DESIGN CONSIDERATIONS FOR THE PASSIVE TREATMENT OF ACID MINE DRAINAGE[1]

by

Edward A. Howard[2], Thomas R. Wildeman[3]
Leslie S. Laudon[4] and Steven D. Machemer[4]

Abstract. An experimental constructed wetland in the Idaho Springs-Central City mining district provides considerations and recommendations for the design of wetland systems in harsh mountain environments. The application of such systems to metal mine drainages in harsh climates is not well known. The wetland at the Big Five Tunnel is designed to passively treat the metal mine drainage found there. Research objectives include: 1) determining if the wetland system will survive in a mountain climate and in high concentrations of heavy metals, 2) determining the best treatment cell layout for the system, 3) determining the best water distribution system, and 4) identifying the best substrate materials and plant species for such systems. The 55.7 m^2 (600 sq ft) structure is divided into three lined cells which are filled with different mixtures of organic substrates and limestone. An influent and effluent distribution system controls the mine drainage flow into and out of the system. Access wells are used to sample interstitial water in each cell. The species of vegetation growing in the wetland include cattails, sedges, and rushes transplanted from locations of similar elevation. Components of a wetland system must be chosen to optimize efficiency of metal removal. Plants, for example, must be able to resist high concentrations of metals and substrates must provide the best conditions for the appropriate bacteria.

Additional Key Words: constructed wetland, low pH, heavy metals pollution.

Introduction

Acid mine drainage is one of the most persistent industrial pollution problems in the United States. Streams and rivers are adversely affected primarily by underground mines that have been abandoned for decades. Methods used for improving the quality of mine drainage include chemical treatments, where toxic constituents are neutralized and made insoluble, and physical storage treatments where anoxic environments are created that inhibit the growth of iron-oxidizing bacteria. These methods are expensive and have many limitations, especially in remote mountain environments where harsh winters and difficult access make conventional methods too costly. Constructed wetlands have been extensively used in the eastern states as a less expensive alternative to treat mine drainage from coal mines. However, the number of wetlands sites that are actually being used in industrial minerals and metals mining situations are very few. Natural wetlands in Colorado have been shown to raise pH and reduce metals concentrations of acid mine drainages (Emerick 1988, Holm pers. comm.), but only a few artificially created wetlands have been constructed to treat drainage

[1]Paper presented at the joint 1989 Meeting, Canadian Land Reclamation Association/American Society for Surface Mining and Reclamation, "Reclamation - A Global Perspective, Calgary, Alberta, Canada, August 27-31.

[2]Professor, Department of Environmental Sciences, Colorado School of Mines, Golden, Colorado 80401.

[3]Professor, Department of Chemistry and Geochemistry, Colorado School of Mines, Golden, Colorado 80401.

[4]Graduate Student, Department of Chemistry and Geochemistry, Colorado School of Mines, Golden, Colorado 80401.

Proceedings America Society of Mining and Reclamation, 1989 pp 651-660
DOI: 10.21000/JASMR89020651
https://doi.org/10.21000/JASMR89010651

from non-coal mines at higher elevations in Colorado (Holm 1983). The objective here is to consider the design parameters necessary for such systems and to provide results from the experimental system at the Big Five Tunnel in Idaho Springs, Colorado.

The Idaho Springs-Central City mining district is located in the foothills of the Colorado Front Range. Around the turn of the century, the region produced a significant amount of precious metal ores. The region is now characterized by massive waste rock dumps, mill tailings piles, and abandoned mine shafts and tunnels. Mine drainage from tunnels typically has low pH and high metal concentrations that create adverse impacts on the aquatic resources of the region. As a result, several sites in the district are included on the National Priorities List under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA or Superfund). The physical characteristics of the Big Five Tunnel make this site a good candidate for investigating the feasibility of using a constructed wetland system to treat the mine drainage (Howard et al. 1988, Guertin et al. 1985). The pilot system is built in a closed configuration to determine the fate of metals in the system, to determine if vegetation exposed to elevated metal concentrations in a mountain climate will survive, to study the occurrence and spatial distribution of various species of bacteria in the system, to identify the organic substrates and plant species that are appropriate for such systems, and to determine the effectiveness of the system in reducing metal concentrations. The design of the system is based on discussions with and findings of experienced investigators (Holm pers. comm., Kleinmann 1983 and pers. comm., Hiel and Kerins 1988). Their suggestions were modified to satisfy the objectives mentioned above and to ensure that the wetland would perform in a harsh mountain climate.

