD can be accomplished by either active or passive treatment systems (Skousen et al. 2000). Active systems require continuous dosing with neutralizing chemicals, consume power, and require regular operation and maintenance, but they are very reliable. Passive treatment systems (PTS) avoid continuous dosing with neutralizing material and power consumption by taking advantage of naturally occurring geochemical, biological, and physical processes and clever use of topography, but can fail if not carefully selected, designed, and monitored (Trumm 2010).

Investment decisions for AMD management at mining operations typically consider AMD treatment costs required for mine closure. Hence, the cost of AMD treatment for the duration of operations and the post-closure period affects mine production planning (Gholemnejad 2009). However, studies that compare active treatment systems and PTS rarely conduct a detailed economic comparison. Skousen and Ziemkiewicz (2005) compared the cost effectiveness of treatment systems, but considered only the construction costs. Zinck and Griffith (2013) compare construction and operational costs but did not consider these costs across the lifetime of the systems. DiLoreto et al. (2016) conclude that mussel shell PTS are cost-effective due to their low cost, but reach this conclusion without detailed economic analysis. Morin and Hutt (2006) assess the life-time costs of AMD treatment systems and relate these to AMD flow rates only.

Installing a passive or active AMD treatment system can have long-term financial consequences, but hydrochemical thresholds for selecting either type of system have become rules-of-thumb: passive systems are not suitable above flow rates of 50 L/s or for acidity loads larger than 150 kg/day. The GARD Guide (INAP 2014) confirms the acidity load threshold for passive systems citing “experience in Australia” (INAP 2014, Sect. 7.5.2) and mentions that most systems treat less than 1000 m^3/day, or 11.6 L/s. However, fluctuations around median flow rates or acidity concentrations occur and the tolerance for passive systems to deal with natural variably are seldom studied. Thus, the implications of hydro-chemical variability on design criteria are poorly quantified.

It is unclear if the rules-of-thumb for selection of passive or active AMD treatment systems also consider the lifetime costs of either type of system. There are no publications that show the lifetime financial behavior of these systems under a range of hydro-chemical conditions. We addressed these gaps in the literature by comparing the lifetime costs of conceptualized passive (mussel shell reactor) and active (lime ($Ca(OH)_2$) addition) AMD treatment systems for six coal mine sites in the Brunner Coal Measures in New Zealand. The characteristics of AMD from these mine sites are chemically similar; however, flows and loads vary. We assessed the influence of flow rate and acid load conditions derived from Monte Carlo simulations on the financial performance of passive and active systems.

Characteristics of AMD at the Study Sites

The Brunner Coal Measures on the West Coast of the South Island of New Zealand contain bituminous coal of Eocene age. AMD from the Brunner Coal Measures mine sites has low pH, high acidity, and elevated concentrations of trace elements. Frequent high-rainfall events in the region increase acid flux with very little dilution of AMD seeps from waste rock dumps or underground workings, particularly at historic and poorly managed mine sites (Pope et al. 2016). The mine sites considered in this study were: Bellvue, Escarpment, Whirlwind, Herbert, Blackball, and Mangatini.

The six study sites can be characterized by AMD acidity and flow rates (Fig. 1, Table 1). Figure 1 also displays the two rules-of-thumb that are often used by the mining industry to select a treatment system: passive systems are thought not to be suitable either for flow rates over 50 L/s or acid loads (the product of acidity and water flow) exceeding 150 kg/day. Variation in the water chemistry and flow rates observations is greatest at Bellvue and Mangatini. Flow rate can vary by more than an order of magnitude and acidity concentrations can vary by a factor of 4-5 as a consequence of high rainfall without much seasonal variation. This suggests that variable annual acid flux at the study sites is driven strongly by flow rates, which must be considered in treatment system design.

AMD at the Bellvue site is characterized by water chemistry that creates high acidity but a very low water flow rate (≈ 1 L/s average). As a result, Bellvue is a site that falls well within the generally accepted flows and load limits for PTS. A mussel shell reactor has been constructed at the site and is currently being monitored (Trumm et al. 2017).

Escarpment, Herbert, and Whirlwind are sites with moderate flow rates between 1 and 10 L/s. Acidity concentrations at these three sites were the lowest of the sites in our study. The sites are closer to the generally accepted acid load limit for PTS but sit comfortably within the limit for maximum flow rates. There are full-scale mussel shell reactors in operation at the Whirlwind site (Weber et al. 2015) and Escarpment coal mine (Robertson et al. 2017).

The flow rate at the Blackball site is above both the 50 L/s flow limit and the 150 kg/day acidity load limit for PTS. According to the industry rules-of-thumb, PTS are not viable at this site, but AMD characteristics are sufficiently close to the limits to consider Blackball as a potential edge case. As an extreme case, we also considered AMD treatment of the Mangatini stream, which drains a mining operation and is characterized by high acidity and very high flow rates that place it far beyond the recommended bounds for PTS.

Cost Models for Passive and Active AMD Treatment Systems

To compare the costs of passive and active AMD treatment systems at our study sites, we applied our general experience from managing AMD to construct cost models. We used our knowledge of the region to determine transport, chemical storage, and operational costs for each site. For model parameters that lacked region-specific information, we incorporated information from international studies. Figure 2 shows the general cost model for active systems on the left and for passive systems on the right. The model structures and analyses were programmed in R version 3.6.1 (R Core Team 2019).

