The Evolving Nature of Active, Passive, and Semi-Passive Mine Water Treatment Technologies

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Abstract

Passive technologies were originally developed to treat small flows of mine water with low to moderate acidity and metal loadings. Semi-passive adaptations, such as occasionally adding amendments to enhance treatment processes, have allowed their use at a greater variety of mine sites. This paper addresses the largely unwritten history of semi-passive water treatment and how it will continue to evolve. We examine factors to consider when making decisions between active, passive, and semi-passive treatment systems, and how such decisions are often based on the personal experience of the decision-making individuals rather than aspects such as water chemistry and flow.

Keywords: ???

Introduction

Those of us who were involved in the early development of passive treatment of mine water never imagined that it 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 prompted efforts to apply this technology at metal mines (Wildeman *et al*. 1990; Sobolewski *et al*. 1995), and within 25 years, passive treatment technologies, including aerobic and anaerobic bacterially-dependent systems, neutralization by limestone, and contaminant removal by adsorption and co-precipitation, were being used at thousands of active and abandoned mine sites around the world. Now, 40 years after that early work, passive and semi-passive systems are treating flows that can exceed 200 L/s and are being employed at arctic and high-altitude mines (Strachotta *et al*. 2009; Ness *et al*. 2014; Lewis-Russ *et al*. 2022). This paper briefly summarizes how semi-passive treatment developed over time and how it is likely to continue to evolve.

Active treatment comprises 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, chemical mixing, aeration, and sludge handling, 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. Active treatment can range from simple mechanical water aeration to a complex reverse osmosis treatment plant.

The early history of passive treatment has already been discussed (Skousen *et al*. 2017; Kleinmann *et al*. 2021). Passive treatment is defined as systems that rely on natural ameliorative processes that are facilitated by providing an appropriate environment for those processes, which include limestone dissolution, aerobic oxidation of iron and manganese (catalyzed by bacteria), anaerobic reduction of iron, selenium, nitrate, and sulfur (again, catalyzed by bacteria), precipitation of metals as sulfide minerals, settling of precipitated contaminants, and various adsorption, co-precipitation, and ion exchange reactions. Ideally, passive treatment requires no grid energy power, no chemical additions after construction, and only occasional or periodic oversight and maintenance. However, passive treatment requires a larger footprint than active treatment and is less suitable at sites with limited land availability or where topography make the construction of passive systems challenging or impossible. Somewhat less obvious problems, such as high seasonal variability of flow, contaminant concentrations, and water temperatures also prove problematic.

The definition of semi-passive treatment is still evolving, but generally lies somewhere between the other two definitions stated above. Gradually, practitioners 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, as well as remotely monitored and operated and/or passively-activated controls. Critically, these systems continue to rely on gravity flow and on the infrequent management of accumulating metal residue (e.g. sludges). Today, as long as systems can operate well without consistent oversight and maintenance, they are considered semi-passive. The inherent advantages of these innovations, which expand and overlap the traditional boundaries of active and passive treatment, have greatly extended what passive systems can accomplish and suggest that semi-passive systems will likely be used at more and more sites in the future.

Examples of Semi-Passive Treatment

Periodic Addition of Limestone or Lime

One of the simplest examples of a semi-passive approach is the strategically-placed, periodic addition of large quantities of fine-grained limestone within streambeds of a contaminated watershed. This approach meets the semi-passive definition because it does not require continual additions of chemical (only occasional or seasonal additions). Limestone sand can be added up-gradient of the contamination (watershed liming) or directly into an acidic stream. With watershed liming, the limestone reacts with rain and snowmelt water in the stream. However, the amount of alkalinity added by the sand is limited by limestone solubility and generally the low acidity of the water. Watershed liming has a higher short-term cost than the in-stream limestone sand method, though long-term cost benefits are most likely equivalent (Sharpe 2017). Given the objective of neutralizing acidic mine water, limestone sand is normally added during base flow conditions. During storm flow, the limestone is then transported downstream where it is incorporated into the stream sediment, resuspended, and dissolves to add alkalinity. This approach is very simple and has been used to treat many acidic streams (Clayton *et al.* 1998; Brown 2005; Simmons *et al.* 2006).

Zurbuch (1963) used a water-powered rotating drum to add alkalinity to the acidic Otter Creek (WV, USA), correctly anticipating that the continuous movement of the limestone would prevent buildup of gypsum and iron precipitates that would slow neutralization. Limestone was added as needed. Various versions of water-powered rotating limestone drums have since been implemented (Clayton *et al.* 2015; Skousen *et al.* 1996; Zurbuch 1996). Their principal disadvantage is that much of the limestone enters the stream largely unreacted, though it continues to contribute alkalinity to the water, especially during higher flows when the river substrates are resuspended.