Design and Construction of the Big Five Demonstration System

Methods and procedures used in building and operating the Big Five pilot treatment system include the design and construction of the foundation structure and individual treatment cells, as well as the design of the sampling and preparation of substrate materials for chemical and bacterial tests. Also included are the sampling and analysis procedures for waters from the output drains and wells in each of the treatment cells and from the mine drainage itself.

The completed design of the pilot treatment system is a reinforced concrete structure with dimensions of 0.61 m (2 ft) in depth, 3.05 m (10 ft) in width, and 18.3 m (60 ft) in length. For these initial investigations, the structure is divided into three 6.1 m (20 ft) sections, with provisions to divide the box into six 3.05 m (10 ft) sections at some later time if this were to be desired (Figure 1). The concrete sections, or cells, are separated by walls constructed from 5 x 15 cm (2 x 6 in.) treated wood. Aluminum channels are grouted into void tubes in the concrete walls to allow the addition of lumber to form sidewalls and endwalls of adjustable height. For this initial study, the walls are built up to a height sufficient to allow the total depth of the cells to be 1.22 m (4 ft).

Each cell is fitted with two drains, one active and one reserve. The reserve drains are installed so that the number of cells could be changed from three to six if desired. The drains are made of 15 cm (6 in.) i.d. polyvinyl chloride (PVC) pipe, and the active drains consist of standpipes initially set at a depth of about 1 m (3 ft). The drains deliver the overflow water to the preexisting drainage pond.

A 0.76 mm (30 mil) Hypalon^R liner is used to line the cells so that they are separated from one another and to prevent chemical reactions between the treated wood, concrete or aluminum channels and the organic substrates and mine drainage.

Rock baskets were constructed at the upstream end of each of the cells to allow the mine drainage to contact as much of the upstream cross-section of the organic substrate as possible. These baskets, approximately 30-45 cm (12-18 in.) thick, were built using expanded plastic fence and extended to the full depth and width of each of the cells. The baskets were filled with washed 10-15 cm (4-6 in.) river rock. Plastic curtains were suspended from supports just above the substrates on the downstream side of the rock baskets. These curtains extend down to 1/2 to 2/3 of the total depth to force the flow downward into the cells.

Six access wells were installed in each cell to allow sampling of interstitial water. These sample wells were made from 15 cm (6 in.) i.d. PVC and completed to allow water to enter from the lowest, middle, and the upper 30 cm (1 ft) of the organic substrates. Holes in the sample tubes were covered with nylon screen to prevent clogging with the substrate material. Two wells of each completed