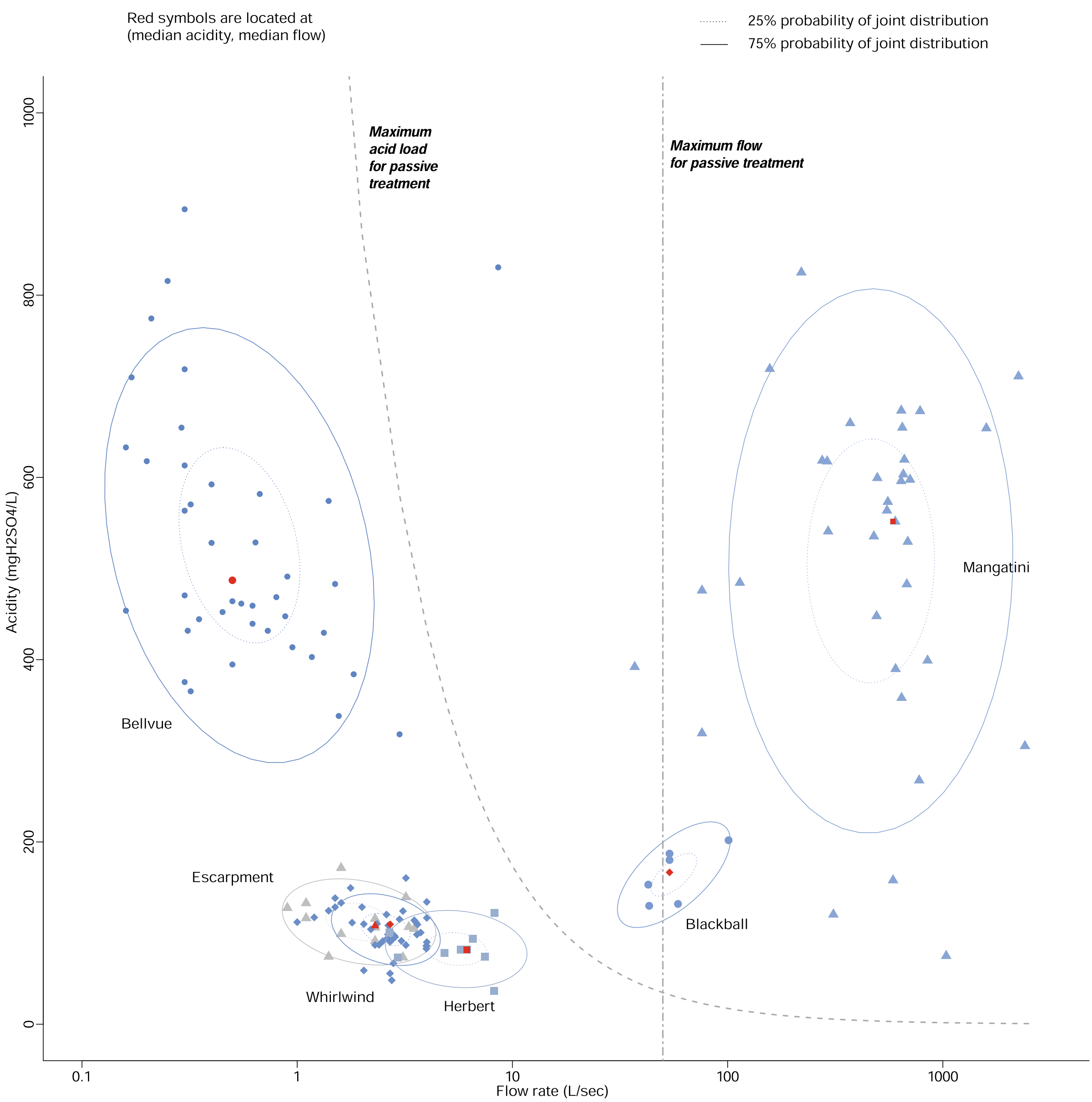


Fig. 1 Water chemistry and flow measurements at each site, with flow on a log scale. The inner and outer dashed circles respectively indicate the 25% and 75% confidence levels of the bivariate probability distribution for each site. For each site, red symbols are placed at the coordinates (median flow, median acidity). The dashed lines show the industry rules of thumb for flow rate and acid load (product of acidity and water flow)

Table 1 Observed medians of water chemistry and flow at the study sites

Site name	AMD Source	Al (mg/L)	Fe3 (mg/L)	pH	Flow (L/s)	Acid (H_2SO_4 kg/day)	Status	References
Blackball	Impacted stream	18.6	11.1	3.2	53.7	753	Abandoned	Trumm and Watts (2010)
Bellvue	Underground mine drainage	39.0	60	2.57	0.5	20.3	Abandoned	Trumm and Cavanagh (2006)
Escarpment	Waste rock dump toe seepage	14.8	4.39	3.5	2.3	19.7	Active	Robertson et al. (2017)
Herbert	Waste rock dump toe seepage	8.4	1.2	3.22	6.14	40.8	Active	Trumm et al. (2008), Trumm and Watts (2010)
Mangatini	Mine site catchment	65	46	2.9	587	22,110	Active	Davies et al. (2011)
Whirlwind	Waste rock dump toe seepage	15.2	1.81	3.4	2.71	22.7	Active	Weber et al. (2015)

Active systems were assumed to use conventional lime ($Ca(OH)_2$) based treatment. At Bellvue, Escarpment, Whirlwind, and Herbert, construction costs were assumed to be the same as the known costs of an active system installed at the Reddale coal mine (Olds et al. 2016). The AMD characteristics of Reddale are comparable to those of these four sites. The construction cost for the active system at Mangatini were also known, and the site conditions at Blackball more closely resembled that site. We conservatively assumed that construction costs were half those of the Mangatini system. This included a storage silo for lime to reduce trip frequency to this remote and hard-to-access site and lower delivery costs.

For active treatment, the cost of the clarifier was set at 27.4% of the construction cost, based on cost averages presented in Zinck and Griffith (2013). System replacement was set at every 20 years. Annual system maintenance costs were assumed to be 2% of the total construction costs.

