The use of constructed wetlands in the treatment of acid mine drainage

Allen Perry and Robert L. P. Kleinmann

US government regulations require that all effluents from industrial operations, including mining, meet certain water quality standards. Constructed wetlands have proven to be useful in helping to attain those standards. Application of this biotechnology to mine water drainage can reduce water treatment costs and improve water quality in streams and rivers adversely affected by acidic mine water drainage from abandoned mines. Over 400 constructed wetland water treatment systems have been built on mined lands largely as a result of research by the US Bureau of Mines. Wetlands are passive biological treatment systems that are relatively inexpensive to construct and require minimal maintenance. Chemical treatment costs are reduced sufficiently to repay the cost of construction in less than a year. The mine waste water is typically treated in a series of excavated ponds that resemble small marsh areas. The ponds are engineered to facilitate bacterial oxidation of iron. Ideally, the water then flows through a composted organic substrate supporting a population of sulphate-reducing bacteria which raises the pH. Constructed wetlands in the USA are described – their history, functions, construction methodologies, applicabilities, limitations and costs.

In the past, mining and mineral processing operations were conducted without adequate concern for human health and the Earth's resources. The adverse environmental impacts of those practices and the concern of society about further detrimental impacts from present and future operations are among the most sensitive issues confronting the mineral industries. Because of this concern, more environmentally compatible mining waste management practices are being introduced. Much remains to be done, however, in both the cleaning up of wastes produced by past mining operations, and in developing techno-logies to ensure that the mistakes of the past are not repeated.

To help mineral industries minimize the environmental impacts of mining and mineral processing operations, the US Bureau of Mines is developing new technologies that address the wastes produced from both past and current operations. This research includes: (i) the development of innovative mining techniques which result in minimal production of waste materials; (ii) the treatment, detoxification and safe disposal of solid wastes; (iii) the control and mitigation of the effects of acid mine drainage from both coal and metal mines; (iv) subsidence abatement and prediction; and (v) controlling abandoned mine fires. This paper will concentrate on one of the methods to control and mitigate the effects of acid mine drainage, the use of constructed wetlands.

The basis of acid mine drainage (AMD) production is fairly well understood [12,17,18]. Pyrite and other sulphide minerals, on exposure to oxygen and water, oxidize to produce dissolved metals, sulphate and acidity. The process is catalysed by iron-oxidizing

Dr Perry is Senior Staff Engineer, US Department of the Interior, Bureau of Mines, 2401 E Street, NW Washington, DC 20241 and Dr Kleinmann is Research Supervisor, US Department of the Interior, Bureau of Mines, Pittsburgh Research Center, PO Box 18070, Pittsburgh, PA 15236, USA.

bacteria, such as *Thiobacillus ferrooxidans*. The resulting solution interacts with other mine waste constituents in secondary reactions such as neutralization, ion-exchange, and acid-induced metal dissolution. Consequently, the discharge water quality can range from the classic AMD formula of high acidity, metals and sulphate concentrations to a neutralized version of low metal and high sulphate content [5].

Acidic drainage is a persistent problem at many active and abandoned mine sites. At thousands of sites that were abandoned prior to the enactment of water pollution laws, or were operated by companies that have gone bankrupt, untreated AMD is polluting receiving streams. According to a recent survey, over 4000 miles of rivers and streams in the USA are adversely affected by acid mine drainage, mostly from mines that have been abandoned for many years [11]. The effect of these discharges on streams and waterways can be very dramatic.

