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TECHNICAL COMMUNICATION

The Evolving Nature of Semi-passive Mine Water Treatment

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Abstract

Passive mine water treatment technologies were originally developed to treat small flows of water with low to moderate acidity and metal loadings. Gradually, semi-passive adaptations and refinements, such as occasionally adding amendments to enhance treatment processes, have allowed passive systems to be used at a greater range of mine sites. This paper addresses the largely unwritten history of semi-passive water treatment and its potential future.

Keywords Cold temperatures · Sulfate-reducing bacteria · Remotely accessible monitoring · Seasonal flow variation

Introduction

Those of us who were involved in the early development of passive mine water treatment never imagined that these systems would one day be used to treat large flows or employed at active mining operations (Kleinmann et al. 2021). Our initial intent in developing natural or "passive" systems was simply to develop a low-cost, low-maintenance technology that could be used to mitigate small flows (a few L/min) of mildly acidic seeps at abandoned coal mines that otherwise would flow completely untreated into receiving streams and rivers. Success at these mines led to the use of similar approaches at metal mines (Sobolewski et al. 1995; Wildeman et al. 1990), and within 25 years, passive treatment, including aerobic and anaerobic bacterially-mediated systems, neutralization by limestone, and contaminant removal by adsorption and co-precipitation, was being used at thousands of both active and abandoned mine sites around the world (Kleinmann et al. 2021; Skousen et al. 1999; Watzlaf et al. 2004). Now, 40 years after that early work, passive and semi-passive systems are treating flows of highly contaminated mine water that can exceed 75 L/sec (e.g. URS Inc. 2003) and are even being used to treat mine water at arctic and high-altitude mines (Moore et al. 2022; Ness et al. 2014; Strachotta et al. 2009).

Passive treatment is defined as those systems that rely on natural ameliorative processes that are facilitated by providing an appropriate environment for those processes. These include neutralization of acidity by limestone, aerobic oxidation of ammonia, iron and manganese, anaerobic reduction of ferric iron, selenium, nitrate, and sulfate, precipitation of metals as sulfide minerals, settling of precipitated contaminants, and various adsorption, co-precipitation, and ion exchange reactions. Many of these processes are catalyzed or accelerated by bacterial activity. The early history of passive treatment development has already been discussed (Kleinmann et al. 2021; Skousen et al. 2017).

Ideally, passive treatment requires no grid energy power, no addition of chemicals after construction, and only occasional or periodic oversight and maintenance. Appropriate sizing criteria were developed for passive treatment systems based on water quality and flow rates or contaminant loads (Hedin and Nairn 1992; Hedin et al. 1994; Gusek 1995). However, the inherent drawbacks of depending on natural chemical and biological reactions and their variable kinetics made passive treatment less suitable at sites with limited land availability or where the topography made the construction of passive systems challenging or impossible. Somewhat less obvious problems such as high seasonal variability

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of flow, changing contaminant concentrations, and fluctuations in water temperatures also proved problematic.

In this paper, we use the term active treatment to include all mine water technologies that rely on controlled addition of chemicals and/or depend on machinery, such as pumps, mixers, reaction tanks, multimedia filters, and clarifiers to manage flows, mix chemicals, aerate, and handle sludge, and therefore require consistent oversight, adjustment, and maintenance. Conventional active treatment methods typically involve neutralization of acidity by the addition of an alkaline chemical (such as lime), oxidation of ferrous iron, and precipitation of contaminant compounds in a clarifier or settling pond. Other technologies considered to be active treatment include membrane filtration-based methods (e.g. nanofiltration or reverse osmosis), ion-exchange, electrocoagulation, and other electrochemical approaches.

