The Beginnings of Passive Treatment of AMD in North America

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Introduction

Only a few of the folks attending this conference are old enough to have been here 40 years ago when the basics of passive treatment were first being discussed here in Morgantown. At the time, we viewed it as a potential way to treat small flows of circumneutral and mildly acidic coal mine drainage that would otherwise flow untreated into streams and creeks. Little did we know that within a decade or so, it would develop into a technology that could be used at both abandoned and active mines, to treat much larger flows than we ever thought possible, and even more contaminated water from metal mines. Jeff thought that some of you younger folks (and that means anyone here is 60 or younger) might want to learn how this pivotal technology was first developed, largely here in northern West Virginia and western Pennsylvania, and how it then continued to evolve.

To be clear, constructed wetlands had been used to treat other wastewater streams, such as municipal wastewater, long before we even considered using the approach to treat MIW (Hammer 1989). In fact, mine water was probably first treated in a constructed wetland system by Seidel (1952), who was working with municipal wastewater that apparently contained some water from the former Grube Ida-Bismarck iron mine (Wolkersdorfer 2021). So, in some ways, we ourselves were guilty of reinventing the wheel when we, unaware of the previous constructed wetlands work, which was quite mature by the 1970s, began to develop the concept of passively treating MIW. Had we known about the earlier work, especially the development of surface and subsurface flow constructed wetlands as well as hybrid systems, our own early work would probably have been more efficient by learning from their results. In addition, we would not have used the term 'constructed wetlands,' since that term had already been enlisted by those treating wastewater that was dominantly contaminated with nutrients and suspended solids. Indeed, many of our old papers from the 1980s and the early 1990s commonly referred to the early passive treatment systems as constructed or engineered wetlands.

Starting with the fundamentals, passive systems sequentially remove metals and/or acidity by using gravity and natural physical, ecological, microbiological and geochemical reactions. Although wetland plants are the most visible aspect of many MIW passive treatment systems, they are only one aspect, and other aspects are often more important. In general, adsorption and ion exchange by the plants and their substrate, abiotic, and bacterial metal oxidation (and associated hydrolysis and precipitation), settling of precipitated metals, acid neutralization through carbonate dissolution and microbial processes, filtration, and sulfate reduction (and associated precipitation of metal sulfides) all contribute, though the relative importance of each varies with the initial water quality, mode of construction, and site-specific conditions; thus, passive treatment systems vary widely in construction details and mode of operation (Ford 2003; Gusek 2009; Kadlec and Wallace

2009; Nairn et al. 2010; Skousen et al. 2000, 2017; URS 2003; Watzlaf et al. 2005; Wieder 1992). Also, since contaminant removal processes in passive treatment systems are slower than conventional chemical treatment, longer retention times and larger areas are often needed to achieve similar results, if they can be achieved at all.

The goal of a passive MIW treatment system is to enhance natural ameliorative processes, so that they occur within the treatment system, not in the receiving water body. Ideally, passive treatment requires no grid energy power and no chemicals after construction and operates effectively for at least a decade with only periodic operation and maintenance activities. Low-maintenance systems that require grid energy power or additions of easily managed amounts of chemicals (e.g. Jenkins and Skousen 1993; Kuyucak and St-Germain 1994) are generally referred to as semi-passive or enhanced passive treatment techniques.

Given that passive treatment systems are based on natural processes, it should surprise no one that the various components of these systems are generally based on observations of what was occurring naturally at and down-gradient of mine sites as well as what can be observed in the geologic record. Pyrite in coal measures, ferricrete, and manganocrete are some of the obvious examples of iron and/or manganese having been deposited in wetland or open channel flow environments (Browne 1852). Moreover, passive treatment of MIW was a concept whose time had clearly come, due no doubt to the increased environmental awareness and U.S. Clean Water Act regulations associated with the 1970s. It is generally considered to have developed in the eastern USA’s Appalachian coalfield (Kleinmann 1985; Kleinmann et al. 1983; Wieder and Lang 1982), though if it hadn’t developed here, it likely would have emerged soon elsewhere (Kleinmann et al. 2021).

The Early Years

It appears that the first step on the discovery path occurred in the 1970s when researchers at Wright State University in Ohio, who were investigating whether low pH, metal-laden coal mine drainage flowing into a natural Sphagnum bog in the Powelson Wildlife Area in Ohio was adversely affecting the bog, discovered no adverse effects. Instead, they found that the mine water was apparently being treated very effectively by the combined effects of ion exchange and adsorption of metals onto the Sphagnum moss and neutralization by a limestone outcrop at the down-gradient portion of the bog. The limestone was not being armored because the iron had already been removed by the moss. They speculated in a presentation in 1978 that similar systems could be artificially created. The first author of this paper, who at the time was a new employee of the U.S. Bureau of Mines (USBM), happened to see the published abstract in the Geological Society of America conference proceedings (Huntsman et al. 1978), contacted the authors, and began a collaborative research effort to advance this concept. The intent was fairly modest – to develop a low-cost, low-maintenance technology that could be used to mitigate small flows of acidic mine drainage originating at abandoned coal mines. No one at that time ever imagined that the technology would someday be used at active and abandoned mine sites around the world, or that it would ever be scaled up to effectively treat flows of more than a few liters per minute.

The USBM-Wright State team followed up their work by constructing what we called a "port-a-bog": a plexiglass pilot-scale test apparatus simulating what appeared to be working in the field. They constructed the system on a steel flat-bed trailer, allowing the system to be taken to other sites and tested with that site's MIW (Fig. 1; Kleinmann et al. 1985). The results were very encouraging, and this led to the design and implementation of full-scale field systems. However, we eventually learned that while the Sphagnum moss systems could handle relatively mild coal mine drainage, it was incapable of handling coal mine drainage with high metal loads unless there was large amounts of dilution available (Figure 2a; Girts and Kleinmann 1986; Kleinmann and Girts 1987).