In the worst cases, virtually all aquatic life disappears, river bottoms become coated with a layer of what looks like rust particles, and the pH plummets. By way of comparison, acid rain has a titratable acidity of 10–15 mg/l (a measurement that reflects the amount of alkaline material ($CaCO_3$) required to neuralize it). AMD is typically 20–300 times more acidic. As a result, acid rain is principally a problem where the rocks and soil contain very little alkalinity. AMD, though much more localized in its influence, is more concentrated, and in sufficient volume, can overwhelm the normal buffering capacity of almost any stream. The impact on streams and rivers would be even greater except for the fact that mines that have been operating in the USA since 1978 must chemically treat their effluent water, which is estim-

ated to cost over $1 000 000/day, nationwide. Current water quality standards in the USA require that mine discharges have a pH between 6 and 9, no net acidity, total iron concentration less than 3.0 mg/l, and manganese less than 2.0 mg/l. At thousands of active and inactive mine sites, drainage does not meet these standards and is being treated before discharge by the mining company, usually by chemical treatment.

Mining companies, reclamation groups and various researchers are currently cooperating in a number of studies to evaluate the use of constructed wetlands as low-cost, low-maintenance treatment systems for acid mine drainage. As a result of observations at natural wetlands, pilot-scale tests and full-scale field trials, over 400 wetland water treatment systems have been built on mined lands in the USA.

Most of the constructed wetlands built to date have been designed to treat acidic coal mine drainage, as opposed to the effluent water from metal mines. The principal contaminants of concern have been excessive acidity, iron, manganese and aluminium. The processes that take place within the constructed wetlands include: adsorption and ion exchange, bioaccumulation, bacterial and abiotic oxidation, sedimentation, neutralization, sulphate reduction and dissolution of carbonate minerals (Figure 1). In general, these processes have been quite effective in removing iron, but inconsistent with respect to other water quality parameters. The removal of most of the iron eliminates much of the need for chemical treatment, but does not, by itself, eliminate its necessity. Indeed, only about 20% of the constructed wetland systems discharge water that completely meets the US effluent standards. At most sites, some supple-
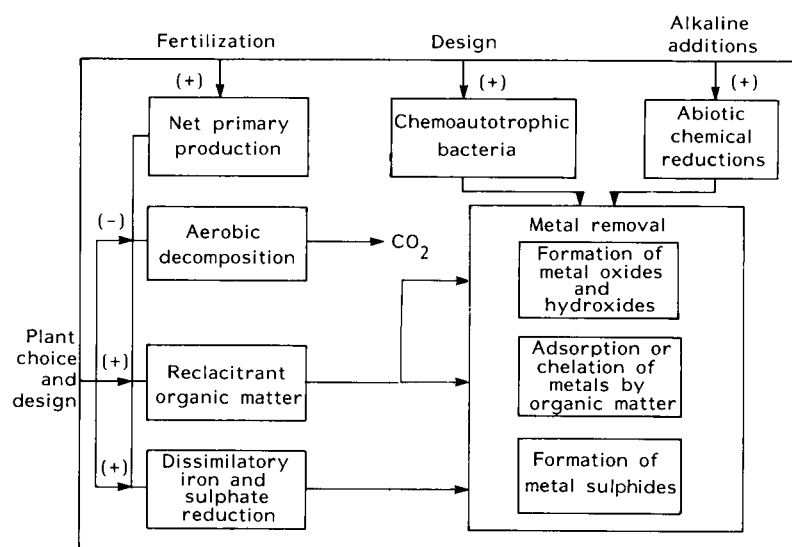

Figure 1.

mental chemical treatment is necessary, but the chemical treatment costs are much lower than they would be if biological treatment had not been utilized. In fact, most operators find that the costs of constructing the wetlands are recovered within one year through savings in chemical usage.

History of the use of constructed wetlands for mine water treatment

The constructed wetlands concept has its roots in observations that natural Sphagnum peat wetlands receiving AMD appeared to clean the polluted water [9,26]. These observations stimulated the idea that wetland systems might be used for the intentional treatment of mine drainage. Because the discharge of AMD into a natural wetland is prohibited, it has been necessary to construct wetlands that act solely as water treatment systems. Initially, most wetland construction efforts mimicked the original Sphagnum peat wetlands [3,13]. Despite promising laboratory results, virtually all field tests of the Sphagnum-dominated constructed wetlands failed to provide sufficient water treatment for more than a few months. Sphagnum proved quite sensitive to the stresses associated with transplanting, abrupt changes in water chemistry, excessive or insufficient water depth, and excessive accumulation of iron. At most sites, the moss died within the first growing season.

