Use of constructed wetlands for acid mine drainage abatement and stream restoration

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Abstract
Constructed wetlands have been used for over two decades for the treatment of acid mine drainage (AMD). Through a variety of physical, chemical, biological processes, these wetlands are effective in reducing acidity and removing up to 99% of iron and aluminium from AMD, but they only remove 20–30% of the manganese loading. The Slippery Rock Creek watershed in northwestern Pennsylvania has been adversely impacted by acid mine drainage (AMD) for over 100 years with 74 mine discharges contributing a total of 1,228.8 kg, 282 kg and 69 kg/day of sulfuric acid, iron and aluminium, respectively to receiving streams. In the Slippery Rock Creek Watershed, aerobic and vertical flow wetlands, along with limestone drains and vertical flow limestone beds help to restore acid mine drainage impacted streams. Since 1995, the construction of seven passive treatment systems currently contribute 192.8 kg of alkalinity and remove 39% of the acid loading to a 4.83 km section of Slippery Rock Creek. When the eight passive treatment currently under construction are in operation, it is anticipated that there will be an additional 34.7% reduction in acidic loading to streams within the watershed. The cost of restoring all streams currently impacted by acid mine drainage within the Slippery Rock Creek watershed is currently estimated at $8,929,500.

Keywords Acid mine drainage; limestone drains; watershed restoration; wetlands

Introduction
Discharges from abandoned coal mines are major contributors to the degradation of surface and groundwater systems throughout the mining regions of the world. In Pennsylvania alone, over 4,050 km (2,400 miles) of streams are currently being degraded by acid mine drainage. In the absence of neutralizing compounds, these drainages are acidic, as well as containing high concentrations of iron, manganese, aluminium and sulfate. Over the last 20 years, several different passive treatment technologies, including constructed wetlands, limestone drains and vertical flow wetlands, have been employed to abate the impact of acidic discharges on freshwater streams. The constructed wetland concept originated from observations that natural Sphagnum wetlands receiving AMD often improved in water quality without any visible ecological effects on the wetland system (Huntsman et al., 1978; Wieder and Lang, 1986). Although problems may occur with these wetland systems, current studies indicate that overall they are more cost effective and ecologically beneficial than conventional chemical treatments (Brenner et al., 1993).

For over four decades, the impacts of acidic discharges have been addressed on a site by site basis without consideration of their cumulated impacts on a watershed. Watershed restoration should involve the identification of the major problem areas and then the application of the best management practices to improve water quality and increase biological diversity in the impacted streams. In the current paper, aerobic and vertical flow wetlands will be examined for their effectiveness in the abatement of acidic discharges and their impact on receiving streams as they relate to watershed restoration.

Historical perspective and construction
Aerobic wetlands
Initially, most of the research on constructed wetlands focused on utilizing Sphagnum and
peat as a medium for removing acidity and metals from mine drainages. Although the early laboratory results were promising (Kleinmann et al., 1983; Burris et al., 1984; Gerber et al., 1985), almost all constructed Sphagnum wetlands ceased to be effective in improving water quality after several months. According to Hedin (1989), these wetlands failed for a variety of reasons including the stress related to transplanting Sphagnum, abrupt changes in water chemistry, excessive or insufficient water depth, and iron toxicity. As the result of this early work, almost all acid mine drainage wetlands are planted with cattails (Typha latifolia) since they have been shown to be tolerant of a wide range of water conditions (Sencindiver and Bhumbla, 1988; Samuel et al., 1988; Brenner, et al., 1993, 1995). Although numerous wetlands were constructed during the decade between 1970 and 1980, little if any research was available to enable the designer to determine the size required to remove the acidity and metals. The size of the wetland was thought to be a function of flow volume without regard to acidity and metal loading into these systems. Wetlands were generally constructed based on the concept that between 5 to 15 m² of wetland were required per L/min flow to remove acidity and metals for mine discharges (Kleinmann et al., 1983). These sizes were also based on discharges with pH >4.0 and iron <50 mg/l and the more acidic discharges and/or those with high iron and manganese concentrated were chemically treated. Hedin (1989) indicated that for discharges with a pH <3.0 and iron concentrations exceeding 150 mg/L, the incorporation of metal loading is necessary in the design criteria. These wetlands were generally designed using the criteria of 0.1 to 2.0 m² of wetland per kg/Fe/yr, but most systems had ratios of less than 0.5 m² per kg Fe/yr (Hedin, 1989). In addition to being undersized, many of these wetlands became channelized; reducing the area of the wetland for treatment (Brenner et al., 1993, 1995). In 1991, Hedin proposed the size of the wetland required to treat acid mine drainage be based on the following criteria: Wetland Size = iron load/10 + manganese load/0.5. This formula is based on the assumption that the entire surface area is being used as a treatment system and does not address the problem of channelization. Brenner and Pruent (1999) indicated that a serpentine design reduced the problem of channelization and leaves the entire wetland surface available for treatment.