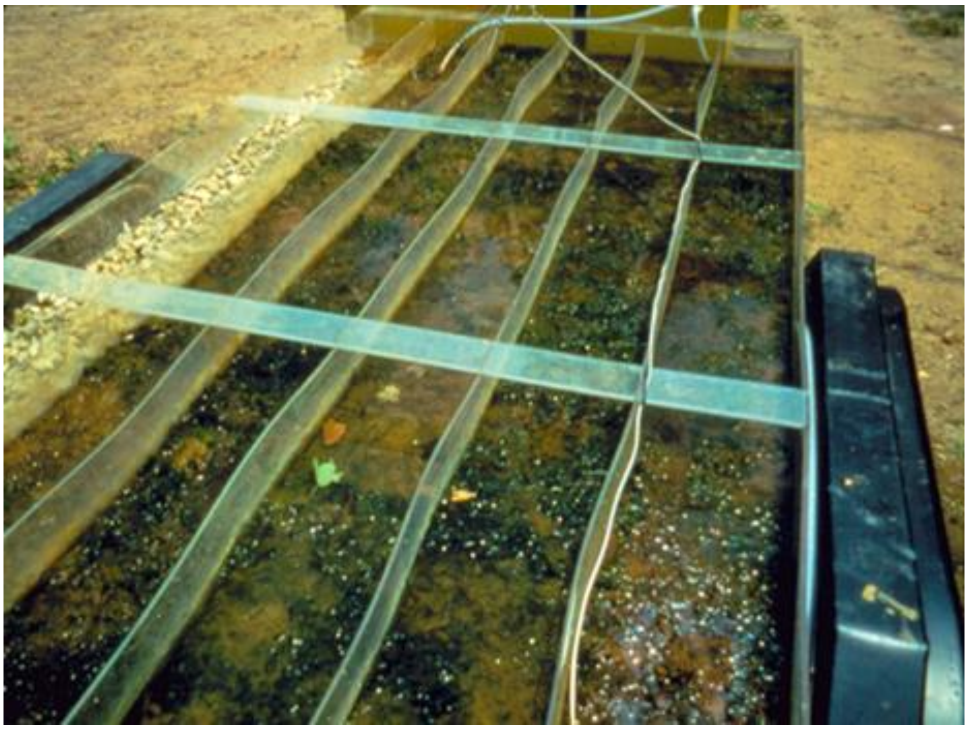

Figure 1. The "port-a-bog" was a pilot-scale wetland constructed on a flat-bed trailer and hauled to sites to test the concept of using Sphagnum moss and limestone to treat MIW.

Independently, another research group here at West Virginia University (WVU) discovered coal mine drainage being treated at Tub Run Bog in northern West Virginia, although their observations included the distinct odors of sulfate reduction occurring there. Indeed, they found that the bog brought the pH of the water from the low 3s to about 6, even though there was no limestone present; the alkalinity was instead being provided by sulfate reduction (Wieder and Lang 1982).

The WVU team followed up their discovery with laboratory tests (Tarleton et al. 1984) and by constructing a pilot-scale (10 m by 27 m) wetland system that they hoped would similarly treat mine water with a pH of 5.6 and iron concentrations of 40 mg/L in a sediment pond at a mine site in western Maryland (Wieder et al. 1985).

Their field tests, like ours, revealed that although the Sphagnum bog concept worked quite well for acidic mine water with low to moderate levels of iron, it could not tolerate iron concentrations above ≈ 100 mg/L, while the ability of the Sphagnum to tolerate a pH of above ≈ 4 varied with the Sphagnum species. The problem with high iron concentrations was that the first meter of Sphagnum moss from the inflow would adsorb so much iron that it essentially petrified; then the next meter of the bog would do the same. This 'advancing wall of death' was a clear indication of the limitations of this approach (Fig. 2b). Other negative aspects were that the Sphagnum proved to be very sensitive to fluctuating water levels and changes in water quality (a common occurrence at and near mine sites). These challenges required replacing old, petrified moss with new moss. This would have mandated the harvesting, transport, and transplanting of Sphagnum from natural wetlands into the constructed system, potentially damaging a natural ecosystem to establish a less ecologically desirable one.

Figure 2A. Attempted recreation of a sphagnum moss bog at the Friendship Hill site by USBM staff; photo shows young versions of Bob Hedin, Michelle Girts, and Trish Erickson. B. Eventual result: the high iron concentrations at the site slowly overwhelmed the moss's adsorptive capacity.

Meanwhile, observations at and near mine sites were suggesting that emergent plants, such as Typha (more commonly known as cattails), were volunteering and thriving in ponds and ditches where acidic coal mine drainage was flowing, and that the water quality was being improved by the process (Kleinmann 1985; Pesavento 1984; Snyder and Aharrah 1984). So, field trials of this approach were soon initiated (Fig. 3). Emergent Typha plants were found to tolerate much higher metal loadings and fluctuating water quality and water levels than Sphagnum. Moreover, although the Typha rhizomes, roots, and leaves did take up significant amounts of iron and manganese when the results were judged by drying and analyzing the plant tissue, the amount actually removed was relatively low when considered by the amount removed over a unit area of the wetland (Sencindiver and Bhumbla 1988). Instead, it appeared that the principal function of the plants was to simply slow down the flow of the MIW, creating an environment in which various bacteria, especially iron-oxidizing bacteria, could be active and the oxidized iron could precipitate. In other words, these wetlands were acting like shallow, abiotic aeration/settling ponds.

Figure 3A. A Typha-based wetland immediately after construction in West Virginia. B. the same site, two months later.

Since iron hydrolysis is actually an acid-generating reaction, at sites where the untreated water or substrate was not alkaline, the pH at the wetland outlet typically decreased as the contaminants, especially the iron, precipitated (e.g. Brodie et al. 1988). At sites where limestone had been incorporated into the wetland's organic substrate, this pH decrease was less of a problem. This limestone is not typically rendered inert because the iron that infiltrated though the organic medium was converted from the ferric form, which would armor the limestone, to the ferrous form, which does not armor it.

Looking back in time, presentations given at conferences held in Pennsylvania, West Virginia, Kentucky, Colorado, and elsewhere, from 1984 onwards, were key to spreading the word about what was being learned. Passive treatment research really accelerated as all the various research groups became aware of each other's work and as other research groups either learned of these developments and began conducting experiments and field tests or had similar discoveries, leading to similar results. These included researchers at the Colorado School of Mines (e.g. Emerick et al. 1988; Wildeman et al. 1993), Pennsylvania State University (e.g. Gerber et al. 1985; McHerron 1986; Stark et al. 1990), Virginia Tech (Duddleston et al. 1992; Hendricks 1991), the Tennessee Valley Authority (TVA; e.g. Brodie et al. 1986, 1988), Montana (Hiel and Kerins 1988), and in Canada (personal communication with Keith Ferguson 1985; Kalin 1988).

As practitioners learned about the research results, more and more began to incorporate wetland systems into their mine plans, first by enhancing wetland vegetation that had volunteered on their mine sites, and then actually constructing wetlands at active and abandoned mine sites. Researchers began to study many of these systems, learning from what worked, what did not work, and from what worked at some sites but not at others. This led to the first of many workshops organized by the U.S. Bureau of Mines and others on how to construct passive treatments systems, sharing the practical aspects of what was being learned empirically (Kleinmann et al. 1986). These continued well into the early 1990s and led to even more wetland systems being constructed by watershed associations, state abandoned mine programs, and mining and consulting companies. Even today, entire sessions at reclamation and water conferences are devoted to passive system application, design, performance, and maintenance, and most importantly innovations and new discoveries.

As these systems were gradually improved, we learned to sequence the passive treatment steps to precipitate the contaminants, generate alkalinity, and correctly size the systems so that they could meet regulatory discharge standards. From the 30 or so such sites that had been constructed in 1984 and 1985 in Pennsylvania (Girts and Kleinmann 1986, 1987; Kleinmann and Girts 1987), the number of such systems more than doubled each year through 1987, and only accelerated after that. The key steps are discussed thematically below. An unintentional outcome of the USBM field trials was that many subsequent applications tended to use the same substrate, spent mushroom compost, that the USBM had used. However, this form of compost was used only because, at the time, it was readily available in Pennsylvania due to the large amount of mushroom farming there. In hindsight, perhaps that should have been clarified.