The subsequent use of *Typha* (cattails) resulted from observation of volunteer (unplanted) growth of these plants in acidic seeps and ponds. Figure 2 is an artist's rendition of a wetland system planted with *Typha* to treat coal mine drainage. Over 400 such *Typha*-dominated wetlands have now been established in the bituminous coal region of the eastern USA. Most have been produced by mining companies to lower their chemical treatment costs, but approximately 30 have been constructed by reclamation agencies at abandoned mine sites, where previously the water received no treatment at all.

Wetlands functions

Constructed wetlands can be used for the treatment of acid mine drainage over a wide range of water quality conditions and flow rates. Although some wetlands have been built to handle large amounts of water (over 100 gallons per minute, or over 400 litres per minute), the system seems best suited to smaller flows, in the range of 5–20 gallons (20–75 litres) per minute.

In most of the constructed systems, the principal metal-removal mechanism appears to be bacterially catalysed oxidation of iron. Subsequent hydrolysis precipitates the metal as an orange sludge that quickly blankets the substrate surface. Manganese-oxidizing bacteria are also present and active in wetland systems, but generally have negligible effect on manganese concentrations unless the pH is above 6. Aluminium is generally only removed when the pH is raised sufficiently to initiate hydrolysis.

Bacterial sulphate reduction is another naturally occurring reaction. It proceeds in many environments in the absence of oxygen and in the presence of suitable organic substrates and sulphate. This reaction results in the production of hydrogen sulphide and
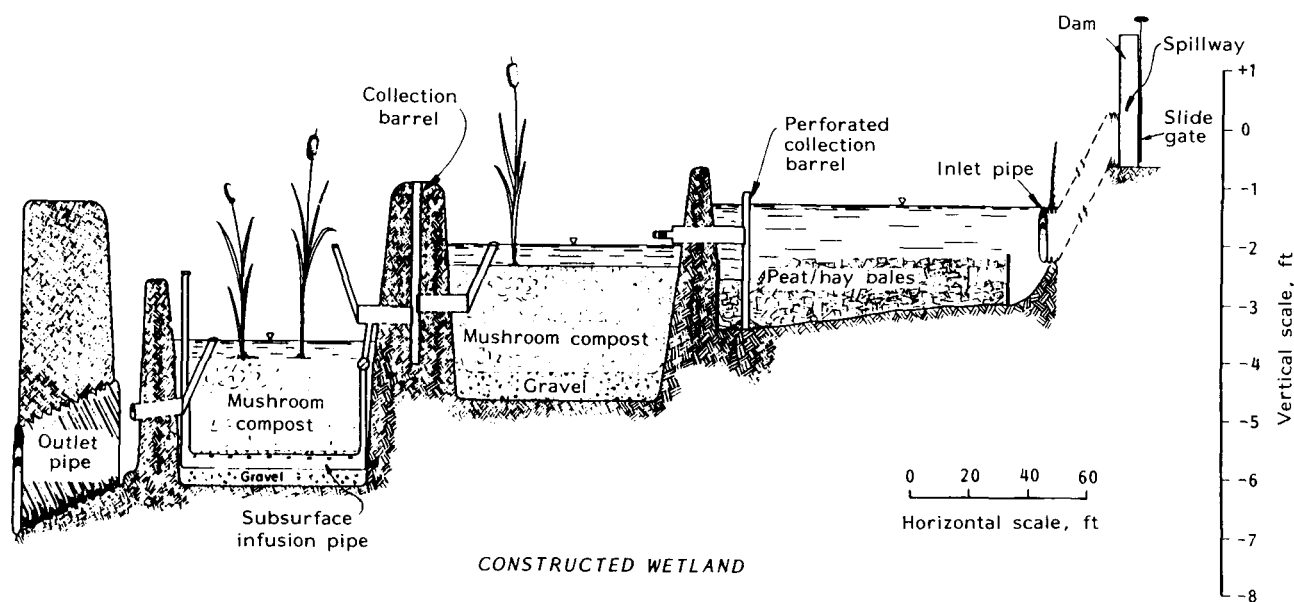

Figure 2.

bicarbonate alkalinity.