**Limestone drains and channels**

Within the last decade, anoxic limestone drains (Hedin and Wetzlaf, 1994) and limestone channels (Skousen, 1977; Brenner and Pruent, 1999) have been used in conjunction with aerobic wetlands to treat acidic mine discharges. In these systems, acidity is reduced resulting in increased pH and retention of ferric iron and aluminium, allowing the wetlands to operate more effectively in removing additional metals. The mass of limestone required for treatment may be calculated by the following equation: $M = Q_p b t_d /V_v + Q C T/x$ where $Q$ is the volume of water flow, $p_b$ is the bulk density of the limestone, $t_d$ is the desired retention time (14–23-hrs), $V_v$ is the bulk voided expressed as a decimal, $C$ is the predicted concentration of alkalinity in the effluent, $T$ is the designed life of the system and $x$ is the CaCO₃ of the limestone expressed as a decimal (Hedin and Wetzlaf, 1994).

**Vertical flow wetland systems**

In 1994, Kepler and McCleary proposed a vertical flow wetland, termed Successive Alkalinity Producing System (SAPS) that theoretically was designed to be a continual source of alkalinity to treat acidic mine drainages. However, the design and effectiveness of these systems was based on limited data obtained over a period of one year or less. In the three systems designed by Kepler and McCleary (1994), the total area and volume varied from 150 m² to 1500 m² (10 m × 15 m × 1.5 m) and 225 m³ to 2250 m³ (60 m × 25 m × 1.5 m) and averaged 534 m² and 801 m³ (26.7 m × 20 m × 1.5 m), respectively. The substrate in all three systems consisted of 45 cm of mushroom compost and between 45 and 60 cm of 1.3 to
1.9 cm diameter limestone with an average of 1.8 m (1.9–1.8 m) of free standing water over the substrate. In the first year of operation, all three systems were effective in removing acidity and iron from the discharges, but the authors did not report the effectiveness of these systems in manganese removal (Kepler and McCleary, 1994). A follow up study of these systems by Demchak (1998) indicated that all these systems began to fail after 18–24 months due to limestone depletion and iron accumulation in the compost. Demchak (1998) also reported that these systems do not remove manganese from acidic mine discharges and that their effectiveness in treating AMD varies seasonally, especially as the systems age. Studies using scale models of these systems also indicated that their effectiveness in removing acidity and metals from AMD also declined in the second year of operation due to limestone depletion and plugging of the compost by iron oxides. Several vertical flow systems are being designed with a PVC pipe distribution system that can be back flushed if plugging occurs and based on preliminary studies, these systems have to be flushed approximately at 6 to 8 month intervals (Brenner et al., 2000).