The definition of semi-passive treatment (sometimes called hybrid system) is still evolving, but generally lies somewhere between the other two definitions stated above. When we first used the term passive treatment, we defined it as requiring no power source except for gravity, so when one innovator installed a small wind turbine to improve the rate of iron oxidation, we referred to that as a semi-passive treatment system. Now many of us consider wind-, solar-, and water-powered installations and associated energy storage systems to be possible components of passive systems, while others feel that their inclusion makes a system semi-passive since such systems typically require more maintenance and supervision. But it is generally agreed that semi-passive treatment systems cannot depend on grid power, can use amendments or chemicals only if they are added without complex machinery, and can include the use of remotely monitored and/or passively-activated controls as long as the system generally operates without consistent oversight, maintenance, and monitoring. Gradually, practitioners have expanded the use of semi-passive treatment technologies, incorporating the periodic or episodic addition of amendments and chemicals using approaches that did not require complex machinery. The inherent advantages of these innovations, which expand and overlap the traditional boundaries of active and passive treatment, have greatly extended the range and application of passive systems and suggest that semi-passive systems will likely be used at more and more sites in the future.

This definition is unfortunately still rather vague. For example, is a system semi-passive if it requires annual delivery of limestone or a more processed chemical, such as quicklime (CaO), but otherwise operates passively? Most of us would say yes, but that is a slippery slope; what if the limestone must be replenished seasonally? What if it must be replenished monthly? At what point should such sites be considered active rather than semi-passive? And what about sludge management? If the water at a site is completely treated passively, but sludge must be removed or handled annually, quarterly, or monthly, is that still passive or is it semi-passive? What about the many sites where the water is pumped to the surface but is then passively treated—should these sites be considered passive or semi-passive? Rather than engage in nomenclature exercises, we have decided to discuss many of the early examples of what might be considered semi-passive treatment in a supplementary file, which will be published along with the on-line version of this paper. Some of these examples are clearly semi-passive, but others fall into a gray zone. From the standpoint of the practitioner, these differences are academic: the practitioner is only interested in practical solutions, whatever others might call them. We have chosen not to take sides on whether these systems should be considered passive, semi-passive, or active. If they worked well, and might be considered semi-passive, we have included them to provide some documentation of these early approaches (many of which are still being used) and to provide some historical perspective.

More Recent Developments

Adaptations for Cold Water Temperatures

Every biological reaction is influenced by temperature, but there are wide differences in their sensitivities. For example, ammonia oxidation is highly temperature-sensitive and practically stops at 1–4 °C (Tchobanoglous and Burton 1991). Other processes like biological sulfate reduction readily occur at very cold temperatures. In fact, cold-adapted sulfate-reducing bacteria (SRB) from arctic sediments can be more active at 4 °C than at 20 °C (Knoblauch et al. 1999). In those environments, the breakdown of complex organic matter, which require a community of various bacteria, is temperature-sensitive and rate limiting. In contrast, breakdown products like simple alcohols and organic acids, are readily metabolized by SRB at cold temperatures (Sobolewski 2010; Sobolewski et al. 2012).

At active treatment plants, decreased biological activity at cold temperatures can be compensated for by heating the influent since power is already available at the site. This is not desirable for passive treatment systems, but an alternative is to feed simple alcohols and organic compounds that are readily metabolized into the untreated water. For example, at the underground Tulsequah Chief Mine, in remote northern British Columbia, few treatment options were available to treat the highly acidic water because space, resources, and access (helicopter-only) was limited (Marsland et al. 2010). A two-stage passive system was designed to treat the water inside the lower level adit, where the water from the mine was redirected. In the first stage, the mine water flowed through beds of

Fig. 1 Ethylene glycol feed drums, connected to a filter and battery-operated and timed drip system (photo by A. Sobolewski)