The relative importance of sulphate reduction was uncertain for some time due to contradictory observations in Sphagnum wetlands and constructed *Typha* wetlands. The sulphide and elemental sulphur content of Sphagnum peat substrate exposed to AMD for 30 years was determined to be only 0.58 mg/g [26]. In contrast, much higher concentrations have been found in *Typha* wetlands constructed with a composted organic substrate. At one site, after only 18 months of operation, the anaerobic substrate contained 8.5 mg/g reduced sulphur, most of which was in the iron monosulphide form. The iron content of these reduced substrate samples averaged 40 mg/g. Dissolved sulphide concentrations in the pore waters ranged up to 500 mg/l [14].

Bacterial sulphate reduction is potentially very important to the long-term prospects for constructed wetlands. As opposed to the voluminous blanketing sludge that results from the oxidation and hydrolysis of the iron, iron sulphide precipitates are more dense and form within the substrate. The processes involved are the reverse of pyrite oxidation; in fact, acidity is consumed. Finally, unlike bacterial oxidation processes, which are not effective in removing most heavy metals, hydrogen sulphide produced by bacterial sulphate reduction reacts with many metals to form virtually insoluble sulphide compounds. This makes it possible to extend biological treatment to mine water contaminated with various heavy metals.

The processes of adsorption, ion exchange and complexation with organic material can also play a role in metal removal. Wieder and Lang [26] estimated that adsorption and organic complexation processes can remove 33 mg of iron per gram (dry weight) of Sphagnum. During the first few months of operation of a new wetland system, adsorption and complexation by the substrate helps compensate for limited initial biological activity. However, once these capabilities are exhausted by saturation, only the addition of new organic material by plant growth supplements this mechanism of metal removal. This productivity is not sufficient to remove a significant amount of metals in currently sized wetlands.

Accumulation of metals by growing plants varies considerably depending on the metal and the plant in question. Sphagnum has a tremendous ability to accumulate iron, but if exposed to even moderate concentrations of iron, it absorbs so much metal that it petrifies [21]. *Typha* is much more tolerant of mine water precisely because it is not as efficient in accumulating metals. Sencindiver and Bhumbla [20] calculated that the bioaccumulation of 19 506 grams of iron per gram of *Typha* rhizome at a site receiving 10 mg/l iron accounted for only 0.2% of total annual inflow of iron. Bioaccumulation of manganese by *Typha* was even less significant.

Algae also accumulate iron and manganese. When calculated on a dry weight basis, the resultant accumulated concentrations appear to be quite impressive. Kepler [10] measured concentrations as high as 56 000 mg/kg of manganese (dry weight) of algae in samples of *Oscillatoria*. The numerous Microspora samples collected by the Bureau, on a dry weight basis contained 30 000–90 000 mg/kg of manganese. However, algae biomass in a wetland is very limited, so that its contribution to metal removal will rarely reach significant levels. Calculations show that very productive algal systems accumulating manganese at 50 000 mg/kg would still only remove 4 mg/l of manganese from AMD, assuming currently-sized wetland systems [6]. Other processes also contribute to water treatment. For example, plants and organic substrate provide sites for bacterial attachment and colony development. Emergent plants are also capable of aerating the sediments by releasing oxygen from their roots. *Typha* roots are often coated with iron oxyhydroxides, which is probably due to plant-induced oxygenation of the rhizosphere and the activity of iron-oxidizing bacteria [23]. In addition, the large surface area of most wetlands enhances aeration of surface waters, which is often a prerequisite for the bacterial oxidation of metals. Finally, the organic detrital material and the carbon excreted by plants provide food for heterotrophic metal-oxidizing bacteria in the aerobic zone and for sulphate-reducing bacteria in the anaerobic bottom waters. Bacterial sulphate reduction and metal sulphide formation in the organic-rich substrate can contribute significantly to improvements in water quality.