Median flow and acidity at each site determine the required annual volume of reagent ($Ca(OH)_2$), with an assumed efficiency of 95% (Trumm 2010). The average costs of sludge management and disposal were set at 28.9% of the average reagent costs (Zinck and Griffith 2013). Other operating costs include labor for weekly system checks ('Labour' in Fig. 2), quarterly water sample collecting and testing ('Monitoring' in Fig. 2), power to run the system (roughly known for Mangatini and scaled by system cost, as a proxy for system size and power use, for the other sites), and annual clearing of access roads using heavy equipment.

The PTS was assumed to be a mussel shell bioreactor (Crombie et al. 2011; Uster et al. 2014), for which capital and operational costs were derived from the installation of full-scale PTS at two of the sites studied (Robertson et al. 2017; Weber et al. 2015). Systems were sized for a hydraulic residence time (HRT) of 36 h at the site's median flow rate. The volume of mussel shells needed was calculated accounting for the target HRT and the porosity of the media (59%). The construction costs consisted of heavy machinery rental to dig an area of sufficient size to a depth of 1.2 m to provide the required volume. Media purchasing cost in this case included the mussel shell transportation cost. The longevity of the media depends on the neutralization capacity of the mussel shells, acidity load, and the system's size. Larger systems last longer, while higher acidity reduces media

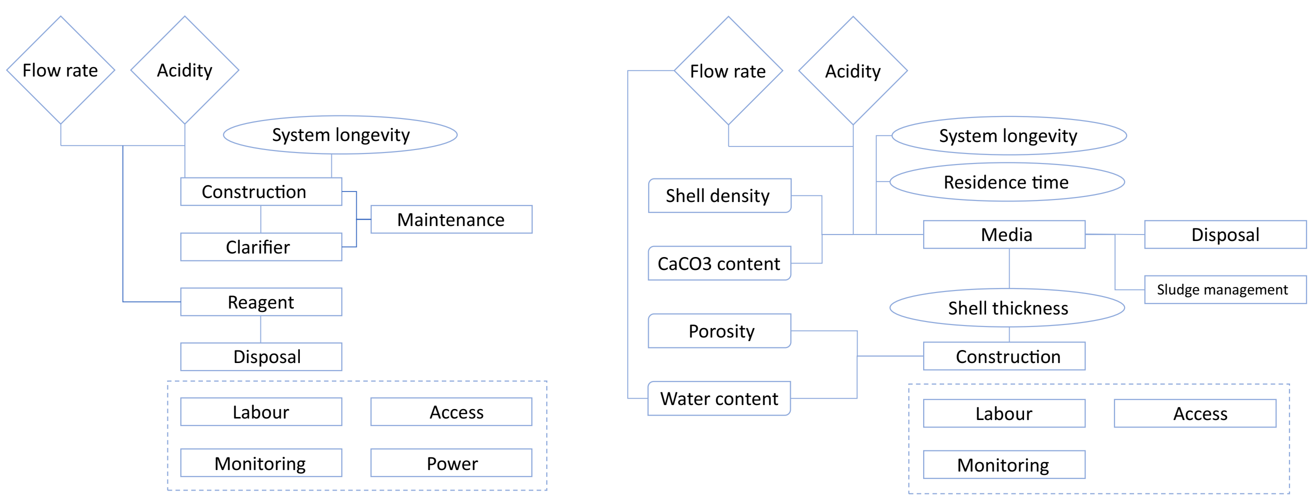


Fig. 2 Economic cost models of active (left) and passive (right) AMD treatment systems. Cost elements are shown in rectangles

longevity. The systems were designed to have the top layer of the media scraped off annually with heavy equipment and disposed of ('sludge management' in Fig. 2) and to require media renewal every 25 years, with disposal of the residual media. The annual system maintenance, access maintenance, and monitoring costs of PTS were assumed to be identical to those of active costs. Labour costs are less, since PTS are less likely to break down and power costs are absent.

A detailed breakdown of the various costs for each system at each study site used in the financial analysis is given in Table 2. The design cost in the last column consists of the capital cost, including significant infrequent costs, and the first year of operating costs. It is meant to capture the costs that would likely be considered when designing and choosing between AMD treatment systems. Design costs indicate generally that passive systems cost less than active systems when AMD characteristics are well within the rule-of-thumb limits. However, when water flow approaches the rule-of-thumb threshold, as it does at the Herbert site, the design cost of PTS starts to exceed that of active systems.

The cost models do not include the externalities of downstream environmental impacts from AMD. Regulations and closure agreements dictate that treatment systems must have sufficient capacity to decrease acidity to levels where downstream environmental harm is negligible. Hence, the externality that could arise from the AMD must be fully internalised by the mining company during construction and operation of the treatment systems.

Financial Modelling

We investigated the financial performance of active treatment and PTS in three ways. First, we compared design costs, as presented in Table 2, with a full, discounted, life-time cash flow analysis. The discounted costs cover the full period that AMD treatment is necessary, assumed to be 100 years. This illustrates how the cost structure of AMD treatment systems changes over longer time spans and emphasizes costs that might not appear as being significant in an overview of capital and operating expenditures (i.e. the design cost).

Second, we conducted a sensitivity analysis for the suite of parameters on the discounted cost ratios of active and passive systems. This analysis identifies cost components that more strongly affect the financial viability of either type of system, which is helpful when there is uncertainty about future prices across a range of AMD conditions. In this step, we also considered the discount rate and the natural rate of acidity reduction determined by Olds et al. (2014).

Third, we introduced uncertainty about acid load using Monte Carlo simulations for acidity and flow. Available time series data of water chemistry and flow were used as inputs to the Monte Carlo simulations. Under the assumption of a joint multivariate lognormal distribution of flow and water chemistry parameters (pH, dissolved aluminium, dissolved iron), combinations of these AMD characteristics were simulated 20,000 times and the interval of the first to third quantiles of flow and acidity were isolated. Affected system capital and operational expenditures (see Fig. 2) were scaled accordingly. With this sensitivity analysis for the assumption of variability in acid load, we more precisely determined threshold levels for cost parameters and associated flow and acidity where the financial advantage of AMD treatment systems switches from one to the other.