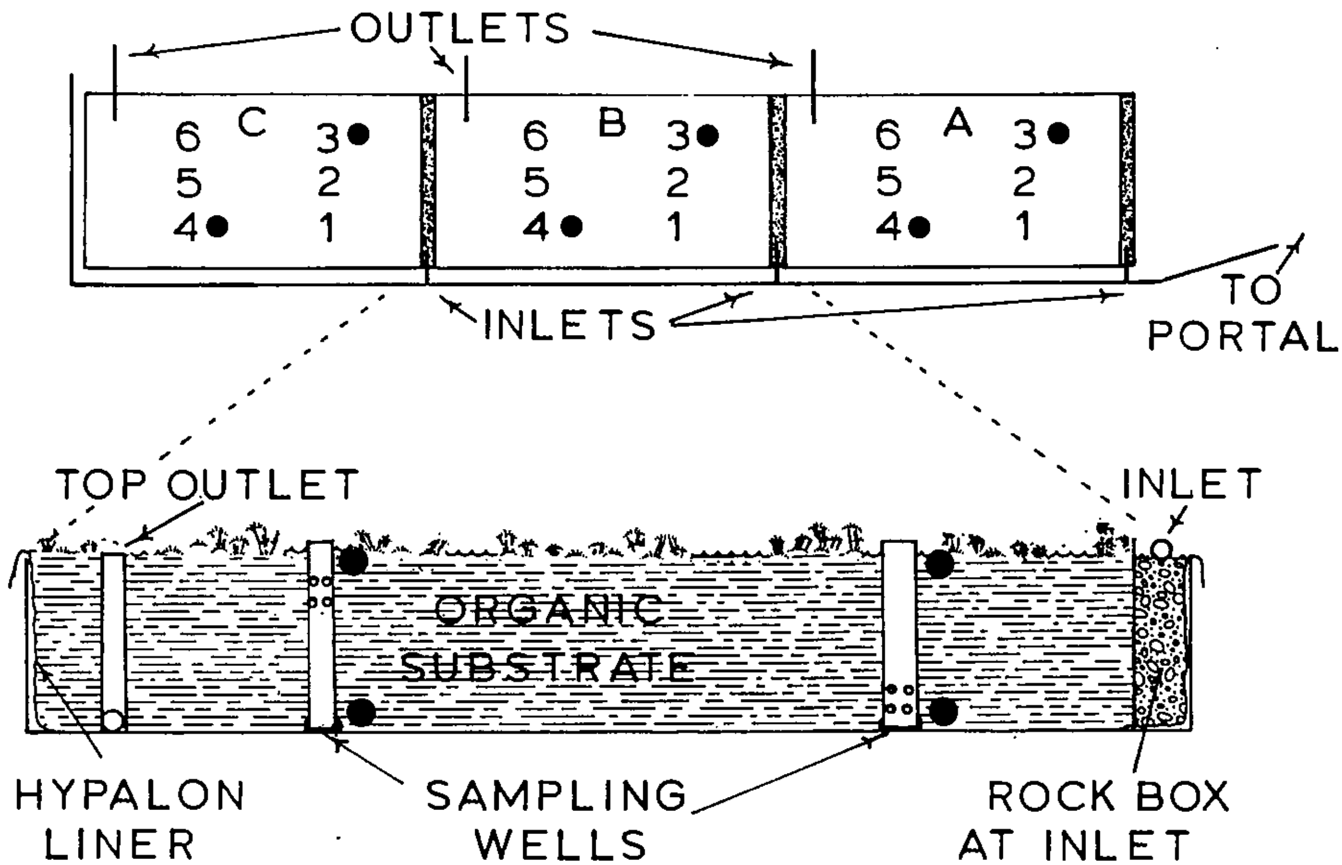

Figure 1. Big Five Wetland Plan View and Cross Section.

depth were placed in each of the 3 cells, for a total of 18 sample wells.

A small concrete dam was constructed just inside the tunnel portal to provide enough head to distribute water to the system. Water is piped from the portal to each of the cells through PVC lines, reduced in size through the system, and fitted with valves to control the total flow and the flow to each individual cell. Due to the harsh winter climate of the location, all plumbing must be insulated by being buried or by using a fiberglass wrap. Water is distributed across the entire width of each cell by allowing it to flow into the rock baskets. Excess water is allowed to drain into the preexisting drainage pond.

After the sample wells were placed and the rock baskets completed, the cells were filled with organic substrates to a depth of about 1 m (3 ft). The first cell was filled with fresh, unused mushroom compost, which consists of approximately 50 percent animal manure and 50 percent barley mash wastes from a local brewery. The second cell received a mixture of equal parts of peat, aged steer manure, and decomposed wood shavings and sawdust. The third cell was filled to a depth of 10-15 cm (4-6 in.) with 5-8 cm (2-3 in.) limestone rock before the cell was filled the rest of the way with the same organic mixture as the second cell. Cattail, sedge, and rush species were transplanted from similar locations to each of the cells. Initially, the organic substrates were saturated with municipal water to reduce stress on the transplanted vegetation. The mine drainage was diverted into the Big Five system on October 25, 1987.

Recommendations for Wetland Treatment Systems Based on the Results of the Big Five System

Research efforts during the past few years have contributed a great deal of knowledge to the design of constructed wetlands for treatment of acid mine drainage. The following suggestions incorporate recent research results with the initial results from the Big Five treatment system. The diversity in individual sites precludes the development of design guidelines that could be applied to all possible situations. Therefore, these recommendations are intentionally restricted to the treatment of discharge from abandoned mines and tunnels in the severe and diverse climates of the Rocky Mountain region.

Preliminary Design Considerations

Preliminary design considerations are based on federal, state and local regulatory requirements. The chemistry of the mine drainage and the hydrology of the site are the two most important factors determining the objectives and decisions to treat wastewater effluent streams (Brodie et al. 1988a and b). Knowledge of the water chemistry and site hydrology are necessary for comparing contaminant concentrations to regulatory standards, and thereby determining the level of treatment required. The availability and costs of plants and substrates, as well as the treatment efficiency of available substrates, must also be determined. These factors, combined with the comparison of long-term economic costs for both constructed wetlands and conventional treatment systems, generally influence the decision on whether or not constructed wetland treatment systems are appropriate in treating acid mine drainage.