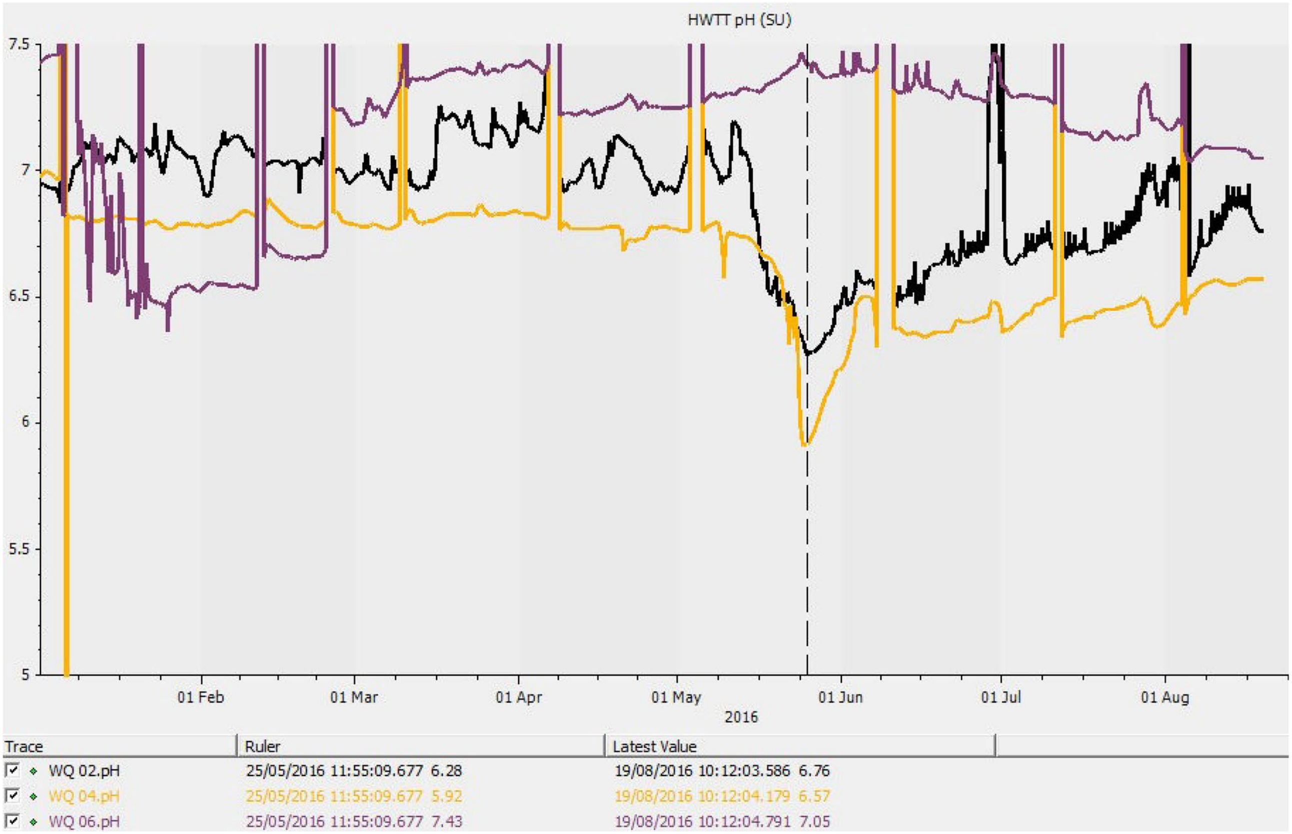
limestone, neutralizing the pH and removing aluminum and iron. In the second stage, the neutralized water flowed through an organic bed that contained SRB, where most of the residual metals were removed.

A wood chipper was originally used to generate organic matter for the SRB, since manure and other organic matter could not be brought economically to this site. However, a preliminary pilot-scale study showed that the water temperature (6.7 °C) was too low to sustain the establishment and activity of SRB. To remedy this, ethylene glycol (EG, an inexpensive carbon source that is neither toxic nor flammable) was added upstream of the organic bed as a nutrient for the SRB through a battery-operated drip-feed system (Figure 1), making the system semi-passive. Note that a flammable liquid (such as methanol, ethanol, or propanol) could not have been stored and used in an underground mine. The system was inoculated with SRB sourced from a ditch draining the Whitehorse airport runways, where EG is used extensively to de-ice airplanes in the winter. The EG dosage was adjusted to maintain a specified range of dissolved sulfide and effluent metal concentrations. This modification to the pilot system was easily implemented into the full-scale system and worked successfully. The annual cost of EG addition totaled less than $10,000, a very low cost for the effective removal of metals it provided. Crucially, this simple system could be brought on site via helicopter, because site access is a key restriction at this mine.

Remotely Accessible in situ *Monitoring Capabilities and Flow Control Measures*

Passive treatment systems are typically not monitored frequently unless they are constructed at active mines. Consequently, their operational parameters are not adjusted in response to changing conditions, which can lead to decreased performance. For instance, in the dry season of a wet/dry annual cycle, low flows can result in stagnant water and production of detrimental levels of dissolved sulfide. Conversely, flows increase dramatically during snowmelt in mountainous regions, and this may require adjustments in retention time or short term chemical additions to maintain consistent performance. The ability to adjust the operation of passive treatment systems during these climate events is desirable, though it might convert the passive system into a semi-passive or even an active system, depending on how much human intervention is required.