Alkalinity Generation

As mentioned above, the organic substrate supporting the cattails typically contained limestone or had limestone added to it. Limestone in the anoxic zone could contribute alkalinity without armoring, so it was recognized early on that placing the limestone beneath a layer of soil or compost was beneficial. However, other ways to add alkalinity without having the limestone becoming coated with precipitated iron were soon developed, including sulfate reduction (discussed below), limestone placed up-gradient of the mine discharges, anoxic limestone drains (ALDs), and reducing and alkalinity-producing systems (RAPS), also sometimes referred to as sequential alkalinity producing systems (SAPS) or vertical flow wetlands.

The first of these, introducing the alkalinity up-gradient of the mine discharge was very easy to implement, but very limited in the amount of alkalinity it could provide if the water dissolving the limestone was not already acidic. Limestone placed into neutral pH water with no acidity will generate less than 50 mg/L as CaCO3 alkalinity. However, many mine water discharges from underground mines are acidic with elevated concentrations of metals, allowing the dissolution of the limestone as long as metal precipitates do not armor the limestone or clog the system, preventing flow-through.

Armoring of limestone with iron hydroxides has plagued many passive treatment systems and caused premature failure. Pearson and McDonell (1974, 1975a, b) showed that armored limestone dissolved, but at a rate about 20% that of unarmored limestone. Based on this work, Ziemkiewicz and Skousen conducted laboratory and field experiments and found that armored limestone was between 20 to 50% as effective as unarmored limestone, depending on the thickness of armoring (Ziemkiewicz et al. 1994, 1997). More effective systems were shown to be at sites that had large elevation changes, which prevented the precipitates from forming, removed them from the limestone surfaces, and flushed out void spaces in the channels. This knowledge resulted in hundreds of open limestone channels being designed and built based on these initial studies; open limestone channels are often the default system when no other passive system type is suitable (Fig. 4).

Figure 4. An open limestone channel (1995)

Turner and McCoy (1990) realized that as long as MIW has not yet contacted the atmosphere, the dissolved iron was most likely in the ferrous state. This meant that the limestone would remain unarmored when the mine water contacted it in an anoxic environment. They used this knowledge to construct the first anoxic limestone drain (ALD) in Tennessee. They excavated a trench to intercept the mine discharge before it reached the surface, filled the trench with limestone, and most importantly, covered the limestone to prevent the iron in the mine water from being oxidized, so that it would not armor the limestone. This was then followed by a settling pond to allow the dissolved iron, which rapidly oxidized when released to the surface in the now circumneutral pH water and precipitated in the settling pond (Fig. 5). Independently, Greg Brodie and Cindy Britt of the TVA identified an "accidental" ALD at the IMP-1 site in Alabama, where an abandoned haul road constructed out of limestone rock sub-base was treating subsurface water and adding alkalinity to an aerobic wetland cell receiving seepage from a coal slurry pond. Subsequently, the USBM and TVA developed detailed design criteria for ALDs, which were shared with the passive treatment community (Brodie et al. 1993; Hedin et al. 1994b; Nairn et al. 1991; Watzlaf and Hedin 1994). Performance data for 19 operating ALDs was provided by Faulkner and Skousen (1994).

Figure 5. An anoxic limestone channel being constructed, soon to be covered with plastic sheeting and a soil cover.

An attempt was made in West Virginia to increase the rate of limestone dissolution in ALDs by placing organic matter within the drain. The hay bales were placed on the top of the limestone and the hay bales and limestone were wrapped with plastic so that degradation of the organic matter would consume oxygen and generate CO_2 (Skousen 1991). However, the organic matter encouraged microbial growth, which eventually clogged the ALD.

But what could be done if the MIW already contained dissolved oxygen or significant amounts of dissolved ferric iron? Kepler and McCleary (1994) reasoned that if dissolved oxygen and ferric iron concentrations of the MIW were being reduced by bacterial activity in the wetland substrate, surely a system could be designed where the oxygenated water could be reduced by flowing through substrate to consume the dissolved oxygen, render the water anoxic, and convert the ferric iron to ferrous. The discharge from such a system should be alkaline and contain ferrous iron, would be readily removed by oxidation and hydrolysis after exposure to the atmosphere. They reasoned that given enough space and vertical gradient, pairs of anaerobic and aerobic units could be arranged in sequence and treat highly contaminated MIW. Kepler and McCleary referred to this approach as successive alkalinity-producing systems (SAPS), although the SAPS term soon become synonymous for the vertical flow anaerobic treatment unit, which was the most original aspect of the technology (Fig. 6). Watzlaf et al. (2000) began referring to SAPS units as reducing- and alkalinity-producing systems (RAPS) to describe the process more accurately, and to include systems that did not put more than one unit in sequence. These systems have also been called vertical flow ponds, vertical flow wetlands, vertical flow bioreactors, or simply vertical flow systems. Aluminum, which is not controlled by manipulating redox conditions, is still retained in these systems, so Kepler and McCleary (1997) suggested a simple gravity-powered flushing mechanism to extend their effective life span. Unfortunately, the removal of solids from organic substrate through flushing did not prove practical. But the layered vertical flow approach proved effective for delaying the plugging of the systems with Al and Fe solids and subsequently become a standard passive treatment technique for acidic MIW waters.

Figure 6. Construction of an early SAPS in 1995, which has subsequently also been referred to as RAPS, vertical flow ponds, and vertical flow systems. A. Initial placement of the limestone base layer with underdrain piping. B. Compost layer being placed on top of the limestone. C. The system filled with water.

Passive aluminum removal without any clogging of the organic substrate was first observed in a pilot-scale sulfate-reducing bioreactor system at the Brewer Gold Mine in South Carolina (Gusek 2000). The SRB received low pH (2.0 to 4.7) MIW with aluminum concentrations ranging from 3.6 to 220 mg/L without clogging due to aluminum oxyhydroxide precipitation. Subsequently, Thomas and Romanek (2002) identified aluminum hydroxy-sulfate precipitates in a limestone-buffered organic substrate (LBOS). The aluminum precipitates appeared to replace gypsum (without clogging) in response to exposure to MIW.

In 1990, a passive system was designed for the Douglas Highwall abandoned mine lands (AML) discharge with a flow rate of 13 L/s, a much higher flow rate than previously attempted with passive treatment systems (Skousen 1995). The MIW had a pH of 2.8, and contained 500 mg/L acidity, 50 mg/L total iron (50% ferrous), 40 mg/L aluminum, and 10 mg/L manganese. The limited available space necessitated a long narrow system, which was later called a wetland-ALD (WALD) system. The wetland component of the WALD system was designed to pretreat the partially oxidized water in a 2.1-m wide × 370-m long front section with a 1.3-m deep layer of compost (370 m length) to remove oxygen and convert the ferric iron to ferrous. The ALD portion followed with a 10-m wide × 350-m long section of limestone rock that was 2 m deep. The WALD system did not use pipes in the limestone to induce downward flow because it was thought that the 5- to 10-cm sized limestone rock at the base would allow flow through the system. The system produced net alkaline water for its first four years, but then the outflow water quality slowly degraded until it reached a steady acidity level of 100 mg/L (as $CaCO_3$) for the next 20 years. This site helped demonstrate the challenge of horizontal flow systems and helped explain why the vertical flow approach became preferable over horizontal systems, which often developed hydraulic problems.