Meanwhile, researchers in Sweden developed alternative approaches like limestone dosers and diversion wells to treat streams adversely affected by acid rain (Tideström and Moberg 1984; Lessmark and Thörnelöf 1986). These were adapted to treat acidic mine water in the USA (Arnold 1991, 1998; Coberly and Rice 2000; Watten *et al.* 2005). Diversion wells are cylindrical structures in which a split of the contaminated stream water flows upward through a bed of limestone gravel at a velocity capable of fluidizing the limestone. The churning action grinds the limestone into finer particles, which in part reacts with the acid and in part is carried into the stream, where it can continue to dissolve and add alkalinity. This typically means that the limestone must be replenished fairly often, so limestone dosers now typically come with silos (info@limedoser.com).

A similar water-powered device was developed to dispense pebble quicklime (CaO) (Jenkins and Skousen 1993). The Aquafix machine uses a flow of water from the stream or AMD outlet to turn a small wheel that turns an auger in the bottom of the hopper to dispense the chemical. Gears can be changed to match the amount needed for treatment. The advantage of the Aquafix is that it operates whenever water flows and ceases when there is no flow. Aquafix also equips their units with a silo to reduce the need for frequent chemical delivery, typically to once a month or less (www.aquafix.com). It has been installed at many sites and has a good success record.

Flushing of Contaminant Precipitates

A problem that developed in anoxic limestone drains (ALDs) and vertical flow reactors (VFRs) is that these systems sometimes become clogged with aluminum precipitates. Skousen *et al.* (1998) described manually flushing ALDs on a monthly or semi-monthly basis to reduce clogging, but this approach became moot when automatic passive flushing mechanisms were developed (Vinci and Schmidt 2001; Hedin Environmental 2008). However, flushing only removes some of the precipitated metals, so these systems gradually lose effectiveness and efficiency (Skousen *et al.* 2017). To combat this, the limestone can be inexpensively cleaned by agitating the limestone in a flowing stream with an excavator (Hedin Environmental 2008; Wolfe *et al.* 2010).

Adaptations for Cold Water Temperatures

Since almost all biological reactions are influenced by temperature, biologically-mediated passive systems commonly become less effective at near-freezing temperatures. However, chemicals and nutritional supplements can be added to aid microbial growth and activity. For example, at the underground Tulsequah Chief Mine in northern British Columbia, a two-stage passive system was developed to treat the acidic, metal-laden drainage. The system was designed to achieve pH neutralization using limestone and metal removal by sulfide precipitation (Marsland *et al.* 2010). A pilot-scale campaign showed that the ambient water temperature (6.7°C) was too low to sustain adequate sulfide production by sulfate-reducing bacteria (SRB), so ethylene glycol (EG, an organic carbon source) was added to stimulate SRB activity using a battery-operated drip-feed system. The EG dosage was adjusted to attain the targeted internal dissolved sulfide concentrations and effluent metal concentrations. The annual cost of EG addition totaled less than $10,000, a very low cost for the effective removal of metals it provided.

Accessible In Situ Monitoring Capabilities and Flow Control Measures

A new development that moves a traditional passive system into the semi-passive category is the installation of sensors, which provides the ability to detect changes in flows and water chemistry during system operation. This is particularly critical when flows drastically change during high precipitation events and rapid spring snowmelt, and when systems are hard to access during these climate events. The Rico-Argentine Demonstration wetlands illustrates this approach. This system used parallel vertical and horizontal flow wetlands to treat water from an abandoned mine at high altitude (2700 m above mean sea level) in the Colorado Rockies (Lewis-Russ *et al.* 2022). The water was alkaline throughout the year, except for a brief period in late spring, when snowmelt mobilized acidic products from underground workings. This decreased the pH and increased flows and metal loading, and it was critical to understand the effect of these changes on treatment performance. To that end, several sensors were installed at key locations throughout the treatment wetland to accurately document ambient conditions within the system. The improved understanding of system performance led to the implementation of operational changes, such as increasing water elevation, which improved system performance. It was also used to guide sampling so that the spring freshet could be captured at its onset.