Recommendations. (1) A review of all regulations that may apply to the construction of wetland treatment systems and the discharge of effluent from these systems must be done to establish the objectives for the discharge treatment. (2) A good knowledge of the surface and groundwater hydrology is the key to success. Preliminary hydrologic investigations should consist of a complete water budget to include all inflows and outflows of surface water, the precipitation regime, losses from evaporation and transpiration, and subsurface gains or losses. If possible, the first examples should be built to treat point sources, such as the Big Five drainage adit, to ensure a simple hydrologic regime. (3) In the West, there are no examples of wetlands to control non-point sources such as seepages from tailings piles or tailings ponds. Also, there are no examples of wetlands used for regional cleanup. Treat either of these situations as highly experimental.

Basic Structure of System

The basic structural components of the Big Five system appear to be functioning as designed. The concrete structure and the separating walls held by the aluminum channels are performing well. The 30 mil Hypalon^{R} liner used to line the cells remains intact and no leakage from the system has been observed. Recently, the liner withstood a severe hailstorm that shredded 10 mil polyethylene.

Recommendations. (1) All components of the system must be sealed or lined to prevent metals from reaching the underlying groundwater. Plastic liners (e.g. Hypalon^{R}) and bentonite seals have been used (Howard et al. 1988, Hiel and Kerins 1988).

Mine Drainage Distribution System

The dam and plumbing constructed inside the Big Five adit continues to function adequately in diverting the desired portion of flow to the cells, although the area behind the dam is slowly filling with metal hydroxide sediment. The PVC lines that distribute the mine drainage to the individual cells are insulated adequately, since no freezing of the inflow water has been observed through two winter seasons. The standpipe drains continue to work well in all three cells and clogging has not been observed.

Metal hydroxide precipitates, however, occasionally clog the mine drainage inflow lines. Even though taken from the surface of the impoundment inside the portal, the incoming flow still retains enough metal hydroxide sediments to clog the lines. The lines have to be periodically flushed to remove the sediments in order to maintain the desired flow rates to each of the cells. The reason for the clogging is a trap created by the requirement for installing a vertical section of pipeline to lift the flow to the top of the cells. The problem could be alleviated by avoiding sharp turns and vertical sections in the incoming lines. The clogging of the lines turned out to be serendipitous, however, in that much larger increases in pH values are found when the flow is reduced. This observation led to further studies to quantify the metal removal efficiencies and increases in pH values under different flow rates and retention times.

The rock baskets fill with metal hydroxides after a few months of operation and possibly reduce the opportunity for the mine drainage to contact the entire cross-section of the substrate. The layer of limestone rock in Cell C appears to be somewhat more effective in distributing the flow through the lower part of the substrate. This may not continue, however, as the interstices in the limestone layer become clogged with sediment.

Some of the nylon screens covering the openings in the sample wells become clogged with organic matter, resulting in very slow recharge once the wells are pumped down. These wells are pumped first during sampling to allow time for recharge.

The method of delivering wastewater to the treatment cells depends on the overall system configuration, objectives, and costs. In general, a simple and inexpensive system is preferred over complex plumbing and pumping arrangements.

Recommendations. (1) Where plumbing is necessary, installation of sharp bends or traps in the mine drainage distribution system should be avoided to prevent the accumulation of hydroxide sediments that may clog the lines. It is also advisable to include the capability for cleaning out the lines periodically, should they become clogged. (2) In harsh climates, all lines must be insulated to prevent freezing. (3) The distribution system should be designed so that the flow can be easily adjusted to optimize the treatment efficiency. (4) The water distribution system should be constructed in a versatile manner to allow a module to be bypassed if a problem should develop. (5) If the system is one meter in depth, it becomes important to consider how the water is to penetrate, flow through, and be collected from the complete cross-sectional area of the substrate. (6) Soil conductivity is important if water is to flow at depth. The substrate should be tested before using it to ensure that it will conduct water sufficiently. (7) A rock box at the inlet works well, although the accumulation of hydroxide sediments appears to clog the boxes and they may eventually have to be cleaned. A collection and outlet system that will allow water to uniformly flow through the entire cross section still needs to be designed. Initial tracer tests should be performed to determine the flow patterns through the system. (8) One or more sample wells should be included in each cell if removal mechanisms are to be studied.