These comparisons focus on Bellvue, which is well within the generally accepted limits of passive systems, and Blackball, which is an edge case for the rule-of-thumb flow rate and above the rule-of-thumb acidity load. Lifetime costs were calculated using the cost parameters shown in Table 2 and applying discounting, which is the practice of making cash flows comparable over time, where higher (lower) discounting rates imply that decision makers place less (more) emphasis on future cash flows when making an investment decision. We use rates of 2%, 4.5%, and 7% as low, medium, and high discount rates. The medium discount rate reflects current policy practice in New Zealand, with the lower and upper deviations selected quasi-arbitrarily to illustrate the effect of comparatively large deviations on the results under AMD conditions at Bellvue and Blackball.

Results

Cost Structures

Over longer time spans, the cost structure of AMD treatment systems changes compared to the cost structure considered during their design and selection. The reason is that operating costs, though small in comparison to capital costs, accumulate over time. As a result, selecting systems based on design costs can be misleading, as the weight of seemingly (un)important costs can (increase) decrease over the system's lifetime.

Figure 3 shows design and discounted life-time cost structures of passive and active AMD treatment systems at Blackball and Bellvue, assuming low, medium, and high discount rates. The cost structure of the design cost is expressed in percentages of the design cost (Table 2), which are simply the capital expenditures and initial operating costs that are generally not presented as discounted costs. The cost structure of the discounted costs is expressed as a percentage of discounted costs over the lifetime of the treatment systems.

For both sites, system construction and first purchase of media or reagent together made up 90% or more of the design cost. However, when the discounted costs were

Table 2 Costs components (NZ$) of passive and active AMD treatment systems at each site, assuming access maintenance for all sites is set at 1000 NZ$

Site name	Passive treatment								
	Capital expenditures	Operational expenditure[a]							Design cost
	Construction	Purchasing (media)[b]	Media disposal[c]	Sludge management	System maintenance	Labor	Monitoring	Power	
Blackball	2784,152	935,859	201,262	33,544	55,683	3380	2140	0	4,017,020
Bellvue	66,400	22,320	4803	900	1328	3380	2140	0	102,271
Escarpment	79,514	26,738	5752	958	1590	3380	2140	0	121,072
Herbert	184,094	61,892	13,310	2218	3682	3380	2140	0	271,716
Mangatini	78,195,794	26,285,102	5,652,708	942,118	1,563,916	3380	2140	0	112,646,158
Whirlwind	101,094	33,992	7310	1218	2022	3380	2140	0	152,156
Site name	Active treatment								
	Capital expenditures	Operational expenditure[a]							Design cost
	Construction	Purchasing (reagent)	Sludge disposal	Sludge management	System maintenance	Labor	Monitoring	Power	
Blackball	631,535	82,445	23,852	0	12,631	13,520	2140	10,000	777,123
Bellvue	189,460	2437	705	0	3789	13,520	2140	3000	216,051
Escarpment	189,460	2364	684	0	3789	13,520	2140	3000	215,957
Herbert	189,460	4901	1418	0	3789	13,520	2140	3000	219,228
Mangatini	1,263,069	2,420,389	700,238	0	25,261	13,520	2140	20,000	4,445,617
Whirlwind	189,460	2726	789	0	3789	13,520	2140	3000	216,424

[a]Annual costs unless otherwise stated

[b]Incurred at the start of 25-year life-span of media

[c]Incurred at the end of 25-year life-span of media

calculated, the percentage of construction and purchasing was much smaller. The reason is that other recurring costs accumulate over time. Therefore, not considering the costs for the duration of AMD treatment when selecting either a passive or active AMD treatment system site may give a decision maker a false sense of where cost savings may be achieved by selecting one system over another. Note that the absolute cost differences between systems were ignored here; we explore that aspect further in the sensitivity analysis below.

The effect of water flow rates on the structures of design and discounted cost also becomes evident. At Blackball, a site with high flow rates, construction and media and reagent purchases remain a sizable portion of total costs for the duration of AMD treatment. The management and disposal of sludge also represent a significant share of the total discounted costs. At Bellvue, a site with very low flow rates, the costs of construction, purchasing, and disposal were limited by system size and acid load. Consequently, other annual operating costs outweigh these costs over the duration of AMD treatment. The labour of the weekly system check-ups by a technician is noticeable. Depending on the flow rate, savings between passive and active systems over time may come from other costs than a large outlay such as construction.

The flow rate also affects the differences between the cost structures of passive and active systems. For a high-flow site like Blackball, the construction and media purchase for a passive system involves a significant upfront investment. However, for the duration of AMD treatment, the purchase of media is a much smaller share of total discounted costs of a passive system than reagent purchases and sludge disposal costs are for an active system. Given the low flow rate at Bellvue, a small passive system that costs less than an active system suffices. But reagent purchases for an active system would be very low, so purchasing would be a larger component for a passive system. Understanding that flow and acidity affect cost structures differently is key to planning for