Initial evaluations of passive treatment performance were based on simple calculations of concentration efficiency or percent removals (e.g. Girts et al 1987). However, this technique failed to provide reliable evaluations of performance under varied field conditions or at widely different sites. A reliable performance measure was needed that could lead to development of empirical design and sizing criteria by allowing comparison of contaminant removal capabilities for systems of various sizes that received MIW with different flow rates and chemical compositions. Concentration efficiency calculations failed to provide true performance insights for different systems because they did not include influent mass loads or system size. The extensive multi-year, monthly monitoring campaign completed at numerous passive treatment systems by the USBM in western Pennsylvania in the early 1990s developed the data to allow valid system performance evaluations and eventually led to reliable design and sizing criteria. The 18 studied systems were of various designs and surface areas (607 to 8100 m2) and received widely variable flow rates (<1 to 8600 L/min) and influent water chemical compositions (ranging from net acidic to net alkaline; pH 2.6 to 6.2; Fe < 1 to 473 mg/L). Volumetric discharge rates were measured (not estimated) and full elemental analyses were completed. Systems that were not load-limited were intentionally studied so that the capacity or capability of the systems could be determined (Hedin and Nairn 1990, 1992, 1993; Hedin et al. 1991; Nairn and Hedin 1992, Nairn et al. 1992). These findings were all incorporated into a comprehensive USBM publication (Hedin et al. 1994a), which included a design decision tree that separated mine waters into chemical classes based primarily on alkalinity and acidity, and secondarily on the metal contaminants, and identified the passive treatment technologies that were most appropriate for the particular water chemistry conditions. This distinction explained much of the variable performance of existing systems and allowed subsequent researchers and designers to better focus on key geochemical needs (e.g. alkalinity generation, rapid Fe removal, Mn removal). The design decision tree (Fig. 7) has been subsequently adapted and modified by many researchers.

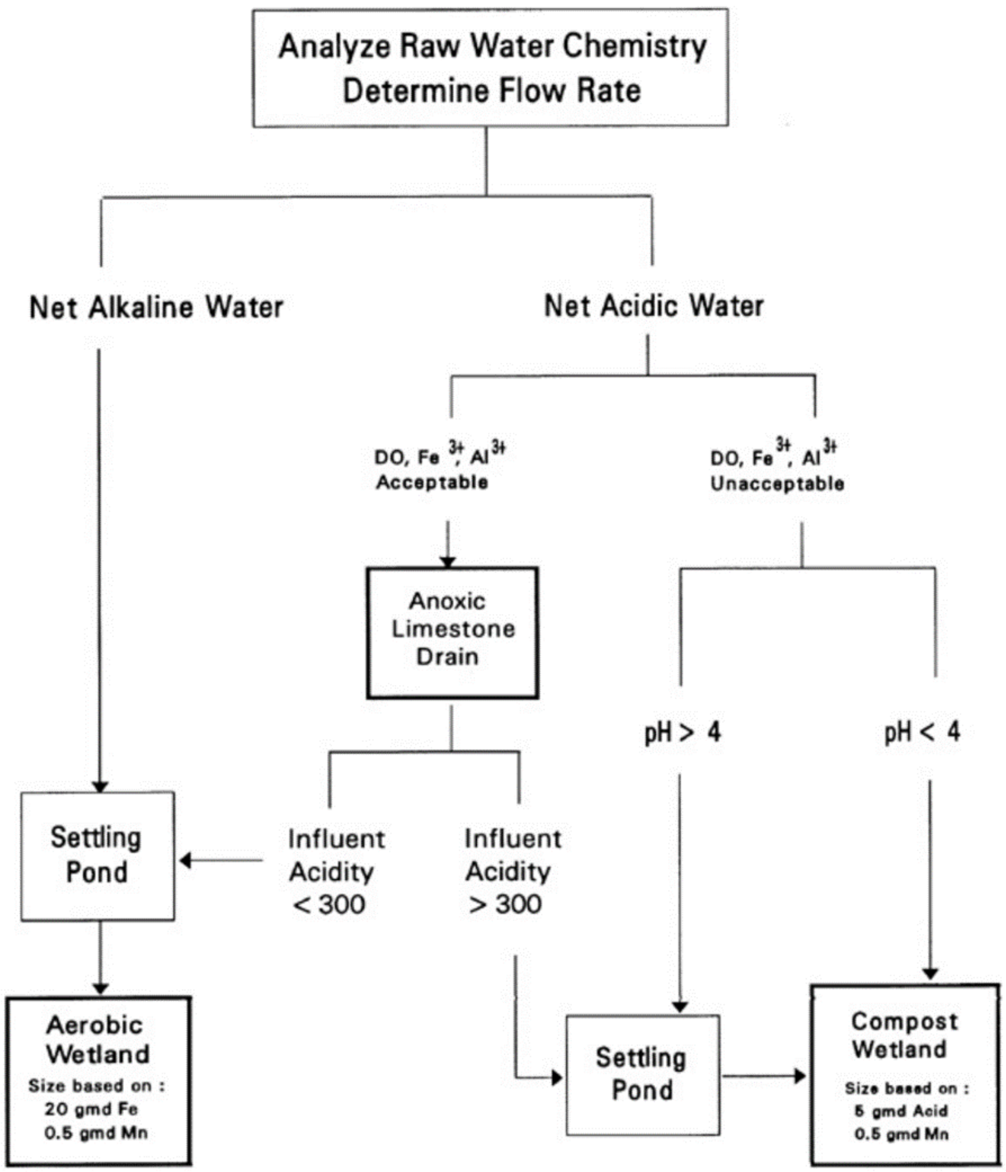

Figure 7. Early decision tree for designing of a passive treatment system for coal mine drainage.

Another contribution of this publication was the development of rate-based sizing criteria for the removal of Fe and Mn. The approach recommended that sizing of passive systems should be based on the contaminant mass load at the site and the expected contaminant removal rate for the proposed technology. The initial report recommended the use of area-adjusted removal rates (gX/day/m^2) because of strikingly consistent area-adjusted Fe removal rates for passive systems treating circumneutral pH alkaline mine water. Subsequently, the rate approach was used to quantify acidity and sulfate removal and modified to reflect volumes and quantities of treatment substrates.