In most of the wetlands constructed to treat coal mine drainage, flow is predominantly above the substrate, so that only a small fraction of the water passes through the anaerobic zone. The water in the substrate is markedly different from the overlying surface water a few centimetres higher. For example, in the pore waters, the pH is 3–5 units higher and dissolved iron concentrations can be 50–99% lower. The US Bureau of Mines is experimenting with wetland designs that utilize subsurface flow to expose a higher proportion of the water to be treated to the anaerobic zone. At a site with water of pH less than 3, acidity values of 1000 mg/l (as $CaCO_3$), and iron concentrations of 150–200 mg/l, promoting flow through the anaerobic zone raised the pH of the water to near-neutral, generated alkalinity (up to 500 mg/l), and decreased iron concentrations to 20 mg/l. This degree of improvement for such an acidic water is quite unusual. Sulphate reduction rates were determined to be approximately 200 $nmol/cm^3/day$, which is

comparable to rates found in coastal marine sediments [14].

Wetland efficiency and suggested construction methodologies

Today, almost all wetlands constructed to treat AMD are planted with *Typha latifolia*. Most constructed wetlands include 15–45 cm of a composted organic substrate in which the emergent plants can root. At sites with very acidic drainage, 8–16 cm of crushed limestone is often spread beneath or incorporated within the organic substrate to provide some neutralization. Constructed wetland systems usually consist of a series of shallow pits or cells. This design makes flow control much easier than with a single, large wetland. The cells are filled with organic substrate, planted with *Typha*, and flooded with mine drainage. In most systems, water depth is 5–15 cm above the substrate and flow is quite slow. Hay bales and logs are sometimes used as barriers to enhance serpentine flow patterns, prevent channelization, and increase the contact of AMD with the wetland substrate and vegetation.

Coal mine water with a net alkalinity can be treated using a simple aerobic system. Many such wetlands have been built that treat this kind of mine water successfully [2,22]. In these cases, the removal of iron and manganese is limited by oxidation and settling rates. Empirical studies have shown that approximately 100 m² of wetland are necessary to remove each kg/day of iron. About 500 m² of wetland are required to remove each kg/day of manganese [7].

When water has a net acidity, treatment with an aerobic design may decrease the iron concentration, but the pH is likely to decrease also, and no removal of manganese will occur. The removal of iron in such a wetland may lower chemical treatment costs, but in order to increase the treatment potential of the wetland, alkalinity must be added to the water. Two methods of passively generating alkalinity currently exist. The first involves the stimulation of bacterial sulphate reduction processes through the construction of a wetland with a rich organic substrate. Presently, the most successful and inexpensive substrate is spent mushroom compost, which can support high rates of sulphate reduction; it also contains limestone, which contributes additional alkalinity. Because sulphate reduction rates are usually slower than iron oxidation rates, compost-based wetlands must be larger. The best estimate currently available is that 200–500 m² of wetland are necessary for each kg/day of net acidity contained in the raw drainage. Net acidity is used as a sizing criterion because it incorporates the acid features of low pH, ferrous iron, ferric iron

and aluminium into a single, easily measured parameter. Removal of manganese from acid water by these systems has not been consistent enough to allow sizing criteria.

Based on field evaluations of functioning wetland systems, it is recommended that aerobic wetland flow should be staged first, to remove as much iron as possible through oxidation. Directing the partially treated flow through cells in which the water level remains within the compost will raise the pH to near neutral. Another aerobic stage can be utilized, if necessary, to remove manganese.