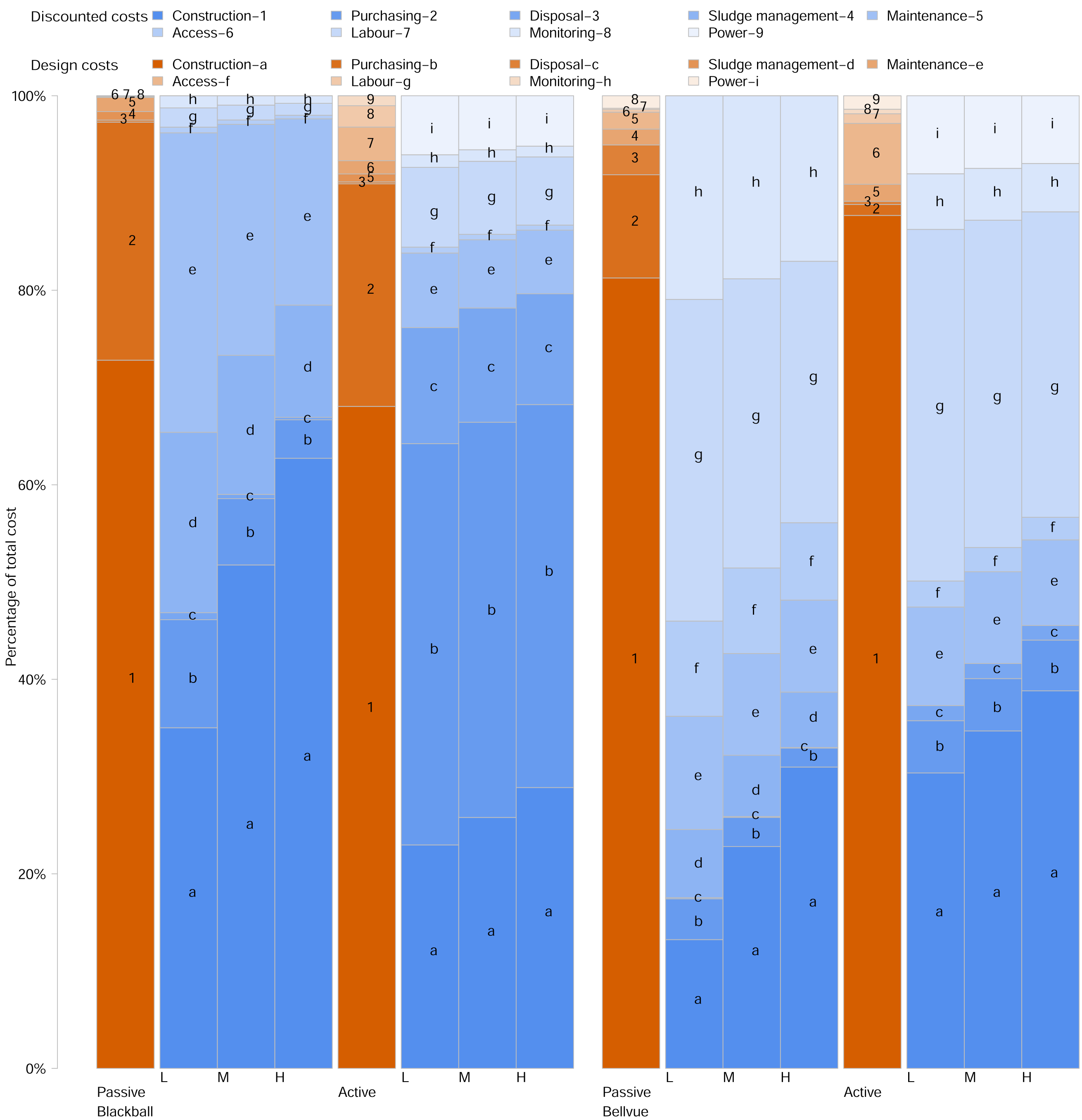


Fig. 3 Cost structures in percentages of total costs of design (orange) and discounted lifetime (blue) costs. Discounted costs are discounted over 100 years using 2% (L), 4.5% (M), and 7% (H) discount rates) for the Blackball and Bellvue study sites

deviations from median AMD characteristics, and is fundamental to the results discussed below.

The selection of discount rate is also important in the modelling. Sensitivity analysis for the discount rate indicates that at lower rates (where the decision maker places more importance on future cash flows), the importance of initial investments for construction is reduced. Instead, the operating costs become more significant as a share of total costs as they are incurred for decades.

Sensitivity Analysis

Figure 4 shows the ratios of discounted costs for passive and active AMD treatment systems, under various assumptions about cost components. This illustrates whether the relative shifts in cost structures translate into absolute cost savings delivered by either system, and which cost components have the largest effect in selecting one type of system over the other.

At Bellvue, Escarpment, Whirlwind, and Herbert, the discounted costs of passive AMD treatment systems were approximately 40–70% less than the discounted costs of active systems. Note that at the latter three sites with comparable flow rates (see Fig. 1), higher acidity tends to favour passive AMD treatment systems more. At Blackball and Mangatini, sites with high flow rates, active systems tend to be financially preferable. Nonetheless, at the edge-case study site Blackball, the cost advantage of an active system appears relatively limited, considering the acidity of AMD at this site is above the rule-of-thumb.

Starting at the top-left plot of Fig. 4, the discount rate has a strong effect on cost ratios. At Mangatini, the cost equivalency of a passive and active system is not reached, even at a low discount rate, but the cost ratio drops by more than 30% between the high and low discount rate scenarios. At Blackball, using a low discount rate almost equalizes the discounted costs of passive and active AMD treatment systems. When acid loads are large, a lower discount rate particularly emphasizes future savings on operational costs.

The next plot shows that changes in the natural reduction of acid have less of an impact, particularly at sites with low to medium flow rates. By the time that natural acid reduction will have started to substantially reduce purchasing and disposal costs, discounting will have mitigated most of the resulting changes in operational costs.

The financial effect of varying construction costs is shown in the next plot. Higher construction costs emphasize the cost advantage of active AMD treatment systems at sites with high flow rates. Passive systems at these sites would be so large that higher construction costs would be difficult to recuperate through less frequent purchasing and lower management costs of used media relative to sludge disposal. Conversely, if construction costs are low, a PTS can be financially preferable at a site like Blackball, where an active system generates a stream of high operational costs due to large acid loads.