In addition, the use of mass removal rates in the design process allowed estimation of passive treatment system lifetimes. For net alkaline MIW, iron oxide accumulation – the physical filling up of ponds as freeboard is lost over time – led to reasonable system lifetimes of 20-25 years, balancing system surface and volume with practical construction and maintenance constraints. Estimated lifetimes of approximately two decades, for most passive treatment system process units, have become common. However, regular (quarterly to annually), periodic (every two to three years), and rehabilitative (perhaps once per decade) maintenance are all still necessary; this must be stressed to responsible parties.

In addition to the previously mentioned open limestone channels, Ziemkiewicz and Skousen (1998, 1999) looked for other low-cost alkalinity sources besides limestone and limestone byproducts for passive systems. Experiments showed that steel slag yielded more alkalinity than equal weights of limestone (from 500 to 2,000 mg/L as $CaCO_3$, compared to 60 to 80 mg/L). Slag leach beds were originally designed for freshwater treatment with the now highly alkaline water being introduced into the MIW. Later, installations with coarser slag materials allowed direct contact with the MIW and prolonged system effectiveness.

All of the systems discussed above were focused on passive treatment of MIW at the surface, but other researchers were investigating ways to use similar approaches to treat contaminated groundwater. Permeable reactive barriers (PRBs) are zones of reactive materials installed in aquifers or in unconsolidated waste materials to remove contaminants as the groundwater flows through the reactive material under a natural hydraulic gradient (Blowes et al. 2000). PRBs have been used to treat a range of contaminant sources including MIW.

Sulfate Reduction

U. S. Bureau of Mines researchers, assessing the performance of a cattail-based wetland that had been constructed to treat acidic water, found that in isolated locations, the coal mine water was being neutralized by sulfate-reducing bacteria (SRB) as well as by the limestone and that some of the iron was being precipitated as a sulfide. Apparently, the water was flowing down through the compost/limestone substrate and then back up again, gaining alkalinity in the process as some of the contaminants precipitated as sulfides (Hedin et al. 1988). Although the observation was an important demonstration of the potential utility of bacterial sulfate reduction in mine water treatment systems, it was not an original discovery. In the 1960s, Tuttle et al. (1969) proposed that sulfate reduction might have utility for MIW treatment, but the concept did not advance. However, in the regulatory environment of the 1980s, the idea gained traction. An early review of the natural wetland literature suggested a typical sulfate reduction rate in natural substrates of 0.3 mol/m^3/day (Hedin et al. 1989), a rate that was confirmed by isotope studies (McIntyre and Edenborn 1990). An approach was developed to optimize this effect and was evaluated at bench- and pilot-scale and in the field (Dvorak et al. 1992; Hammack and Hedin 1989; McIntyre and Edenborn 1990;

McIntyre et al. 1990; Nawrot and Klimstra 1990); these anaerobic or compost wetlands added alkalinity, but were not very efficient for iron removal, and thus required sequential placement of aerobic and anaerobic steps. Thus, for MIW at coal mining sites, alkalinity generation by limestone dissolution and metal removal by aerobic abiotic and microbial processes was simpler to implement and operate than sulfate reduction systems.

However, sulfate reduction was found to be very useful for treating metal mine drainage, since for most metals other than the iron, manganese, and aluminum that dominate coal mine drainage, sulfides are less soluble than the oxides/hydroxides, allowing the removal of copper, zinc cadmium, lead, and other inorganic constituents typically encountered in MIW at hard rock mines (Wildeman et al. 1990, 1994).

The published research on the use of wetlands to control coal mine drainage led Region VIII of the U.S. EPA in 1987 to assess “constructed wetlands” as a treatment option for metal mine drainage. Funded by a Superfund Innovative Technology Evaluation or “SITE” grant, the Colorado School of Mines (CSM) was chosen to explore sulfate reduction processes and a project was initiated at the Big Five Tunnel in Idaho Springs, Colorado. This project had an important feature. It assembled an interdisciplinary team that included a plant ecologist, environmental engineer, geochemist, and an applied microbiologist, each of whom brought a different perspective to the project. This team relied on civil engineering consultants for building and maintaining the pilot system.

Based on the work of the USBM group (Kleinman and Girts 1987), they decided to build three pilot cells with various mixes of organic substrates and wetland plants. They quickly found that sulfate reduction in the substrate was a major removal process and that designing a system where the water flowed through the organic substrate rather than over it was important. After a few failed attempts, a system where the water was added at the top and flowed through the substrate and out the bottom was found to be the best configuration. In addition, unlike the early versions, which simulated the USBM work, the final big Five pilot-scale facility had no wetland plants.

This primitive SRB led to a number of concepts and practices that are still being used. Since this treatment structure looked nothing like a constructed wetland, the term passive treatment used a decade earlier by Holm and Bischop (1983) was a more appropriate term to describe what was occurring. Also, since bacterial activity, rather than plants, were the critical component, laboratory studies could be used to find the best substrate and inoculum for a given site (Wildeman, et al. 1994a, 1994b).

Because laboratory studies were the logical starting point, standard engineering practices that progressed from laboratory studies to bench-scale tests, to pilot-scale systems, to full-scale systems could be used. This helped convince some mining companies to initiate a program without a large fiscal commitment. This staged design process was also used to address manganese removal (Clayton and Wildeman 1998; Wildeman et al. 1993), and later, other contaminants.

Once it was realized that sulfate reduction catalyzed by bacteria was the important removal mechanism, it became necessary to determine a volume-based sulfide generation rate for a bioreactor. This was especially important for metal-mine drainage because mineral acids could overwhelm the system and destroy the sulfate-reducing bacteria. Like the USBM, the CSM group (Reynolds et al. 1991) conducted an isotopic lab study to determine the rate using substrates from the Big Five pilot system. They found an initial honeymoon period where the sulfate reduction rates were quite high. However, after a month, rates settled down to 0.5 µmol/g/day. Using this result along with the USBM results, it was decided that a volume-based sulfate reduction rate of 0.3 mol/day/m^3 was a reasonable rate (Wildeman et al. 1993). This has turned out to be a basic "rule of thumb" for the design of an SRB. It is imperative that the loading of metals into a volume-based SRB bioreactor is maintained at a level that is below this value. This value presumes that the entire substrate mass participates equally in sulfate reduction. Consequently, sulfate reduction rates within the active microbial zone may be greater than 0.3 mol/day/m^3 as the "reaction front" moves into unreacted substrate over time.

Final Thoughts

Passive treatment technology developed in fits and starts and faced great skepticism from some regulators who saw the tremendous range in the performance and effectiveness of the various passive systems and saw no way to ensure adequate effluent water quality from these systems. Nonetheless, because it was the only affordable option to no treatment at many abandoned mine sites, it found a natural niche there. The subsequent refinement of passive treatment was greatly aided and accelerated by the good working relationships and collaboration that existed at the time between researchers, practitioners, and industry. Gradually, as its high cost effectiveness (compared to active treatment) became obvious, and the performance of passive systems improved and became more predictable, regulators became more open to having them placed on active mine sites, as long as there was a contingency plan in place to implement chemical treatment if water quality requirements were not being met.

