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Engineered Wetlands as a Tailings Rehabilitation Strategy

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Acid mine drainage from sulfur-bearing waste rock and tailings is one of the most serious environmental challenges facing the mining industry today (Campbell and Marshall 1991). It is caused when metal sulfides in the waste material react with water and oxygen to form sulfuric acid, which in turn dissolves residual metals such as nickel, copper, iron, lead, or zinc. This process is dramatically accelerated by bacteria. The composition of acid mine drainage water is highly variable from site to site. The pH can vary from 3 to 6, and the concentration of metals can vary by several orders of magnitude.

While existing surface run-off is presently being treated, acid mine drainage is a particularly serious long-term problem in the Sudbury area. The approximately 3000 ha of acid-generating tailing ponds in Sudbury contain nearly 0.5 billion tonnes of tailings. This is more material than was excavated in the construction of the Panama Canal. It is roughly estimated to represent 25% of all the sulfide tailings in Canada. Conventional treatment costs and financial assurances to mitigate acid mine drainage in Canada are in the billions of dollars. New treatment technologies are therefore being sought by mining companies to address this problem.

Wetlands

Wetlands are one of the new technologies being explored because of their ability to establish conditions to prevent or treat acid mine drainage. Treatment occurs when wetlands are established downstream of tailing ponds to filter and remove contaminants by biological and chemical processes. Prevention of acid mine drainage may occur when wetlands are created on the surface of tailing ponds. Wetlands form the transition zone between land and water and are often highly productive biological ecosystems.

One of the initial studies on the benefits of natural wetlands for controlling acid mine drainage was conducted at the Tub Run Bog in West Virginia (Wildeman 1991). Researchers observed that the wetland affected acid mine drainage water by increasing pH from 3.5 to 5.0, decreasing sulfate from 250 mg/L to 10 mg/L and decreasing iron from 50 mg/L to less than 2 mg/L. Many other researchers have since shown that various chemical characteristics of acid mine drainage water can be improved by passing it through natural or constructed wetlands (Wheeland 1987; Hammer 1989; Wildeman 1991; Davé 1993; Kalin 1993).

Although considerable research is required before all the chemical processes that lead to these improvements are understood, several processes by which wetlands ameliorate acid mine drainage have been identified. Perhaps the most common method of dissolved metal removal is by an ion exchange mechanism

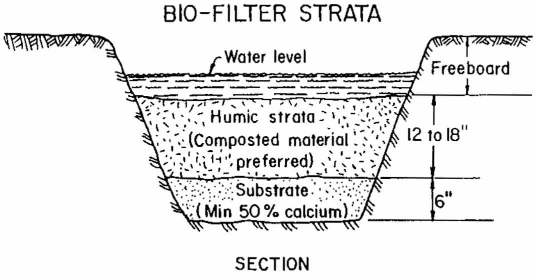


FIGURE 10.1. Cross section of a constructed wetland designed to promote subsurface flows. In this design the effluent is piped into the substrate below the layers of organic matter (Wildeman 1991).

with the organic material. Metals are complexed and bound to organic molecules or particles as the contaminated effluent passes through the wetland. Falconbridge Limited has studied the binding and release of these metals and has found that they remain complexed only if the conditions are anaerobic (Fyfe 1990).

Another predominant removal mechanism is by bacterially catalyzed sulfate reduction, which results in the precipitation of insoluble metal sulfide. Sulfate-reducing bacteria such as *Desulfovibrio* require low pH values and reducing conditions, which is exactly what is found in swamps or wetlands. These bacteria also require carbon as a nutrient, and this is provided in natural wetlands, by the rotting vegetation. Therefore, in an artificially created or engineered wetland, one must establish plants or incorporate organic material substrates such as compost or peat moss as the carbon source for bacteria.

These processes are simplified in the following equation:

$$\underset{\text{(sulfuric acid)}}{2H_2SO_4} + \underset{\text{(dissolved metals)}}{2M} \underset{\text{Aerobic bacteria}}{\overset{\text{sulfate-reducing bacteria}}{\rightleftarrows}} \underset{\text{(metal sulfides)}}{2MS} + \underset{\text{(water)}}{2H_2O} + \underset{\text{(oxygen)}}{3O_2}$$

Other less significant metal removal mechanisms that may operate in the engineered wetland include the following:

1. precipitation of ferric and manganese ions as hydroxides
2. adsorption of metals by ferric hydroxides
3. uptake of sulfur and metals by plants such as cattails or algae
4. neutralization and precipitation through the generation of NH_3 and HCO_3 by bacteria
5. filtration of suspended solids by plants

Natural versus Constructed Wetlands

From an environmental and societal standpoint rather than a scientific perspective, it will become increasingly difficult to use natural wetlands for pollution abatement. Wetlands are becoming an endangered ecosystem, and pressure for their protection is increasing. It has been estimated that 440,000 acres of wetlands in North America were annually altered or lost during the 1950s to the 1970s (Wheeland 1987). The answer is to construct artificial wetlands. To do this, natural systems must therefore be studied so that we can apply and perhaps even improve their acid-neutralizing processes in the constructed wetlands.