Purchasing costs for media and reagent also have a significant effect on the financial comparison of passive and active AMD treatment systems. At first glance, it is counterintuitive that active systems at low-flow sites become more attractive as purchasing costs increase. However, at these sites, reagent purchases are small and hence discounted cost increases are unimportant compared to the relatively large initial purchase of media for PTS. For sites with high flow rates, higher purchasing prices create a cost disadvantage for active systems. The higher media cost for PTS is incurred only on a 25-year cycle that allow discounting to reduce their discounted value, whereas higher reagent costs for active systems are incurred in the early, undiscounted years.

The effect of varying costs for sludge disposal, system maintenance, and labour on the cost ratios are shown on the bottom row of Fig. 4. Higher disposal costs create a cost advantage for active AMD treatment systems. As the top layer of sludge from PTS is removed annually, these costs may not be offset by the continuous but smaller annual disposal costs incurred by active systems. Only when sludge from active systems forms in very large volumes, such as at the Mangatini site, is this cost advantage for active systems reversed. System maintenance costs are derived from construction costs, so active systems with relatively low construction costs have a cost advantage. Higher labour costs increase the discounted costs of active systems more, creating a cost advantage for PTS, although the effect is generally limited.

Acid Load Uncertainty Analysis

The cost ratios based on Monte Carlo simulations of the variability of flow rate and acidity are shown in Fig. 5 for the Blackball study site, and illustrate how variability of flow and acidity affect the cost ratio of passive and active treatment systems. The vertical and horizontal axes cover the first to third quantile of acidity and flow, respectively, and the median flow rate and acidity are located in the center of the plot.

In Fig. 5, a passive/active AMD treatment system is preferred to the left/right of the dashed line, which indicates the approximate cost equivalence of either type of system. Results for normal (left-hand pane) and low (right-hand pane) discount rates are shown to illustrate how the Monte Carlo simulation of flow and acidity analysis extends the earlier sensitivity analyses. As in Fig. 4, a lower discount rate reduces the cost disadvantage of a PTS, shown in Fig. 5 as a shift to the right of the cost equivalency line when comparing the left and right-hand panes.

Similar plots can be made for each cost parameter. As parameters are changed to benefit PTS, the cost equivalency line shifts to the bottom right of the plot. If the cost equivalency line is located to the right of the center of the plot, to the right of median flow and acidity, a passive system is financially viable under expected AMD conditions. In the right-hand panel of Fig. 5, the median flow rate cost equivalency is achieved when the acidity is close to the 75th percentile. The latter does not reflect expected AMD conditions; however, it would need to be much closer to the median before cost equivalency has practical relevance.

Conversely, this analysis can be used to determine how much cost parameters need to change before cost equivalency is achieved at or near median acidity. We varied the parameters earlier shown to have the largest impact on cost