As discussed in the beginning of this paper, we wrote this paper to provide the readers with some background and history of the initial conceptual ideas of passive treatment. Undoubtedly, we have missed the contributions of many additional individuals who contributed to the development of this field. It should also be mentioned that during the time frame that this paper covers, the successful results observed in North America led to many active research teams in other countries retailoring the procedures demonstrated to work here to their local MIW, sources of alkalinity, and sources of suitable organic substrates (e.g. Nuttall and Younger 2000; Sen and Johnson 1999; Younger 1998). In addition, semi-passive systems began to be installed where totally passive treatment proved inadequate (e.g. Jenkins and Skousen 1993; Kuyucak and St-Germain 1994).

One of the more intriguing parts of this story is how the ideas surrounding passive treatment of MIW emerged rather independently to several observant individuals around the late 1970s and early 1980s. Once the researchers and practitioners began discussing their observations and small-scale experiments with others, and collaborating with each other and with industry, a continual expansion of concepts and additional possibilities flourished. When problems appeared, like clogging of wetland substrates or armoring of limestone, new discoveries appeared, such as the development of ALDs, vertical flow wetlands, and open limestone channels. And a variety of substrates have been used to preserve hydraulic conductivity and maintain alkalinity generation, including the use of microorganisms, algae, and other biota to enhance treatment. Today, new ideas are being implemented and we feel fortunate to have provided some of the undergirding of this important field of passive treatment of MIW.

References

Blowes DW, Ptacek CJ, Benner SG, McRae CWT, Bennett TA, Puls RW (2000) Treatment of inorganic contaminants using permeable reactive barriers. J Contam Hydrol 45: 123–137

Brodie GA, Britt CR, Tomaszewski TM, Taylor HN (1993) Anoxic limestone drains to enhance performance of aerobic acid drainage treatment wetlands: experiences of the Tennessee Valley Authority. In: Moshiri GA (Ed), Ch 12, Constructed Wetlands for Water Quality Improvement

Brodie GA, Hammer DA, Tomljanovich (1986) Man-made wetlands for acid drainage control. Proc, 5th Annual National Abandoned Mines Conf

Brodie GA, Hammer DA, Tomljanovich (1988) Constructed wetlands for acid mine drainage control in the Tennessee Valley. Mine Drainage and Surface Mine Reclamation, U.S. Bureau of Mines (USBM) I.C. 9183, Vol 1, pp 325-331

Browne D (1852) The American Muck Book. C.M. Saxton, New York City

Clayton LD, Wildeman TR (1998) Processes contributing to the removal of manganese from mine drainage by an algal mixture. Proc, 15th Annual Meeting of American Soc for Surface Mining and Reclamation, pp 192-201

Duddleston KN, Fritz E, Hendricks AC, Roddenberry K (1992) Anoxic cattail wetland for treatment of water associated with coal mining activities. Proc, 19th Meeting of the American Soc for Surface Mining and Reclamation, pp 249-254

Dvorak DH, Hedin RS, Edenborn HM, McIntyre PE (1992) Treatment of metal-contaminated water using bacterial sulfate reduction: results from pilot-scale reactors. Biotechnol Bioeng 40: 609-616

Emerick JC, Huskie WW, Cooper DJ (1988) Treatment of discharge from a high elevation metal mine in the Colorado Rockies using an existing wetland. Mine Drainage and Surface Mine Reclamation, USBM I.C. 9183, Vol. 1, pp 345-351

Faulkner BB, Skousen JG (1994) Treatment of acid mine drainage by passive treatment systems. Proc, International Land Reclamation and Mine Drainage Conf and 3rd International Conf on the Abatement of Acidic Drainage (ICARD), pp 250-256

Gerber DW, Burris JE, Stone RW (1985) Removal of dissolved iron and manganese ions by a sphagnum moss system. In: Brooks RP, Samuel DE, Hill JB (Eds), Wetlands and Water Management on Mined Lands, Pennsylvania State Univ, pp 365-372

Girts MA, Kleinmann RLP (1986). Constructed wetlands for treatment of acid mine drainage: a preliminary review. In: Graves DH (Ed), Proc, National Symp on Surface Mining, Hydrology, Sedimentology, and Reclamation, Univ of Kentucky, pp 165–171

Girts MA, Kleinmann RLP, Erickson PM (1987) Performance data on Typha and Sphagnum wetlands constructed to treat coal mine drainage. Proc, 8th Annual Surface Mine Drainage Task Force Symp

Gusek J (2000) Reality check: passive treatment of mine drainage as emerging technology or proven methodology? Proc, SME Annual Meeting, preprint 00-43

Gusek J (2009) A periodic table of passive treatment for mining influenced water. Proc, ASMR Annual Meeting, pp 550-562. DOI: 10.21000/JASMR09010550

Hammack RW, Hedin RS (1989) Microbial sulfate reduction for the treatment of acid mine drainage: a laboratory study. Reclamation – A Global Perspective, Proc, Joint meeting of the Canadian Land Reclamation Assoc and the American Soc for Surface Mining and Reclamation, pp 673-680. DOI: 10.21000/JASMR89010673

Hammer DA (Ed) (1989) Wastewater Treatment: Municipal, Industrial, and Agricultural, CRC Press, Boco Raton, FL

Hedin RS, Dvorak DH, Gustafson SL, Hyman DM, McIntyre PE, Nairn RW, Neupert RC, Woods AC, Edenborn HM (1991) Use of a constructed wetland for the treatment of acid mine drainage at the Friendship Hill National historic Site, Fayette County, PA. Interagency Agreement 4000-5-0010

Hedin RS, Hyman DM, Hammack RW (1988) Implications of sulfate-reduction and pyrite formation processes for water quality in a constructed wetland: preliminary observations. Mine Drainage and Surface Mine Reclamation, USBM I.C. 9183, Vol. 1, pp 382-388

Hedin RS, Hammack RW, Hyman DM (1989) Potential importance of sulfate reduction processes in wetlands constructed to treat mine drainage. In: Hammer DA (Ed), Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural, pp 508-514, CRC Press, Boca Raton

Hedin RS, Nairn RW (1990) Sizing and performance of constructed wetlands: case studies. In: Skousen J, Sencindiver J, Samuel D (Eds), Proc, 1990 Mining and Reclamation Conf and Exhibition, pp 385-392

Hedin RS, Nairn RW (1992) Design and sizing of mine drainage treatment systems. Proc, 13th Annual West Virginia Acid Mine Drainage Task Force Symp, pp 111-121. https://wvmdtaskforce.files.wordpress.com/2015/12/92-hedin.pdf

Hedin RS, Nairn RW, Kleinmann RLP (1994a) Passive Treatment of Coal Mine Drainage. US Bureau of Mines IC 9389

Hedin R, Watzlaf GR, Nairn R (1994b) Passive treatment of acid mine drainage with limestone. J Environ Qual 23: 1338-1345. DOI:10.2134/JEQ1994.00472425002300060030X

Hendricks, AC (1991) The use of an artificial wetland to treat acid mine drainage. Proc, International Conf on the Abatement of Acidic Drainage (ICARD).