**Wetland processes in acid mine drainage**

**Aerobic wetlands**

Several different physical, chemical and biological processes are involved in the chemical changes in mine waters as they flow through constructed wetlands. Although some dilution occurs through the addition of surface and groundwater in the wetlands, this is probably a minor component in the reduction of acidity and heavy metals. Wieder and Lang (1986) reported that the substrates used in wetland construction may remove metals from mine discharges via a process of absorption, chelation and cation exchange. However, detailed studies on these mechanisms have not been completed. But in most constructed wetlands, the capacity of substrate to remove heavy metals should be exhausted within several months of construction. A considerable amount of the original research on constructed wetlands focused on metal accumulation in plants (Burris et al., 1984; Gerber et al., 1985) and, although *Sphagnum* has been shown to accumulate iron, metal accumulation reaches toxic levels within a single growing season (Spratt and Wieder, 1988). The common cattail (*Typha latiflora*) has been shown to be more tolerant of mine drainage than *Sphagnum*, probably because it does not accumulate metals to toxic concentrations (Sencindiver and Bhumbla, 1988). Because of the lack of metal accumulation, the role of cattails as an iron sink is negligible (Hedin, 1989) usually less than one per cent of the annual iron loading (Sencindiver and Bhumbla, 1988; Brenner et al., 1993, 1995). It has been speculated that blooms of *Oscillatoria* (Kepler, 1986), *Microspora*, *Oedogonium* (Dionis and Stevens, 1985) and *Ulothrix* (Robbins et al., 1999) have been associated with decreased manganese concentrations. Attempts at periodic fertilization of open water wetlands to stimulate algal blooms for enhancing manganese removal are confounded by abiotic metal removal reactions that occur when phosphate is added to AMD (Hedin, 1989). Overall algal removal of manganese is probably a minor component in wetland function, except when manganese occurs in low concentrations. Based on the assumption that algal productivity is 2,500 g/m/yr and if manganese accumulation by algae approaches 50,000 µg/g, then 4.2 m² would be required to remove a kg Mn annually (Hedin, 1989).

The most accepted theory for the removal of metal by wetlands involves oxidation and hydrolysis reactions resulting in the precipitation of metals. Wieder and Lang (1986) reported that 93 per cent and 27 per cent of iron and manganese accumulation, respectively, was in oxidized forms. In aerobic wetlands, abiotic processes and bacterial action oxidize hydrolyzed ferrous iron forming iron oxyhydroxides, as well as the precipitation of aluminium oxides. In wetlands with a pH greater than 6, abiotic precipitation of iron and aluminium compounds occurs rapidly. Therefore, the use of either anoxic limestone drains...
or limestone channels to reduce acidity and increase pH in conjunction with aerobic wetlands will enhance iron and metal removal. In addition, the longer the retention time of the acidic discharge within the wetland, the greater will be the precipitation of iron and aluminium compounds. But in drainages with a pH less than 6, these abiotic reactions are reduced and the iron oxidizing bacteria become an important component of wetland function (Kleinmann and Crerar, 1979; Brenner et al., 1995). These chemoautotrophic and chemoheterotrophic bacteria have been reported to increase the oxidation of ferrous iron, thereby enhancing the formation of iron precipitates. Brenner et al. (1995) reported a greater amount of iron oxidizing bacteria occurred in association with cattail rhizomes than elsewhere in the substrate suggesting increased iron oxidation activity. The increase in oxidation associated with the rhizosphere may be due to a combination of plant induced oxygenation and iron bacteria (Sencindiver and Bhumbla, 1988; Brenner et al., 1995). These authors further stated that higher bacteriological activity occurred at pHs between 5.5 and 6.5 than at pHs <5.0, again indicating the value of limestone drains or channels to increase the pH prior to discharging AMD into aerobic wetlands.

Although numerous studies have demonstrated the effectiveness of aerobic wetlands in removing in excess of 95 per cent of iron and aluminium from mine discharges (Brenner et al., 1993, 1995; Brenner and Pruent, 1999; Brenner et al., 2000), they are only effective in removing between 20–30 per cent of manganese from AMD (Brenner et al., 1993, 1995; Demchak, 1998; Brenner and Pruent, 1999) According to Owens (1963), manganese oxidation is limited in water with a pH of less than 9.5 and in chemical treatment systems, some removal of manganese occurs due to coprecipitation with iron oxyhydroxides (Watzlaf, 1988), but in constructed wetlands, manganese oxidizing bacteria and fungi appear to be the primary source of manganese removal from AMD (Brenner et al., 1995; Robbins et al., 1999). As with iron bacteria, manganese activity was greater in rhizosphere of cattails.