Water in a natural wetland flows mainly across the surface due to the low permeability of the organic substrata. To improve the contact time between the contaminated effluent being treated and the organic material in the wetland, water in an engineered wetland can be introduced as subsurface flow so that it flows up through the organic layers. An effective distribution and dispersal design can also be engineered to prevent short circuiting of the flow path of the water (Figs. 10.1 and 10.2).

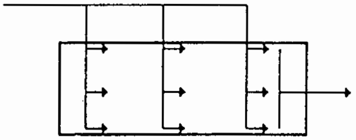
Another limitation to natural wetlands for treatment of acid drainage is that natural wetlands tend to be weakly acidic because they generate large quantities of humic acids. The predominantly surface flow in natural wetlands results in aerobic reactions that tend to produce hydrogen ions or more acidity. Because acidity is one of the concerns that mining companies with sulfide ore bodies are trying to resolve, an improvement in the acid/base conditions of a natural wetland is therefore required. This can be accomplished in some cases by using a bed of limestone in the substratum to neutralize any acid produced (Fig. 10.1). By placing the limestone in the anaerobic substrate and forcing the water to flow up through it, the iron remains in the ferrous form. This prevents the armoring or coating of the limestone by ferric iron precipitates. Successful preliminary field testing of this approach has recently been completed in the United States (Kepler and McCleary 1994).

Constructed wetlands can be designed to operate under anaerobic (reducing) conditions that are required by sulfate-reducing bacteria. These bacteria promote the formation of hydrogen sulfide, which in turn complexes with dissolved metals to form highly insoluble metal sulfides. Some of these microbes release hydrogen gas and lead to the production of hydrogen sulfide gas (Wildeman 1991). These mechanisms increase the pH by complexing and precipitating hydrogen or releasing hydrogen ions into the atmosphere. Bacterially driven denitrification and methanogenesis also lead to hydrogen ion consumption and pH increases (Fig. 10.3).

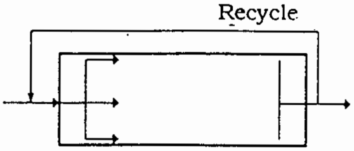
Other reactions that facilitate the removal of iron and manganese require aerobic conditions to produce iron and manganese hydroxides. Certain bacteria, such as *Thiobacillus ferro-oxidans*, which catalyze the oxidation of iron sulfide, also require oxygen. To facilitate these reactions, a two-step process may be needed in the engineered wetland, with an aerobic system established downstream of an anaerobic system.

In conclusion, constructed wetlands can be designed to reduce the contaminants in the acid mine drainage to environmentally acceptable concentrations. In some cases, depending on the specific contaminants present in the acid mine drainage, a multistage wetland may be required that incorporates an anaerobic wetland design, followed by a system providing aerobic conditions to remove different contaminants under different conditions.

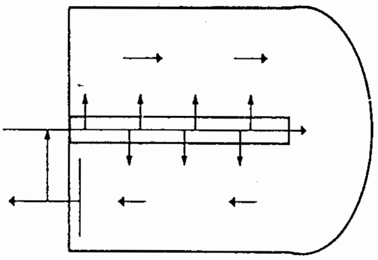
a. Plug flow



b. Step feed



c. Recirculation



d. "Jelly roll" step feed-recirculation cell

FIGURE 10.2. Various flow patterns for constructed wetlands (Wildeman 1991).