In general, passive and semi-passive treatment systems are very attractive mine closure options if the appropriate land is available and if it can be shown that they will operate with minimal assistance. This is especially true now that it is possible to remotely monitor a site. For example, the ability to assess changes in water chemistry and to remotely adjust flow into and within system components was incorporated into the semi-passive treatment system constructed at the abandoned Rico-Argentine Mine, where vertical and horizontal flow wetlands treat water in the



Trace	Ruler	Latest Value
☑ ◆ WQ 02.pH	25/05/2016 11:55:09.677 6.28	19/08/2016 10:12:03.586 6.76
☑ ◆ WQ 04.pH	25/05/2016 11:55:09.677 5.92	19/08/2016 10:12:04.179 6.57
☑ ◆ WQ 06.pH	25/05/2016 11:55:09.677 7.43	19/08/2016 10:12:04.791 7.05

Fig. 2 The pH readings at the inlet (black) and internally (orange) in the horizontal flow wetland at the Rico-Argentine Mine. Measurements made from fall 2015–2016 show a pronounced pH decrease in late spring 2016. Off-scale readings are associated with sensor calibration or clean up

Colorado Rockies at an elevation of 2700 m (Moore et al. 2022). The mine water is alkaline there through most of the year, except for a brief period in late spring, when acidic products are released from underground workings during snowmelt. During the trial of these wetlands, it was critical to understand the effect on performance of increased acidic conditions, metal concentrations, and flows. To that end, several sensors were installed at key locations in the treatment wetland to accurately document ambient conditions within the system. Data from these sensors were collected by dataloggers and relayed to a server that offered remote access. This allowed for continuous monitoring of key operating parameters, such as temperature, pH, ORP, and dissolved oxygen, along with water elevation and flow rates at the wetland inlets and outlets. These parameters provided a snapshot of conditions within the wetlands and were used to guide sampling associated with the Spring freshet. Figure 2 shows the sharp decrease in water pH in late May/early June, recorded by sensors at the wetland inflow and mid-wetland. Despite fluctuations in water pH throughout the year, the rapid decrease in water pH during the Spring freshet was unmistakable.

It is even possible to remotely monitor dissolved ions like sulfate using vibrational spectroscopy (Knorke et al. 2019). In fact, technology is already being marketed for this purpose and is reportedly being field tested by the Geological Survey of France (the BRGM) at a semi-passive mine water treatment site (Mantescu 2022).

An additional advantage of remotely-accessible sensors is that unexpected or abnormal readings can indicate problems and instigate a system inspection. Indirectly, this should increase confidence in the operation of passive treatment systems, by operators and regulators alike, because problems can be detected and remedied early.

Environmental Benefits of Passive and Semi-passive Treatment Systems

The creation of lime from limestone produces large amounts of carbon dioxide, as does transportation of the lime to the mine site. In contrast, dissolution of limestone in acidic mine water creates bicarbonate, a natural chemical buffer. In addition to the removal of contaminants, passive treatment systems such as wetlands host a thriving biota that incorporate carbon dioxide to create plant tissue. With large wetlands (> 10 ha) increasingly being constructed at mine closure and with the promotion/enhancement of biodiversity increasingly becoming an objective of corporate policy (Sobolewski and Sobolewski 2022), passive and semi-passive systems have many environmental advantages over conventional active treatment systems.

Future Outlook

Tighter Integration with Mine Reclamation as Part of Closure

Modern mining companies plan a mine with closure in mind. Potential sources of contaminant release are fully characterized at the outset and should be managed, as much as possible, to prevent contaminant release at mine closure. Waste rock is disposed from the bottom up, in a manner that minimizes contaminant leaching (INAP 2020a, b). These dump construction methods may not completely eliminate contaminant release, but their design at closure can and should integrate elements that will capture the leachate and direct it towards a passive or semi-passive system for treatment or at least for final polishing.