Hiel MT, Kerins Jr. FJ (1988) The Tracy wetlands: a case study of two passive mine drainage systems in Montana. Mine Drainage and Surface Mine Reclamation, USBM I.C. 9183, Vol. 1, pp 352-358

Holm JD, Bischop MB (1983) Passive mine drainage treatment: selected case studies. In: Medine A, Anderson M (Eds), Proc, National Conf on Environmental Engineering, pp 607-618

Holm JD, Elmore T (1986) Passive mine drainage treatment using artificial and natural wetlands. In: Shuster MA, Zuck RW (Eds), Proc, High Altitude Reclamation Workshop no. 7, pp 41-48

Huntsman BE, Solch JG, Porter MD (1978) Utilization of sphagnum species dominated bog for coal acid mine drainage abatement. Abstracts, 91st Annual Meeting of the Geological Soc of America, Toronto

Jenkins M, Skousen J (1993) Acid mine drainage treatment with the Aquafix system. Proc, West Virginia Acid Mine Drainage Task Force Symp. https://wvmdtaskforce.files.wordpress.com/2015/12/93-jenkins.pdf

Kadlec RH, Wallace SD (2009) Treatment Wetlands. 2nd edit, CRC Press, Boca Raton

Kalin M (1988) Ecological engineering and biological polishing methods to economize waste management. Proc, 20th Annual Meeting of the Canadian Mineral Processors, pp 302-318

Kepler DA, McCleary EC (1994) Successive alkalinity-producing systems (SAPS) for the treatment of acidic mine drainage. Proc, International Land Reclamation and Mine Drainage Conf, USBM SP 06B-94, Vol 1, pp 195-204

Kepler DA, McCleary EC (1997) Passive aluminum treatment success. Proc, 18th WV Surface Mine Drainage Task Force Symp, Morgantown, WV

Kleinmann B, Skousen J, Wildeman T, Hedin B, Nairn B, Gusek J (2021) The early development of passive treatment systems for mining-influenced water: a North American perspective. Mine Water Environ 40(4):818-830

Kleinmann RLP (1985) Treatment of acid mine water by wetlands. Control of Acid Mine Drainage. USBM IC 9027, pp 48-52

Kleinmann RLP, Erickson PM, Girts MA, Hyman DM (1986) Workshop on passive treatment of mine drainage (unpublished)

Kleinmann RLP, Girts MA (1987) Constructed wetlands for treatment of mine water--successes and failures. Proc, 8th Annual National Abandoned Mine Lands Conf, Montana Dept of State Lands, pp 67-73

Kleinmann RLP, Tiernan TO, Solch JG, Harris RL (1983) A low cost, low maintenance treatment system for acid mine drainage using sphagnum moss and limestone. In: Graves DH (Ed), Proc, Symp on Surface Mining, Hydrology, Sedimentology and Reclamation, Univ of Kentucky, pp. 241-246

Kuyucak N, St-Germain P (1994a) Evaluation of sulphate reducing bacteria and related process parameters for developing a passive treatment method. In: Holmes DS, Smith RW (Eds), Proc, Engineering Foundation Conf, pp 287-302

McHerron LE (1986) Removal of iron and manganese from mine drainage by a wetland: seasonal effects. MS thesis, Pennsylvania State Univ

McIntyre PE, Edenborn HM (1990) The use of bacterial sulfate reduction in the treatment of drainage from coal mines. Proc, Mining and Reclamation Conference and Exhibition, pp 409-416. doi.org/10.21000/JASMR90010409

McIntyre PE, Edenborn HM, Hammack RW (1990) Incorporation of bacterial sulfate reaction into into constructed wetlands for the treatment of acid and metal drainage. In: Graves DH, De Vore (Eds), Proc, 1990 National Symp on Mining, pp 207-213

Nairn RW, Hedin RS (1992) Designing wetlands for the treatment of polluted coal mine drainage. In: Landin MC (Ed.), Wetlands: Proc, 13th Annual Conf of the Society of Wetland Scientists, pp. 224-229

Nairn RW, Hedin RS, Watzlaf GR (1991) A preliminary review of the use of anoxic limestone drains in the passive treatment of acid mine drainage. Proc, 12th Annual West Virginia Surface Mine Drainage Task Force Symp, pp 23-38

Nairn, RW, Hedin RS, Watzlaf GR (1991) A preliminary review of the use of anoxic limestone drains in the passive treatment of acid mine drainage. Proc, 12th Annual WV Surface Mine Drainage Task Force Symp, pp 23-38. https://wvmdtaskforce.files.wordpress.com/2015/12/92-hedin2.pdf

Nairn RW, Hedin RS, Watzlaf GR (1992) Generation of alkalinity in an anoxic limestone drain. Achieving Land Use Potential through Reclamation, Proc, 9th Annual American Soc for Surface Mining and Reclamation Meeting, pp 206-219

Nairn RW, LaBar JA, Strevett KA, Strosnider WH, Morris D, Neely CA, Garrido A, Santamaria B, Oxenford L, Kauk K, Carter S, Furneaux B (2010) A large, multi-cell, ecologically engineered passive treatment system for ferruginous lead-zinc mine waters. Proc, Mine Water and Innovative Thinking, International Mine Water Assoc, pp 255-258

Nawrot JR, Klimstra WB (1990) Biochemical treatment of mine drainage through a reedgrass wetland. In: Skousen J, Sencindiver J, Samuel D (Eds.). Proc, Mining and Reclamation Conf and Exhibition. West Virginia Univ. https://wvmdtaskforce.com/past-symposium-papers/1990-symposium-papers/

Nuttall CA, Younger PL (2000) Zinc removal from hard circum-neutral mine waters using a novel closed-bed limestone reactor. Water Res 34:1262-1268

Pearson FH, McDonell AJ (1974) Chemical kinetics of neutralization of acidic water by crushed limestone. Proc, no. 18, Water Resources Problems Related to Mining, American Water Resources Assoc, Columbus, OH, pp 85-98

Pearson FH, McDonell AJ (1975a) Use of crushed limestone to neutralize acid wastes. J Env Eng Div-ASCE 101:139-158

Pearson FH, McDonell AJ (1975b) Limestone barriers to neutralize acidic streams. J Env Eng Div-ASCE 101: 425-440

Pesavento BG (1984) Factors to be considered when constructing wetlands for utilization as biomass filters tof an innoo remove minerals from solution. In: Burris JE (Ed), Treatment of Mine Drainage by Wetlands, Dept of Biology, Pennsylvania State Univ

Reynolds JS, Machemer SD, Wildeman TR, Updegraff DM, Cohen RR (1991) Determination of the rate of sulfide production in a constructed wetland receiving acid mine drainage. Proc, National Meeting of the American Soc of Surface Mining and Reclamation, pp 175-182

Seidel K (1952) Pflanzungen zwischen Gewässern und Land. Mitteilungen Max-Planck Gesellschaft zur Förderung der Wissenschaften 8:17-21