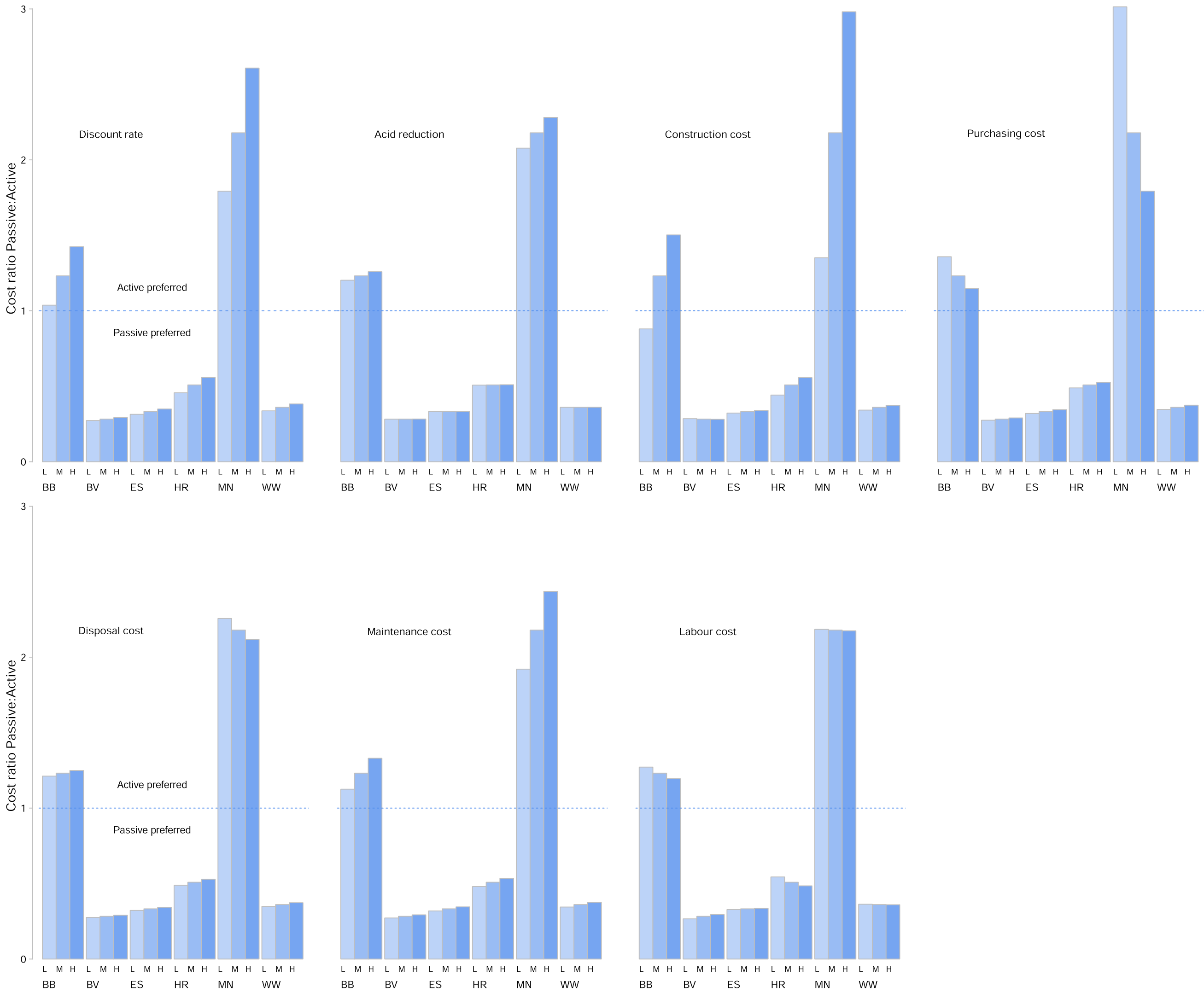


Fig. 4 Cost ratios of discounted costs for passive and active treatments at each study site (*BB* Blackball, *BV* Bellvue, *ES* Escarpment, *HR* Herbert, *MN* Mangatini, *WW* Whirlwind). From top-left to bottom-right, the parameters varied at low, medium, and high (L, M, H) settings are the discount rate (2%, 4.5%, 7%), the natural acid reduction rate (0.3%, 0.6%, 0.9%), and costs for construction, purchasing, disposal, maintenance, and labour (50%, 100%, 150%)

ratios and therefore cost equivalence, i.e. the discount rate, and construction and purchasing costs while fixing AMD variables at the median flow rate to determine the corresponding acidity level for cost equivalency. The results (Table 3), indicate how far these cost parameters need to be pushed to achieve cost equivalency at the median acidity level.

Earlier results confirmed that the discount rate needs to be quite low before cost equivalency is achieved for the median flow and acidity for a site like Blackball. Table 3 shows that the assumed discount rate needs to be set at 1% or less to achieve cost equivalency of passive and active systems near the median AMD conditions. This suggests that using even lower discount rates is unlikely to change the outcome of discounted life-time financial analyses, even if the cost ratio is close to unity at slightly higher discount rates.

Construction costs were assumed to be 50% of the standard construction costs in an earlier analysis to achieve a financial advantage for passive treatment systems at Blackball. Table 3 shows the results of reducing that benefit for PTS by assuming smaller decreases in construction costs. If construction costs are 60% of the standard cost, a passive system would still be preferable under median AMD conditions. When constructions costs are 70% of the standard cost, however, PTS would no longer be financially viable at the expected acid load. Therefore, if construction costs can be reduced by at least 30–40%, a PTS would be financially viable at Blackball.

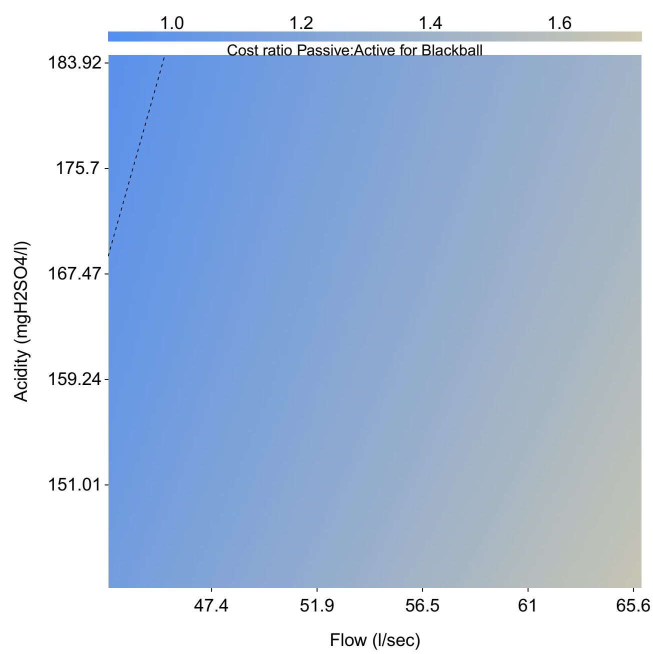
Purchasing costs were assumed to be 50% higher than the standard cost in an earlier analysis, at which point a passive system still was not financially viable under expected AMD conditions. By increasing the purchasing costs further to 160% of the standard cost, cost equivalency of passive and active systems was achieved at close-to-median AMD conditions. However, increasing purchasing costs even further does not much expand the AMD envelope in which a PTS would be financially preferred.

Discussion and Conclusion

Treatment of AMD can be achieved with passive and active systems. These systems have different cost structures over time that are determined by flow rate and acidity, and AMD conditions therefore influence the selection of which treatment system to use. Industry rules-of-thumb currently limit the use of PTS, but such systems can also be evaluated by comparisons of financial performance. We developed detailed cost models of passive and active AMD treatment systems at sites that span a range of hydro-chemical conditions.

Conducting a financial analysis that discounts all costs over the lifetime of AMD treatment systems is necessary for optimal AMD treatment. However, previous economic analyses of AMD treatment systems have done so with only a limited scope. They considered a subset of costs, did not consider lifetime costs, or both. Previous analyses therefore were unable to illustrate how costs interact over time and in response to changing hydro-chemical conditions. Considering only design costs of initial capital and operating costs risks selecting a system based on a false understanding of total costs accumulated over the system's lifetime. Capital costs are less important over time under all AMD conditions than they appear in design costs. Initial operational costs may also be misleading: for systems at low-flow sites, for instance, a large share of total discounted costs can be generated by simple regular system check-ups.