Water Quality of the Big Five Mine Drainage and Wetland Outputs

The analytical results of metal concentrations in the cell output waters and mine drainage show promising results for the Big Five treatment system (Table 1). The most abundant metals of concern in the Big Five Tunnel mine drainage are Fe, Mn, Zn, and Cu. These concentrations for the mine drainage remain relatively consistent throughout the year and are the basis for the initial wetland design objectives. Metal concentration reductions range from basically none for Mn to essentially complete removal for Cu. Reductions in concentrations for Fe of up to 60 percent and for zinc of up to 100 percent have been found. Cell A with the mushroom compost has the highest metal removal efficiency and effluent pH.

Recommendations. (1) The chemistry of the mine drainage should be one of the most important factors in determining the objectives and decisions of treating such wastewater effluent streams. Thus, the first step is to build up a data base concerning the mine drainage chemistry.

Substrates

After about 20 months of operation, the mushroom compost in Cell A shows a much better capability to remove metals and raise the pH than the substrates in the other two cells given similar flow rates. The substrate in Cells B and C consists of peat, aged manure, and a wood waste mixture. The bottom of Cell C is also lined with limestone gravel. This difference in the effectiveness of the two types of substrates has been tentatively attributed to the presence of more microbiological activity (Wildeman and Laudon 1988). The substrate in Cells B and C may have experienced a greater degree of decomposition and/or contains fewer nutrients, suppressing the necessary biological activity.

Some investigations have shown that once the microbial-substrate-plant system becomes established, the type of substrate is relatively unimportant (Stillings et al. 1988). This may not be the case for treatment of discharge from metal mines in harsh environments.

Recommendations. (1) Analysis of the substrate prior to its use is imperative. Substrate hydraulic conductivity, pH, buffering capacity, plant nutrient levels, and microbiological activity are tests that should be made. Although some controversy exists, a substrate with near-neutral pH values should be considered so that the activity of sulfate-reducing bacteria will not be suppressed by acidic conditions. (2) Incorporation of gravel beneath the organic substrate material may be advisable to improve permeability and enhance the contact area of the substrate. If substrates have low hydraulic conductivity, some material should be incorporated to increase the permeability. (3) Limestone placed in the treatment system before the metal hydroxides are removed may be quickly coated and therefore

Table 1. Concentrations (mg/L) of metals and sulfate, percent reduction of metals, and pH in the Big Five mine drainage and cell output waters. Cell output flow rates are given in gallons/minute. The area of each cell is 18.6 m^2 (200 ft^2).

	Mn	% red.	Fe	% red.	Zn	% red.	Cu	% red.	SO_4^{2-}	pH	flow rate
December 11, 1987											
Mine Drainage	34		32		10.6		1.02		1750	2.8	
Output A	27	21	18	45	7.8	27	0.44	57	1560	4.6	1.0
Output B	33	1	24	26	9.8	8	0.89	12	1430	3.1	1.0
Output C	34	0	22	32	9.6	9	0.91	10	1520	3.3	1.0
February 13, 1988											
Mine Drainage	28		28		8.2		0.89		1750	3.3	
Output A	27	4	18	36	5.9	28	0.14	84	1690	4.7	1.0
Output B	31	0	28	0	7.6	7	0.92	0	1780	3.4	1.0
Output C	29	0	28	0	7.9	4	0.92	0	1700	3.4	1.0
May 31, 1988											
Mine Drainage	25		44		8.1		0.75		1500	3.0	
Output A	25	0	27	39	5.4	33	0.03	96	1330	4.3	1.0
Output B	25	0	17	61	7.4	9	0.64	15	1570	3.0	1.0
Output C	25	0	21	52	7.7	5	0.68	9	1220	3.0	1.0
August 19, 1988											
Mine Drainage	26		37		8.1		0.91		1460	2.9	
Output A	25	4	20	46	<0.1	100	0.17	81	650	5.5	0.51
Output B	26	0	15	59	6.1	24	0.55	40	<980	3.2	0.24
Output C	25	4	11	70	5.8	28	0.38	58	1920	3.5	0.34
December 18, 1988											
Mine Drainage	29		38		9.2		0.80		1710	3.0	
Output A	28	3	31	18	8.6	7	0.62	23	1710	3.4	1.21
Output B	28	3	30	21	7.8	15	0.74	8	1700	3.2	1.15
Output C	28	3	29	24	7.7	16	0.69	14	1710	3.3	1.25
February 21, 1989											
Mine Drainage	27		32		9.3		0.56		1860	3.0	
Output A	22	19	12	63	4.5	52	<0.01	100	1690	5.1	0.28
Output B	27	0	28	13	6.1	34	0.82	0	1880	3.4	0.31
Output C	25	7	31	3	7.2	23	0.26	53	2060	3.5	0.32