The second method of increasing alkalinity is to pretreat the mine water by flow through limestone gravel before it ever enters the wetland. Mine water intercepted before exposure to the atmosphere is often very low in oxygen and dominated by ferrous rather than ferric iron. Diverting such water through an anoxic drain filled with limestone can add 100–200 mg/l of alkalinity to the mine water. The system must remain anaerobic or else the limestone will be rendered useless by a coating of ferric hydroxide. The water flows from the anoxic drain into a settling basin, from which it flows into the wetland. The net effect of such a pretreatment step is to decrease significantly the size of the wetland required. This concept was first proposed by the Tennessee Department of Health and Environment, and is now being tested at sites throughout Appalachia [1,16,24].

Costs, applicabilities and limitations

Conventional mine drainage treatment involves three unit operations: aeration to oxidize ferrous iron, neutralization of acidity by addition of alkaline chemicals, and sludge settling. The neutralization step allows formation of relatively insoluble metal hydroxides. Capital costs increase as the aeration and neutralization steps become more mechanized, with mechanical aerators and chemical feed and mixing devices. A large fully automated plant can cost over $1 million to construct. For small flows, more typical plant construction costs are of the order of $50 000. Annual operational costs (chemicals, sludge disposal, personnel, maintenance etc) can range from $10 000 to over $1 million, depending on the size of the facility.

The wetlands that have been built to date average about 1–3 acres (0.4–1.3 hectares) in size. A typical system might cost $20 000 to $60 000 to construct, and usually pays for itself within a year in savings over conventional treatment systems. These passive biological treatment systems are particularly effective in removing iron, and thereby helping mining companies meet discharge regulations.

Current research findings and recommendations for future research

Research is being conducted by numerous government agencies, academic institutions and private companies throughout the world. Major areas being addressed include the distribution and fate of contaminants in the biological systems; the mechanisms of contaminant removal; the capacity and longevity of typical designs; and the engineering requirements of various drainage types.

The Bureau expects to continue work on the optimization of the design of constructed wetlands, under varying geologic, hydrologic and climatic conditions. Metal removal by sulphate reduction also appears to be very promising. Although sulphate-reducing bacteria are inhibited at low pH, their activity increases the pH in their immediate environment, allowing their activity in the sediments beneath extremely acidic waters [8,19]. Recent work indicates that metals such as cadmium, copper, lead, mercury, nickel, silver and zinc can be biologically precipitated as insoluble sulphides [15]. Concerns about potential bioaccumulation in plants and animals have led to tests with contained sulphate reduction systems consisting of barrels or tanks with sufficient composted organic matter to maintain anaerobic bacterial activity [4]. Pilot-scale studies are currently underway at several locations, including the US Bureau of Mines research mine in Pittsburgh, Pennsylvania, a zinc smelter Environmental Protection Agency Superfund site near Palmerton, Pennsylvania, and a copper/nickel ore stockpile in northern Minnesota.

It should be recognized that precipitation of sulphide minerals will only continue if there is sufficient organic matter to maintain an anaerobic environment. If seasonal decay of emergent species and the excretion of organic compounds by plants is inadequate, then periodic addition of selected organic materials may be necessary. However, if one can afford periodically to add organics, there are several potential advantages to biological treatment without wetlands, especially for metal mine drainage. First, the areal requirements can be reduced, for instead of a shallow system, one can emphasize depth. For example, an abandoned pit could serve as the primary biological treatment basin. Second, seasonal variations in performance could be minimized. It may be possible to treat mine water in a pipeline-type reaction vessel filled with composted organic waste; presumably, this could even be done inside an active or abandoned section of an underground mine.

Summary and conclusions

At present, there is no general solution to the problem of acid drainage from mined lands. There are many options, each of which may diminish acid discharges, but there are very few cases where acid generation can be completely controlled. National and international research programmes are in place to address the various aspects of the mine drainage problem, including basic hydrogeochemistry of the system, economical control and treatment strategies, and a technological base for regulatory implementation and compliance.

The most common AMD control strategy is treatment of contaminated water at the discharge point. Conventional water treatment is costly in terms of capital and operation and maintenance requirements. In addition, the need for water treatment usually persists for decades after revenues from mineral sales cease.