Prevention versus Remediation

Most of the work to date has involved the use of constructed wetlands as a downstream remediation system for contaminated effluent. Many examples of this approach can be found in the literature. For example, the Tennessee Valley Authority is currently operating seven

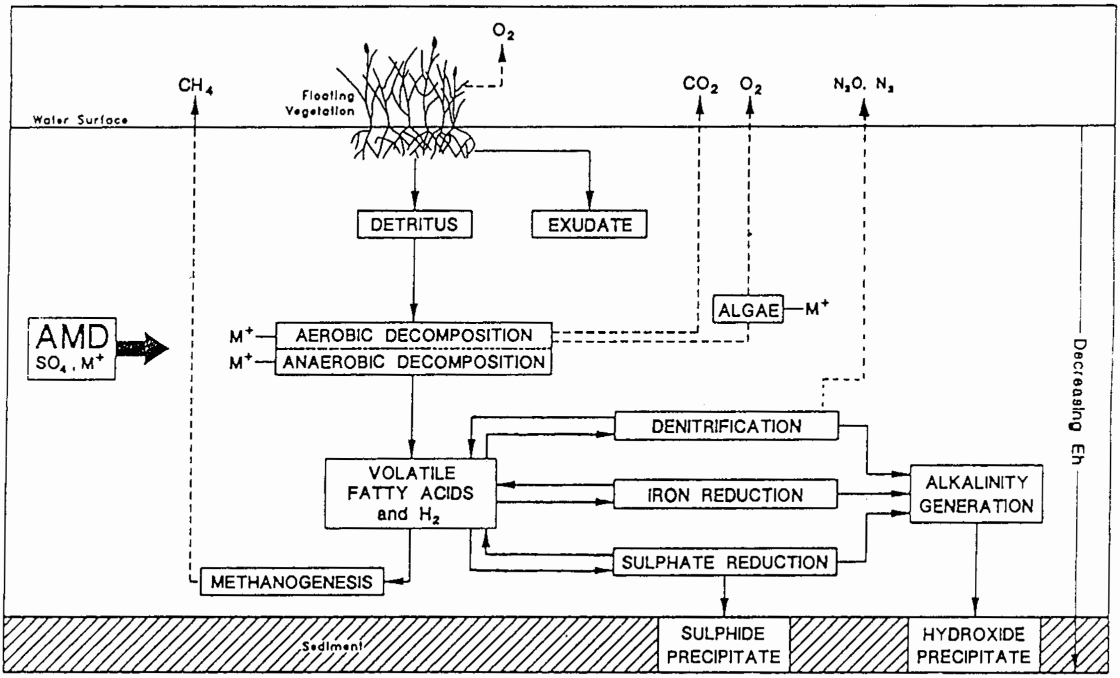


Figure 10.3. Schematic of floating vegetation wetland process (Kalin 1993).

constructed wetlands and has plans for eight more to treat acidic coal mine drainage. Typically, required treatment areas vary from 300–15,000 m^2 of wetland per liter of effluent per second, depending on the degree of contamination. The average constructed wetland has a treatment area of about 1000 m^2/L/s (Hammer 1989).

In Idaho Springs, the Big Five Wetland was constructed in 1987 to treat acid mine drainage from metal mining operations. The wetlands were able to remove almost 100% of the copper and zinc from the contaminated seepage, 63% of the iron but virtually none of the manganese. Interestingly, the pH rose from 3.0 to 6.2, indicating that wetlands can be very effective in reducing acidity (Wildeman 1991).

An extensive field evaluation was conducted using test cells to treat Inco's tailings seepage at Makela, Sudbury. This project, sponsored by the Mine Environment Neutral Drainage (MEND) committee, also demonstrated that metals and pH could be ameliorated by the wetlands. It was discovered that the most active metal removal processes were taking place in the sediments (Kalin 1993). This led to a floating cattail design, so that the cattails suspended from rafts would not deplete the nutrients in the sediments required by the bacteria but would still provide them with a source of carbon. The Makela test cells removed 80–87% of the nickel, 77–98% of the copper, 10–20% of the sulfur, and 47–73% of the acidity from the loading water. A schematic diagram of the process is shown in Figure 10.3.

Falconbridge Limited has developed a 150-ha wetland downstream of their smelter waste water treatment system (Fig. 10.4). Nickel concentrations were observed to decrease 0.5 mg/L to 0.2 mg/L during the summer months. Preliminary investigations by Laurentian University have indicated that some of the metals are being removed by algae. Future studies will investigate the role and relative contributions of bacteria in the removal of heavy metals. The effluent from this system consistently meets the new provincial limits set under the

FIGURE 10.4. Wetland area below the Falconbridge smelter.

Municipal Industrial Strategy for Abatement limits and is non-toxic to fish and zooplankton (*Daphnia magna*). Various fish species such as minnows, white suckers, stickleback, and perch now inhabit the wetland.