Integration of Internal Sensors Data with System Operation

Being able to remotely access data on flow, pH, and dissolved ions has obvious implications for remotely operated semi-passive and active mine water treatment sites. With such information on internal conditions, it is possible to remotely change operational parameters, such as increasing or decreasing water elevation to adjust retention time or adjust the dosage of neutralizing chemicals or organics to feed the sulfate-reducing bacteria. While such systems with remotely operated controls appear to be more active than semi-passive treatment, what if the system is automated to adjust the retention time or perhaps to turn the battery-operated drip feed of a liquid organic carbon at a site like the Rico-Argentine Mine? We believe that such sites should and will be classified as semi-passive treatment. The use of sensors that can be monitored remotely and switches that can be operated remotely is a relatively recent development that holds promise for semi-passive treatment systems. Potential applications include:

1. Increasing or decreasing water levels using an Agri-drain system when triggered by a set parameter;
2. Re-routing water to a by-pass system when conductivity decreases below a set limit;
3. Adding liquid organic carbon to stimulate sulfate reduction when the internal oxidation–reduction potential (ORP) increases past a setpoint. Carbon dosing can be adjusted relative to flows and ORP using a programmed logic-controlled system.
4. Alarms triggered when a parameter falls outside of a set range, such as when plugging causes a drastic decrease in flow rates

These applications require sensors that are designed for long-term deployment, such as those used in oceanographic studies (e.g. YSI EXO2 multiparameter sondes). These applications will continue to improve treatment performance and reliability and will further blur the distinction between passive and active treatment systems.

Removal of Selenium and Sulfate

One of the first treatment wetlands used to remove selenium was operated at the Richmond, CA, refinery (Duda 1992). This wetland was effective in decreasing selenium concentrations from 20–30 μg/L to < 5 μg/L, but it was also controversial because the wildlife that it attracted were susceptible to selenium bioaccumulation (Chevron 1995; Hansen et al. 1998). Subsequent modification of the wetland design effectively separated wildlife from the anaerobic cells that removed selenium, demonstrating the feasibility of this concept.

Selenium is an emergent contaminant that is best removed by biological processes, though membrane filtration and chemical treatment may also be considered. In their largest implementation, Teck Coal has built saturated rock fills by filling empty pits with rock and applying contact water containing nitrate and selenium, dosed with liquid organic carbon (Klein et al. 2019). The original full-scale semi-passive system treated flows of 833 m^3/hr (3670 gpm) and it is being expanded to treat flows of 1980 m^3/hr (8700 gpm). The amortized cost is reported to be about half to one-third of the cost of an active mine water treatment plant (Teck 2022). Teck Coal's semi-passive saturated rock fill system reduces selenium concentrations from ≈ 100 μg/L to 2–8 μg/L. Such systems will likely become more common in the future as more and more jurisdictions implement stringent selenium discharge limits. Indeed, further improvements in the technology may be necessary. For example, Canada is considering adopting British Columbia's water quality guideline of 2 μg/L, or a lower value, 1 μg/L, for very sensitive environments (Government of Canada 2022).

Global sulphate limits range from 2000 mg/L for surface water discharge in Chile to 10 mg/L in the U.S. state of Minnesota (where unique circumstances in that state dictate the need for low effluent standards[1]) and typically range between 250 and 1000 mg/L (Kinnunen et al. 2017). Some locations have established stringent ecotoxicity-based, hardness-dependent standards for sulfate (e.g. BC MoE 2013). Since many sulfide mines discharge elevated sulfate concentrations, such regulatory limits are proving problematic at many mine sites.

One possible option is to develop passive and semi-passive treatment systems that rely on the anaerobic transformation of sulfate for its removal as hydrogen sulfide or metal sulfides. Most anaerobic passive treatment systems designed for metal removal only remove 5–15% of incoming sulfate, but bioreactors that were designed to remove sulfate have achieved higher removal rates, as high as 2.2 mol SO_4^{-2}/m^3-day (Fattore et al. 2017; Walker 2017). Higher sulfate removal rates have been observed in permeable reactive barriers, where retention times are much higher (Benner et al. 2002). This suggests that anaerobic systems with greater hydraulic retention times, on the order of 10–15 days, could remove higher sulfate loads, which contrasts with typical retention times of 1–4 days for metals removal. A concerted effort will be required to develop such systems. While such systems will have a significantly larger footprint, they will be less expensive than active treatment plants and may be preferable at mine closure.