A better alternative for pollution control at mine sites is inhibition of sulphide oxidation at the outset. At least in the theoretical sense, every system component is susceptible to alteration that would reduce pollutant discharges. Exclude oxygen, as it is limited prior to mining, and oxidation occurs at an insignificant rate. Eliminate iron-oxidizing bacteria, and the rapid catalysed reaction cycle cannot occur. Structure the flow path to bypass sulphidic material, and oxidation products remain in place. Although easy to conceptualize from basic knowledge of the reaction system, it is difficult to find and engineer methods that accomplish reaction control under field conditions.

Passive biological water treatment systems appear to represent the first real alternative to the expense of chemical neutralization and aeration. Although not universally applicable, these systems have the advantage of being simple and requiring little in terms of installation, operation and maintenance. In the future, it is expected that constructed wetlands will be used internationally to treat most low and medium flows of acid mine drainage.

References

1   C. R. Britt, G. A. Brodie, D. Turner and M. N. Taylor, 'Use of passive anoxic limestone drains to increase effectiveness of wetlands and drainage treatment systems', *Proceedings of the 12th Annual Meeting of the National Association of Abandoned Mine Land Programs*, Breckenridge, CO, 1990.

2   G. A. Brodie, 'Treatment of acid drainage using constructed wetlands-experiences of the TVA', in D. H. Graves, ed, *Proceedings, 1990, Symposium on Mining*, University of Kentucky, Lexington, KY, 1990, pp 77–83.

3   J. E. Burris, D. W. Gerber and L. E. McHerron, 'Removal of iron and manganese from water by Sphagnum moss', in J. E. Burris, ed, *Treatment of Mine Drainage by Wetlands*, Pennsylvania State University, University Park, PA, 1984, pp 1–13.

4   D. H. Dvorak, H. M. Edenborn, R. S. Hedin and P. E. McIntire, 'Treatment of metal-contaminated

water using bacterial sulfate reduction: results from pilot-scale reactors', preprint, SME Annual Meeting, 1991.

5 G. Geidel and F. T. Caruccio, 'Time as a factor in acid mine drainage pollution', in *Proceedings, 7th Symposium on Coal Mine Drainage Research*, 1977, pp 41–50.

6 R. S. Hedin, 'Treatment of acid coal mine drainage with constructed wetlands', in S. K. Majumdar, R. P. Brooks, F. J. Brenner and R. W. Tiner, eds, *Wetlands Ecology, Productivity and Values: Emphasis on Pennsylvania*, Pennsylvania Academy of Science, Easton, PA, 1989, pp 349–362.

7 R. Hedin and R. Nairn, 'Sizing and performance of constructed wetlands: case studies', *Proceedings, 1990 Mining and Reclamation Conference and Exhibition*, Vol 2, West Virginia University, Morgantown, WV, 1990, pp 385–392.

8 A. T. Herlihy, A. L. Mills, G. M. Hornberger and A. E. Bruckner, 'The importance of sediment sulfate reduction to the sulfate budget of an impoundment receiving acid mine drainage', *Water Resources Research*, Vol 23, 1987, pp 287–292.

9 B. E. Huntsman, J. G. Solch and M. D. Porter, 'Utilization of Sphagnum species dominated bog for coal acid mine drainage abatement', *Geological Society of America, (91st Annual Meeting) Abstracts*, Toronto, Ontario, Canada, 1978, 322 pp.

10 D. A. Kepler, 'Manganese removal from mine drainage by artificial wetland construction', *Proceedings, 8th Annual National Abandoned Mined Lands Conference*, Billings, MT, 1986, pp 74–80.

11 R. L. P. Kleinmann, 'Acid mine drainage in the United States', *Proceedings, First Midwestern Region Reclamation Conference*, Carbondale, IL, Southern Illinois University, 1990, pp 1–8.

12 R. L. P. Kleinmann, D. A. Crerar and R. R. Pacelli, 'Biogeochemistry of acid mine drainage and a method to control acid formation', *Mining Engineering*, Vol 33, 1981, pp 300–305.