In addition to iron and manganese oxidizing bacteria, Brenner et al. (1995) isolated the anaerobic sulfur reducing bacteria from both water and substrate in constructed wetlands. In anoxic environments, these bacteria use sulfate to oxidize organic matter and release, as a waste product, carbonate resulting in additional alkalinity and hydrogen sulfate which ionizes to bisulfate, which combines with ferrous iron and perhaps manganese, forming insoluble sulfate compounds. Although numerous studies have demonstrated the importance of bacteria in the oxidation and reduction processes occurring in AMD treatment wetlands, little is known about the ecology, physiology and temporal and spatial relationships of these micro-organisms in these systems.

**Vertical flow wetland systems**

The processes occurring in vertical flow wetlands (VFWS) are similar to those described for aerobic systems with alkaline addition occurring by the dissolution of limestone and the sulfate reduction and precipitation of iron and aluminium in the substrate. Although VFWS will remove up to 99+ percent of the iron and aluminium (Brenner et al., 2000), they are not effective in removing manganese (Demchak, 1998). It is interesting to note that in their original one year study, Kepler and McCleary (1994) did not address the removal of manganese by their systems. In theory, these systems function anaerobically, but in a recent study by the author, iron, manganese and sulfate bacteria were isolated under both anaerobic and aerobic conditions suggesting the occurrence of both oxidative and reduction processes in VFWS (Brenner et al., 2000). Despite the promising first year results reported by Kepler and McCleary (1994), systems based on their design begin to fail after 18–24 months of operation (Demchak, 1998) and similar results occurred in scale models of these systems (Brenner et al., 2000). When these scale models were dissected, the upper third of the substrate was plugged with iron precipitates. The efficiency of these systems may be
improved by modifying the design with limestone drains and/or an aerobic wetland to remove the iron and aluminium prior to the VFWS. This would reduce the accumulation of iron and aluminium thereby, allowing the VFWS to provide additional alkalinity to enhance manganese removal. Although VFWS have only been used in the treatment of AMD for a few years in combination with aerobic wetlands and limestone drains with some design modifications, they may be an effective method of treating acid mine drainages.

Watershed restoration

The ultimate goal of the installation of AMD passive treatment systems is restoration of watersheds impacted by acidic mine discharges. In the Slippery Rock watershed in northwestern Pennsylvania, a total of 74 mine drainages have been identified within the watershed and of these, 59 are contributing acid loading to receiving streams with approximately 90% of the acid loading occurring from 35 discharges. The total acid loading in the watershed is 1288.8 kg/day and iron and aluminium loading averages 282 and 69 kg/day, respectively. Since the initiation of the restoration efforts within the Slippery Rock Creek watershed in 1995, seven passive treatment systems have been installed which are currently removing 39% of the acid loading to a 4.83 km section of Slippery Rock Creek. In addition, during peak flows, these systems contribute approximately 192.8 kg/day of alkalinity to the stream systems. The passive treatment systems installed in this portion of the watershed include two anoxic limestone drain/wetland systems, two vertical flow wetlands (VFWs), one retention pond/wetland system, one ALD and one retention pond with a total cost of $272,000. In addition, reclamation efforts in the watershed have restored approximately 32.4 ha of an abandoned coal tipple, refuse piles and open pits through the application of fly ash and landowner reclamation programs.

An additional, eight passive treatment systems, including four anoxic limestone drain/wetland systems, and four VFWs, are proposed for the watershed at a total cost of $712,500. When these projects are completed, there will be an anticipated acidity reduction of 34.7% to Slippery Rock Creek. The severity of the iron and aluminium loading in the watershed reveals that passive treatment alone may not be sufficient for long term metal reduction. It is anticipated that an additional $5,029,500 would be required for continued alkaline addition, along with passive treatments to remediate the 50 point source discharges and improve water quality in the affected 50.6 km of streams in the watershed. In addition, an estimated $2,943,000 and $954,000 would be required for abandoned surface mine and refuse pile reclamation, respectively. Based on these figures, an estimated cost of $8,926,500 would be required to implement the entire reclamation/remediation plan for the Slippery Rock Watershed.

Conclusions and recommendations

Constructed wetlands are an effective means of addressing stream restoration on a watershed basis. But, prior to the installation of any pollution abatement programs, the effect of these measures on water quality and habitat restoration must be considered for the entire watershed and not on a site by site basis. Not only must the construction, installation and effectiveness of these pollution abatements be considered, but the long term maintenance as well.

References