Greater Resource Recovery

A number of studies have historically examined and rejected the possibility of recovering valuable metals from acid mine drainage (MEND 1991). However, some reports had indicated that natural uraniferous bogs can accumulate uranium to sufficiently high concentrations that it could be economically recoverable (Zielinski et al. 1987).This observation held the promise that metals accumulated in passive treatment systems could also be recovered economically. Indeed, it was reported a few years ago that iron oxides retained in oxidation ponds were sufficiently free of contaminants that they could be recovered and sold as paint pigments or stock for other applications (Hedin 2016). This has led to at least one commercial venture (http://www.environoxide.com/).

Other opportunities for resource recovery from mine water have been pursued. Rare earth elements are commonly extracted by methods that resemble acid generation from waste rock and several workers have examined the possibility of recovering them from acid drainage (Hedin et al. 2020; Hermassi et al. 2022; Ziemkiewicz et al. 2021). The latter report includes an economic analysis indicating that the recovery of certain rare earth elements may be commercially viable. However, passive water treatment systems would have to be modified to incorporate resource recovery; these modifications would likely cause the systems to be designated semi-passive.

Application of New Genomic Technologies

Ever since the realization that most microbes cannot be recovered by culture methods, microbiologists have developed genetic techniques to define microbial populations and activities in environmental soil and water samples (Riesenfeld et al. 2004). These methods have been applied to solving water treatment problems (Kantor et al. 2017). These techniques become powerful when they characterize shifts in response to perturbations and when these changes are related to operational parameters. Thus, we can investigate how microbial populations and their activity respond to changes in pH, water fluxes, or the addition of liquid organic carbon, and how these relate to internal changes in pH, ORP, dissolved sulfide, hydrogen activity, and metal removal. The use of such techniques will allow us to study the inner workings of passive and semi-passive treatment systems.

Greater Integration Between Scientific and Engineering Design

There remains a great disconnect between the scientific understanding of treatment processes and engineering design. For example, plant selection in a wetland is typically based on availability and tolerance for water fluctuations, but it is known that different species affect sediment redox potential through their root system, which may affect metal retention and maturation. One of us has observed that addition of elemental sulfur can enhance sulfate reduction and metal removal in cold climates.[2] It has also been observed that a wetland substrate containing clay removed ammonia at a 30% higher rate compared to adjacent cells lacking clay.[3] These observations and other scientific understanding of treatment dynamics and processes must find their way into system designs.

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[1] The Minnesota Pollution Control Agency has provided a rationale for its stringent regulation of sulfate: https://www.pca.state.mn.us/water/protecting-wild-rice-waters.

[2] Sobolewski A. Personal observation.

[3] Sobolewski A. Unpublished observations.

Conclusions

Passive and semi-passive mine water treatment systems have evolved far beyond what was once thought possible, in terms of contaminant removal and potential contaminant loading. Moreover, there is every reason to believe that this trend will continue. Given their long-term cost effectiveness and environmental advantages, passive and semi-passive mine water treatment should at least be considered at any site where appropriate land for such systems is available. Even at sites where contaminant loading is extreme (i.e. will lead to plugging unless metal sludge is actively managed), passive treatment should be considered as a potential polishing step.

This is not to suggest that passive or semi-passive treatment is appropriate for every site, only that innovators have found ways to overcome many of the limitations that once existed, such as extreme water temperatures or high flow volumes. The capability to remotely monitor water characteristics and adjust operational parameters greatly shifts the limits of what is possible. We believe that future technical advances will continue to provide new ways to harness natural processes. Moreover, the new generation of environmental managers are more open to concepts that were once considered radical.

The key advantages of passive and semi-passive systems, long-term cost effectiveness and environmental benefits, must always be balanced with the potential risks associated with relying on natural processes. In addition, it is important to remember that although passive and semi-passive systems require much less monitoring and oversight than conventional active treatment systems, they do still require some oversight and maintenance.

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Data availability Data is available on request from the authors.

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