Sen AM, Johnson DB (1999) Acidophilic sulphate-reducing bacteria: candidates for bioremediation of acid mine drainage. In: Amils R, Ballester A (Eds), Biohydrometallurgy and the Environment: Toward the Mining of the 21st Century, Process Met 9: 709-718. doi.org/10.1016/S1572-4409(99)80073-X

Sencindiver JC, Bhumbla DK (1988) Effects of cattails (Typha) on metal removal from mine drainage. Mine Drainage and Surface Mine Reclamation, USBM I.C. 9183, Vol 1, pp 359-368

Skousen J (1991) Anoxic limestone drains for acid mine drainage treatment. Green Lands 21: 30-35

Skousen J (1995) Douglas abandoned mine land project: description of an innovative acid mine drainage treatment system. Green Lands 25: 29-38

Skousen, J, Zipper C, Rose A, Ziemkiewicz P, Nairn R, McDonald LM, and Kleinmann RLP (2017) Review of passive systems for acid mine drainage treatment. Mine Water Environ. 36:133-153. https://doi.org/10.1007/s10230-016-0417-1

Skousen J, Sexstone A, Ziemkiewicz P (2000) Acid mine drainage control and treatment. Reclamation of Drastically Disturbed Lands, Vol. 41. Agronomy Monographs, Madison, WI.

Snyder C, Aharrah (1984) The influence of the Typha community on mine drainage. Proc, National Symp on Mining, Sedimentology and Reclamation, Univ of Kentucky, Lexington, pp 149-153

Stark LW, Stevens SE, Webster HJ and Wenerick WR (1990) Iron loading, efficiency and sizing in a construction wetland receiving mine drainage. In: Skousen J, Sencindiver J, Samuel D (Eds.). Proc, Mining and Reclamation Conf and Exhibition. West Virginia Univ. https://wvmdtaskforce.com/past-symposium-papers/1990-symposium-papers/

Thomas RC, Romanek C (2002) Passive treatment of low-pH, ferric iron-dominated acid rock drainage in a vertical flow wetland II: metal removal. JASMR, pp 752-775. DOI:10.21000/JASMR02010752

Turner D, McCoy D (1990) Anoxic alkaline drain treatment system, a low-cost acid mine drainage treatment alternative. Proc, National Symp on Mining, Sedimentology and Reclamation, Univ of Kentucky

Tuttle JH, Dugan PR, Randles CI (1969) Microbial sulfate reduction and its potential utility as an acid mine water pollution abatement procedure. Appl Microbiol 17: 297-302

URS (2003) Passive and semi-active treatment of acid rock drainage from metal mines - state of the practice. Prepared for the U.S. Army Corps of Engineers. https://semspub.epa.gov/work/01/43547.pdf

Watzlaf GR, Hedin RS (1994) A Method for predicting the alkalinity generated by anoxic limestone drains. Proc, West Virginia Acid Mine Drainage Task Force. https://wvmdtaskforce.files.wordpress.com/2015/12/93-watzlaf.pdf

Watzlaf GR, Schroeder KT, Kairies C (2000) Long-term performance of alkalinity-producing passive systems for the treatment of mine drainage. Proc, National Meeting of the American Soc for Surface Mining and Reclamation, pp 262-274. DOI: 10.21000/JASMR00010262

Wieder RK (1992) The Kentucky wetlands project: A field study to evaluate man-made wetlands for acid coal mine drainage treatment. Final Report to the U.S. Office of Surface Mining, Villanova University, Villanova, PA.

Wieder RK, Lang GE (1982) Modification of acid mine drainage in a freshwater wetland. In: McDonald BR (Ed), Proc, Symp on Wetlands of the Unglaciated Appalachian Region, West Virginia Univ, WV

Wieder RK, Lang GE, Whitehouse AE (1985) Metal removal in sphagnum-dominated wetlands: experience with a man-made wetland. In: Brooks RP, Samuel DE, Hill JB (Eds), Wetlands and Water Management on Mined Lands, Pennsylvania State Univ, pp 353-364

Wildeman TR, Machemer SD, Klusman RW, Cohen RRH, Lemke P (1990) Metal removal efficiencies from acid mine drainage in the Big Five constructed wetland. In: Skousen J, Sencindiver J, Samuel D (Eds.). Proc, Mining and Reclamation Conf and Exhibition. West Virginia Univ. https://wvmdtaskforce.com/past-symposium-papers/1990-symposium-papers/

Wildeman TR, Duggan L, Phillips P, Rodriguez-Eaton S, Simms R, Bender J, Taylor N, Britte C, Mehs D, Forse J, Krabacher P, Herron J (1993) Passive treatment methods for manganese: preliminary results from two pilot sites. Proc, National Meeting of the American Soc of Surface Mining and Reclamation, pp 665-677

Wildeman TR, Brodie G, Gusek JJ (1993) Wetland Design for Mining Operations, BiTech Publishers, Richmond, B.C., Canada

Wildeman TR, Filipek LH, Gusek J (1994a). Proof-of-principle studies for passive treatment of acid rock drainage and mill tailing solutions from a gold operation in Nevada. Proc, International Land Reclamation and Mine Drainage Conf, U.S. Bureau of Mines Special Publ 06B-94, Vol. 2, pp 387-394

Wildeman TR, Cevaal J, Whiting K, Gusek JJ, Scheuring J (1994b) Laboratory and pilot-scale studies on the treatment of acid rock drainage at a closed gold-mining operation in California. Proc, International Land Reclamation and Mine Drainage Conf, U.S. Bureau of Mines Special Publ 06B-94, Vol 2, pp 379-386.

Wildeman T, Updegraff D (1998), Passive bioremediation of metals and inorganic contaminants. In: Macalady DL (Ed), Perspectives in Environmental Chemistry, Oxford University Press, New York City, pp 473-495

Wolkersdorfer C (2021) Reinigungsverfahren für Grubenwasser. Springer, Heidelberg

Younger PL (1998) Design, construction and initial operation of full-scale compost-based passive systems for treatment of coal mine drainage and spoil leachate in the UK. Proc, International Mine Water Assoc Symp, Vol 2, pp 413-424

Ziemkiewicz P, Skousen J, Lovett R (1994) Open limestone channels for treating mine drainage: a new look at an old idea. Green Lands 24: 36-41

Ziemkiewicz P, Skousen J, Brant D, Sterner P, Lovett R (1997) Acid mine drainage treatment with armored limestone in open limestone channels. J Environ Qual 26: 560-569

Ziemkiewicz P, Skousen J (1998) The use of steel slag in acid mine drainage treatment and control. Proc, West Virginia Acid Mine Drainage Task Force Symp, pp 651-656. https://wvmdtaskforce.files.wordpress.com/2016/01/98-ziemkiewicz.pdf

Ziemkiewicz P, Skousen J (1999) Steel slag in acid mine drainage treatment and control. Proc, American Soc of Mining and Reclamation. https://www.asrs.us/Portals/0/Documents/Conference-Proceedings/1999/0651-Ziemkiewicz.pdf