At sites with high to very high flow rates, construction costs and purchases of media and reagent become critical determinants of the total costs of AMD treatment. Passive treatment systems carry higher capital costs than active systems but accumulate savings on recurring costs for purchasing and disposal. Whether the cost savings outweigh the higher initial investment depends on relative differences in these costs and the discount rate used in the financial analysis. A larger capital cost differential coupled with smaller differences in purchasing and disposal will tend to favor active treatment systems. Lower discount rates increase the magnitude of operational cost savings over time. Beyond a certain point, however, lowering discount rates is unlikely to change the relative financial performance of either system.



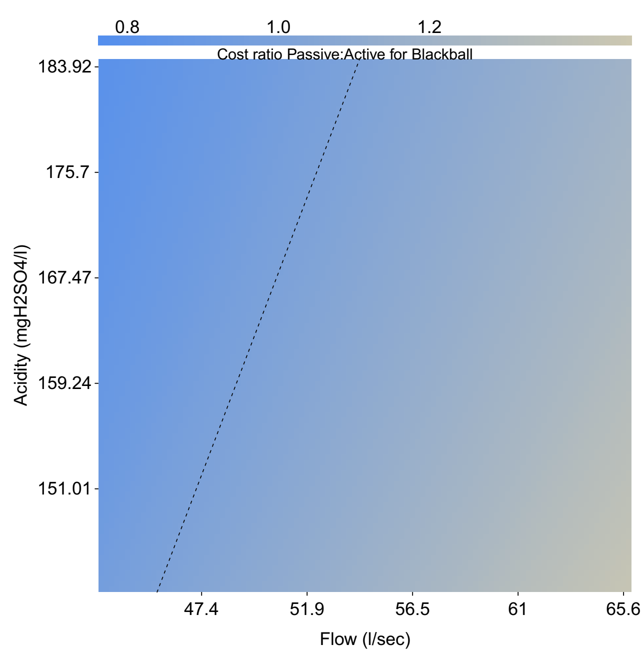


Fig. 5 Cost ratios of passive and active AMD treatment systems at the Blackball study site for all combinations between the first and third quartile of expected acidity and flow rate of AMD. The dashed line indicates approximate cost equivalence of passive and active systems. Discount rate is 4.5% (left) and 2% (right)

Table 3 Effect of varying discount rate, and construction and purchasing costs on the cost equivalency of passive and active AMD treatment systems at Blackball at the median flow rate

	Discount rate			Construction			Purchasing		
Assumed value (%)	1	1.5	2	50	60	70	170	160	150
Percentile of acidity at median flow rate at which cost-equivalence is achieved	54	64	75	32	50	71	45	53	64

In other words, the system that costs less at commonly used discount rates will cost less at lower discount rates as well.

The industry rules-of-thumb suggest that PTS are not suitable for sites with flow rates over 50 L/s or acid loads larger than 150 kg/day. The median flow rate at Blackball is just beyond the first limit (≈ 54 L/s) and the median acid load (≈ 750 H_2SO_4kg/day) is far beyond the second. Our cost model suggests that a passive system can nonetheless financially perform quite similar to an active system at this site in some circumstances. Sensitivity analysis on individual key cost model parameters suggests that a PTS could be financially preferable at Blackball, provided the cost differences in construction and purchasing are sufficiently large. When passive and active systems perform roughly similar financially, other considerations may enter the selection process, such as reliability, convenience, or public perceptions.

Variability around median flow rates and acidity levels imply that the expected acid load can at times be exceeded. Constructing larger systems could accommodate overflow events and reduce downstream environmental damage. Doing so implies a financial disadvantage to PTS at sites with highly variable flows, like Blackball, due to the resulting increase in construction costs to accommodate high flow events. Our model illustrates that higher acidity improves the financial performance of PTS for a given flow rate. PTS can be financially preferable, especially when acidity is high or when prices for treatment capital or inputs are expected to change favorably.

Up to a point, the models and analyses in this paper reflect the reality that mine sites have unique AMD characteristics. However, we ignored practical aspects such as space available and system size, which could have a major impact on costs or even prevent PTS from being built. We also made various simplifications in the cost models and analyses. For instance, we fixed the construction of the passive system at all sites in a way that causes an almost linear increase in construction costs with flow rate. Alternative construction approaches would lead to different costs. Other assumptions we made that affect costs, such as the efficiency of active treatment systems and one maintenance rate as a function of capital expenditure for both system types, would affect the financial viability of PTS as well. We also implemented the sensitivity analysis on one cost only and in the same direction and degree for both types of treatment system. It is unlikely that, for instance, the costs of mussel shells and limestone would move in tandem in real markets. Different cost developments for either type of system could significantly change the outcome of a financial analysis.

Nonetheless, our modelling illustrates how to conduct financial analysis on AMD treatment systems and the main economic trade-offs that are likely to be found. In real decision making, detailed cost models for all systems under consideration should be developed. Preferably, this should be done in parallel with the development of the mining plan because the implications of financial analysis of AMD treatment potentially extends into site operations and ultimately to overall project economics. How waste rock is handled, for instance, affects both the costs of waste rock management and acid load, which in turn affects the costs of AMD treatment over decades. Revisiting the financial model at relevant points in time, such as when AMD treatment systems are due for major overhauls or replacement, would help minimize the costs of mitigating the environmental impact of mining.

Our analysis presents the difference between two common rules of thumb for decision making between passive and active mine drainage treatment systems (Fig. 1). In general, the modelling indicates the rules of thumb are set at appropriate levels. One of the systems we have modelled is a boundary case for the 50 L/s rule of thumb; our modelling demonstrates that cases can be made for either passive or active systems depending on the assumptions made in the models. In these boundary cases, it is likely that site specific factors and financial assumptions will be important factors in selecting between active and passive systems. In addition, our modelling explored how flow variability was a decision-making factor. There is a financial disadvantage for PTS under highly variable flow rates, but the site-specific details related to desired downstream outcomes such as percentage compliance, dilution regime, and lag times between mine drainage and the rest of the catchment will be important in decision making.

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