13 R. L. P. Kleinmann, T. O. Tiernan, J. G. Solch and R. L. Harris, 'A low-cost, low-maintenance treatment system for acid mine drainage using Sphagnum moss and limestone', in S. B. Carpenter and R. W. Devore, eds, *Proceedings of the 1983 Symposium on Surface Mining, Hydrology, Sedimentology and Reclamation*, University of Kentucky, Lexington, KY, 1983, pp 241–245.

14 P. E. McIntire and H. M. Edenborn, 'The use of bacterial sulfate reduction in the treatment of drainage from coal mines', *Proceedings, 1990 Mining and Reclamation Conference and Exhibition*, Vol 2, West Virginia University, Morgantown, WV, 1990, pp 409–416.

15 P. E. McIntire, H. M. Edenborn and R. W. Ham-

mack, 'Incorporation of bacterial sulfate reduction into constructed wetlands for the treatment of acid and metal mine drainage', in D. H. Graves, ed, *Proceedings, 1990 Symposium on Mining*, University of Kentucky, Lexington, KY, 1990, pp 207–214.

16 R. W. Nairn, R. S. Hedin and G. R. Watzlaf, 'A preliminary review of the use of anoxic limestone drains in the passive treatment of AMD', *Proceedings, West Virginia Surface Mine Drainage Task Force Symposium*, Morgantown, WV, 1991.

17 D. K. Nordstrom, 'Aqueous pyrite oxidation and the consequent formation of secondary iron minerals', *Acid Sulfate Weathering*, Soil Science Society of America, 1982, pp 37–56.

18 S. J. Onysko, *Chemical Abatement of Acid Mine Drainage Formation*, PhD dissertation, University of California, Berkeley, 1986, 315 pp.

19 K. Satake, 'Microbial sulphate reduction in a volcanic acid lake having a pH 1.8 to 2.0', *Japanese Journal of Limnology*, Vol 38, 1977, pp 33–35.

20 J. C. Sencindiver and D. K. Bhumbla, 'Effects of cattails (Typha) on metal removal from mine drainage', *Mine Drainage and Surface Mine Reclamation*, Vol I, *Mine Water and Mine Waste*, Bureau of Mines IC 9183, Pittsburgh, PA, 1988, pp 359–369.

21 A. K. Spratt and R. K. Weider, 'Growth responses and iron uptake in Sphagnum plants and their relations to acid mine drainage (AMD) treatment', *Mine Drainage and Surface Mine Reclamation*, Vol I, *Mine Water and Mine Waste*, Bureau of Mines IC 9183, Pittsburgh, PA, 1988, pp 279–286.

22 L. Stark, E. Stevens, H. Webster and W. Wenerick, 'Iron loading, efficiency, and sizing in a constructed wetland receiving mine drainage', *Proceedings, 1990 Mining and Reclamation Conference and Exhibition*, Vol 2, West Virginia University, Morgantown, WV, 1990, pp 393–403.

23 G. J. Taylor, A. A. Crowder and R. Rodden, 'Formation and morphology of an iron plaque on the roots of Typha latifolia grown in a solution culture', *American Journal of Botany*, Vol 71, 1984, pp 666–675.

24 D. Turner and D. McCoy, 'Anoxic alkaline drain treatment system, a low cost acid mine drainage treatment alternative', in D. H. Graves, ed, *Proceedings, 1990 Symposium on Mining*, University of Kentucky, Lexington, KY, 1990, pp 73–76.

25 R. K. Wieder and G. E. Lang, 'Modification of acid mine drainage in a freshwater wetland', in B. R. McDonald, ed, *Proceedings of the Symposium on Wetlands of the Unglaciated Appalachian Region*, West Virginia University, Morgantown, WV, 1982.

26 R. K. Wieder and G. E. Lang, 'Fe, Al, Mn and S chemistry of Sphagnum peat in four peatlands with different metal and sulfur input', *Water, Air, and Soil Pollution*, Vol 29, 1986, pp 309–320.