ineffective in neutralizing the acidity. If limestone channels are necessary to increase the pH to desired values, they should be placed downstream from the treatment system to be effective or in the anaerobic zone where iron exists as Fe^{2+} and will not precipitate at the equilibrium pH of a $CaCO_3$-H_2O system. (4) In harsh climates, depth of the substrate is important if the system is to operate year-round. At least one meter of substrate is needed to maintain an unfrozen anaerobic zone. At 3-4°C, sulfate-reducing bacteria will still function (Batal et al. 1988).

Vegetation

The vegetation transplanted in the fall of 1987 has recovered well in Cells B and C. The plants in Cell A do not appear to be quite as vigorous, possibly due to the differences in the substrate and microbiological processes believed to be occurring in this cell. The speculation is that the level of ammonia was initially too high in the fresh mushroom compost. The health of the plants in Cell A appears to be improving as the decomposition processes continue. Metal uptake by the plants is measurable (around 1%) but remains insignificant when compared to metal removal through the activity of bacteria and algae present in the organic substrate.

Some channelization of surface water is caused by the hasty placement of the transplanted vegetation with respect to maintaining appropriate water levels in the system. Channelization may reduce contact between the acid mine drainage and the organic substrates and thereby reduce the efficiency of the system. Careful placement of the different species of vegetation may be more effective in reducing the channelization. However, in the beginning of the second growth season, the cattails are found dominating the wetland and preventing channelization.

Thus, the presence of vegetation appears to be more important for stabilization of the substrate, reduction of channelization in the surface flow, and continual additions to the biomass of the system than for metal uptake. Metal uptake by plants is also found to be insignificant in comparison to metal removal through other processes by Sencindiver and Bhumbia (1988). The choice of the species of vegetation, therefore, is not of primary importance, as long as they are able to tolerate the conditions of the acid mine drainage and local climate. Since the concept is to emulate a natural ecosystem, complexity may be favored rather than simpler systems (Hammer and Bastian 1988).

Recommendations. (1) Local species of vegetation that are tolerant of the environment and climate are the best choices. (2) Any vegetation available on site should be saved and used. Plant species from other local mine drainage situations are good candidates. (3) Any method that can save labor in transplanting vegetation and still make a uniform planting should be used. Since providing biomass is a primary objective, neat plantings are not necessary, although placement should be done so that channelization is minimized.

Area Requirements

Once the decision to construct a wetland system is made, an estimate of the area required to treat the mine drainage must follow. This estimate must be based on data obtained through the preliminary survey including water chemistry, site hydrology, desired discharge quality and, equally important, the expected efficiency of the planned system. One of the most critical factors that determines the efficiency of the system is the retention or contact time in each cell. The interrelationship of all these factors is imperative for the design of successful systems, but presently is not well known. The lack of success of some systems can be attributed to insufficient treatment area and inadequate knowledge of site hydrology (Hiel and Kerins 1988, Brodie et al. 1988c).

Brodie et al. (1988a) developed preliminary general guidelines for treatment area requirements for desired effluent discharge concentrations of Fe = 3 mg/l or less and Mn = 2 mg/l or less as follows:

$$\text{Fe: } 2\ m^2/mg < pH\ 5.5 > 0.75\ m^2/mg \qquad (1)$$

$$\text{Mn: } 7\ m^2/mg < pH\ 5.5 > 2\ m^2/mg \qquad (2)$$

These values suggest a treatment area for Fe of 2 m^2/mg/min, and for Mn, 7 m^2/mg/min, when the pH is less than 5.5 units.