Factors to Consider when Making Decisions Between Active, Passive, and Semi-Passive Mine Water Treatment Systems

The Obvious: Regulatory Requirements, Land Availability, Cost Effectiveness, Flow, Contaminant Concentrations, Seasonal Variability

Early in the development of passive systems, the quality of water exiting these systems was difficult to predict because of the limited amount of data and experience with treatment process effectiveness. For abandoned mine lands where no effluent limits were established or assigned, any treatment with a passive system was seen as beneficial and desirable. At active sites, regulators were reluctant to approve passive systems because meeting National Pollutant Discharge Elemination System (NPDES) limits was unreliable and unpredictable; hence chemical treatment was deemed necessary. Semi-passive systems can remove some of this uncertainty with flow and chemistry monitoring.

Certain contaminants are far more amenable to biological treatment, such as nitrogenous compounds. At gold mines, ammonia, cyanide derivatives, and nitrate are effectively removed by biological processes, such as treatment wetlands and bioreactors, though the decision to use passive vs. active treatment depends on available land and incoming concentrations. At the Antamina mine site in Peru, the low levels of TSS, nitrate, and zinc, combined with the high flows from the North Tucush dump, were ideal for passive treatment (Strachotta *et al.* 2009).

Selenium is best removed by biological processes, though membrane filtration and chemical treatment may also be considered. Teck Coal has built saturated rock fills by filling empty pits with rock and applying 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 m3/h (3,670 gpm) and is being expanded to treat flows of 1,980 m3/h (8,700 gpm). The amortized cost is reported to be half to one-third what an active mine water treatment plant would have cost.

In general, passive and semi-passive treatment systems are very attractive mine closure options if the appropriate land is available and if they will operate consistently with minimal assistance and at low cost. This is especially true now that it is possible to remotely monitor a site. In general, mining companies would prefer to send a contractor to periodically sample, inspect, and maintain a semi-powered treatment system than to staff and operate an active treatment plant.

The 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, 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 the potential to be sinks for atmospheric carbon dioxide.

The Personal Experience of the Mining Company, Their Consultants, and Regulators

Positive (expertise and experience with successful passive and semi-passive systems) and negative (unsuccessful experiences with passive and semi-passive systems) can bias a mine operator or regulator against using a passive or semi-passive approach. For example, Placer Dome had successfully removed ammonia and cyanide complexes from mine water in an enhanced natural wetland at the Musselwhite Mine (Hayes 2000). This gave them the confidence to develop a 10-ha mine water treatment wetland at the Campbell Mine, which treated similar contaminants seasonally (Martin *et al*. 2015).

Conversely, the Saskatchewan Dept. of Environment and Public Safety developed an unfavorable view of treatment wetlands after a particularly bad experience. A sphagnum moss/sedge wetland was previously shown to remove copper and cyanide effectively from the effluent of the Star Lake/Jasper gold mill (Gormley *et al*. 1990). However, its integrity required continuous irrigation with mine water. When irrigation stopped after the mill shut down, wetland vegetation died and flaked off, releasing desiccated, copper-laden particulates. This resulted in a disastrous surge of copper in receiving streams and the department declined to accept further proposals to use treatment wetlands for mine drainage. Thus, despite two decades worth of data on metal removal by the Island Lake Fen, they would not accept using this natural wetland to polish effluent from the closed Cliff Lake Mine until studies on the stability of metals in desiccated wetland vegetation were conducted (Sobolewski 2006).

In some states in the USA, regulations allow and even encourage watershed organizations and similar groups to install passive or semi-passive mine water treatment systems at abandoned mine sites as long as their actions don't worsen effluent quality, while elsewhere, similar "good Samaritan" groups risk becoming liable for the costs of meeting effluent standards in perpetuity, even if their actions improve water quality but don't attain water quality limits. Obviously, such regulations greatly influence whether anyone decides to install passive systems at abandoned mine sites. Similarly, regulations and the way they are enforced affect whether passive, semi-passive, or active treatment systems make sense at operating mines. In some locations, mining companies are held to strict effluent standards all year long, regardless of whether the mine discharge flows into a pristine body of water or one that is already contaminated from contamination upgradient. The performance of biologically-based systems can be vulnerable to sudden changes in temperature, water quality, and water flow, any of which might cause the effluent to occasionally exceed tightly written standards. When the regulations allow some flexibility, passive and semi-passive treatment options can be considered, typically with no harm to down-gradient water quality or ecology.

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, and 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 area for such systems is available. Even at sites where contaminant loading is extreme, passive treatment should be considered as a potential polishing step. This is not to suggest though 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, initial industry and regulatory reluctance has shifted. This generation of environmental managers is more open to what was once considered a radical concept.

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 monitoring and maintenance.

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