During the 1980s, Falconbridge Limited started looking for alternative methods to grassing for tailings as an abandonment strategy. The downstream wetland approach was known, but this was considered a remediation technique, not a permanent solution. It was theorized that a more permanent solution could be achieved by covering the tailing with water. By creating an oxygen barrier by this means, the oxidation of iron sulfide could be reduced, thereby preventing acid mine drainage and metal leaching (literature reviewed by Itzkovich 1993). Falconbridge Limited started testing this approach in 1986 using a shallow water cover and aquatic plants over highly oxidized tailings. Although the results showed some improvement, especially with respect to nickel concentrations, they were not adequate for a "walk-away strategy" (Dave and Michelutti 1991). It was hypothesized by the researchers and supported by the literature that oxidation was continuing without the presence of atmospheric oxygen. Because the test wetlands were established on highly oxidized pyrrhotite, ferric ion was most likely continuing the oxidation reaction (Wheeland 1987; Wildeman 1991).

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightleftarrows 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

Using isotope data, it was found that 35–80% of the dissolved sulfate is produced by a reaction not involving free (dissolved) oxygen (Wheeland 1987). Therefore, these initial experiments by Falconbridge Limited suggested that it was important to prevent the tailings from oxidizing before covering with a wetland. If the tailings are already in an oxidized state, then considerable time may be necessary to flush out the ferric ions and oxidation products before seeing any improvements. Falconbridge Limited and the University of Waterloo, with MEND support, have developed a model (FALCTAIL) to estimate the number of years required to flush latent oxidation products from a tailings area.

Another wetland that has been extensively studied is the Rio Algom Panel site in Elliot Lake. A uranium tailings spill into a small basin was subsequently recolonized naturally by cattails such that a 13-acre wetland resulted. At the west end of this wetland area, partially exposed tailings resulted in dissolved solids concentrations of 600–2000 mg/L, iron from 1 to 80 mg/L, and sulfates from 50 to 100 mg/L (Dave 1993). In the central to eastern section of the wetland, where the tailings were completely submerged, the pH was 6.2–9.8, dissolved solids were 100–300 mg/L, iron was 0.002–0.4 mg/L, and sulfates were 50–100 mg/L. Of particular interest was that there were no strong seasonal differences in water quality in the submerged areas. It was estimated that due to iron complexing and the extremely slow rate of pyrite oxidation and release, it would take 32,000 years for all the pyrite to oxidize and 926,000 years for all the mobilized iron to leave the system. At these slow rates, impacts to downstream ecosystems would be nil.

Perhaps the most ambitious wetland cover field study is that being conducted by Rio Algom at their Quirke mine tailings. In preparation for flooding, half the 64-ha site was leveled and had limestone incorporated into the top 20 cm. The leveling was performed to reduce the requirement for higher dams to flood the area, and the limestone was added to counter any acidity that may occur in the event of severe droughts that would expose the tailings. After some initial start-up problems, the area was flooded in October 1992 (Vivyurka 1993). As the flooding was taking place, lime slurry at the rate of 100 mg/L of $CaCO_3$ was added to the inflow water to counter the existing acidity. Flooding took place by diverting a portion of the discharge from a small upstream lake. By mid-December 1992, the total area was flooded to a minimum depth of 0.3 m. Subsurface water sampling (using a piezometer nest) is ongoing, and although it is too early to draw any conclusions, preliminary data indicate good water quality. To date, pH values have been all above neutral, but that would have been expected with the limestone and lime that had been initially added. This testwork is also unique in that it will determine the impact of water cover on the fate of radionuclides. A similar large-scale flooding scenario is also being evaluated at Stekenjokk, Sweden (Broman and Goransson 1994). Evaluations of historically flooded tailing are ongoing within the MEND program and also indicate the long-term stability of unoxidized tailing deposited underwater (Fraser and Robertson 1994).

Conclusions/Recommendations

Although promising results are being obtained in the wetland research, there are still many unknowns.

1. **Are there seasonal variations in treatment capabilities of the wetland?**
2. **Will a wetland in time become totally saturated with metals and cease to be effective?**
3. **Will the process continue to work as the wetland naturally evolves into a dryland ecosystem?**
4. **What is the potential for re-release of organically bound metals?**
5. **What are the fates of metal ions in this ecosystem (i.e., is there bioaccumulation occurring with long-term impacts)?**
6. **Can a self-sustaining biological community be maintained in the constructed wetland?**

Initial studies and field evaluations indicate that wetlands could become an acceptable walk-away strategy for acid-generating sulfide wastes. Two basic approaches to wetlands are downstream remediation and pollution prevention by a water cover. Both concepts could be incorporated into one abandonment strategy. This is perhaps one of the most promising technologies to emerge as a walk-away abandonment strategy for acid-generating sulfide wastes.

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