Applying these values to the mine drainage of the Big Five demonstration site, with a discharge to each cell of 3.8 l/min (1 gpm) and concentrations of Fe and Mn of 50 and 32 mg/l, respectively, the area requirement can be estimated. For iron, the rate factor is 2 m^2/mg/min, therefore the area required is:

$$(2\ m^2/mg/min)(3.8\ l/min)(50\ mg/l) = 380\ m^2 \qquad (3)$$

For manganese, the rate factor is 7 m^2/mg/min, and the area required is:

$$(7\ m^2/mg/min)(3.8\ l/min)(32\ mg/l) = 850\ m^2 \quad (4)$$

Under these conditions, Mn becomes the limiting factor for the area required. In order to reduce Mn concentrations to 2 mg/l, the treatment area requirement would be 850 m^2 (9160 ft^2) or about 0.25 acre. Research conducted at the Big Five Tunnel demonstration site, however, shows that the pH of the effluent is very responsive to changes in flow. Good results for heavy metal removal are obtained using a substrate of fresh mushroom compost with flow rates equivalent to 400 sq ft/gpm.

Recommendations. (1) All area requirements are crude rules of thumb. Research and demonstration sites have to be studied over a period of years to establish better guidelines. (2) Area requirements are substrate dependent. In places where flat land is at a premium, preliminary study of possible substrates is essential. (3) A wetland should be used as the first or last stage of a several-stage design that would include some sort of maintained operation or standby chemical treatment system. In this context, the wetland serves to make the treatment plant a small part of the operation. (4) Never commit to cleanup with an area of less than 1000 sq ft/gpm.

Configuration

In field scale constructed wetland systems, great diversity exists in the number and arrangement of cells. The basic intent is to maximize contact time in the wetland while still treating the entire discharge. As shown in Figures 2A and 2B, a typical configuration may be a parallel or series arrangement of cells. The Big Five System uses a parallel arrangement in order to assess the performance of three different substrate mixtures. Some systems have been constructed with a limestone layer as in Cell C at the Big Five system and other systems have additional aeration structures to exsolve CO_2. Some designs also include limestone channels to neutralize acidity (Hiel and Kerins 1988, Hedin et al. 1988).

Recommendations. (1) The best configuration for any system and the only configuration for a large system is a modular design incorporating parallel and series components (Figure 2C). The parallel portions allow for overflow, backup, and easier uniform distribution of influent. The series portions allow for different ecosystems to treat different aspects of the problem. In this type of system, failure of one cell would not destroy the whole project.

Summary

Preliminary results indicate that wetland systems can survive in harsh mountain climates and in high concentrations of heavy metals. Such systems can be used as primary treatment of acidic drainages with high metal concentrations and must optimize an entire ecosystem. Optimization of many parameters is necessary to increase the efficiency of metal removal in wetland treatment systems. Such parameters include layout of treatment cells, substrate composition, influent and effluent distribution systems, access wells for sampling, and types of plants. Plants must be able to resist high concentrations of metals, and substrates must provide the best conditions for the appropriate bacteria to thrive. Many aspects of the design of wetland systems must be site specific and depend on such things as area available for the system, climate at the site, wastewater metal concentration and pH, site hydrology, and degree of treatment needed.

Literature Cited

Batal, W., Wildeman, T. R., Mohdnoordin, N. and L. S. Laudon. 1988. Bacteriological tests from the constructed wetland of the Big Five Tunnel, Idaho Springs, Colorado. Presented at the International Conference on Constructed Wetlands for Wastewater Treatment. (Chattanooga, TN, June 13-17, 1988).

Brodie, G. A., Hammer, D. A. and D. A. Tomljanovich. 1988a. Constructed wetlands for acid drainage control in the Tennessee Valley. In Proceedings of a conference on Mine Drainage and Surface Mine Reclamation Vol. I: Mine Water and Mine Waste. U.S. Department of the Interior, Bureau of Mines Information Circular IC-9183, p. 325-331.

Brodie, G. A., Hammer, D. A. and D. A. Tomljanovich. 1988b. An evaluation of substrate types in constructed wetland acid drainage treatment systems. In Proceedings of a conference on Mine Drainage and Surface Mine Reclamation Vol. I: Mine Water and Mine Waste. U.S. Department of the Interior, Bureau of Mines Information Circular IC-9183, p. 389-398.

Brodie, G. A., Hammer, D. A. and D. A. Tomljanovich. 1988c. Wetlands treatment of coal ash pond seeps. Presented at the International Conference on Constructed Wetlands for Wastewater Treatment. (Chattanooga, TN, June 13-17, 1988).

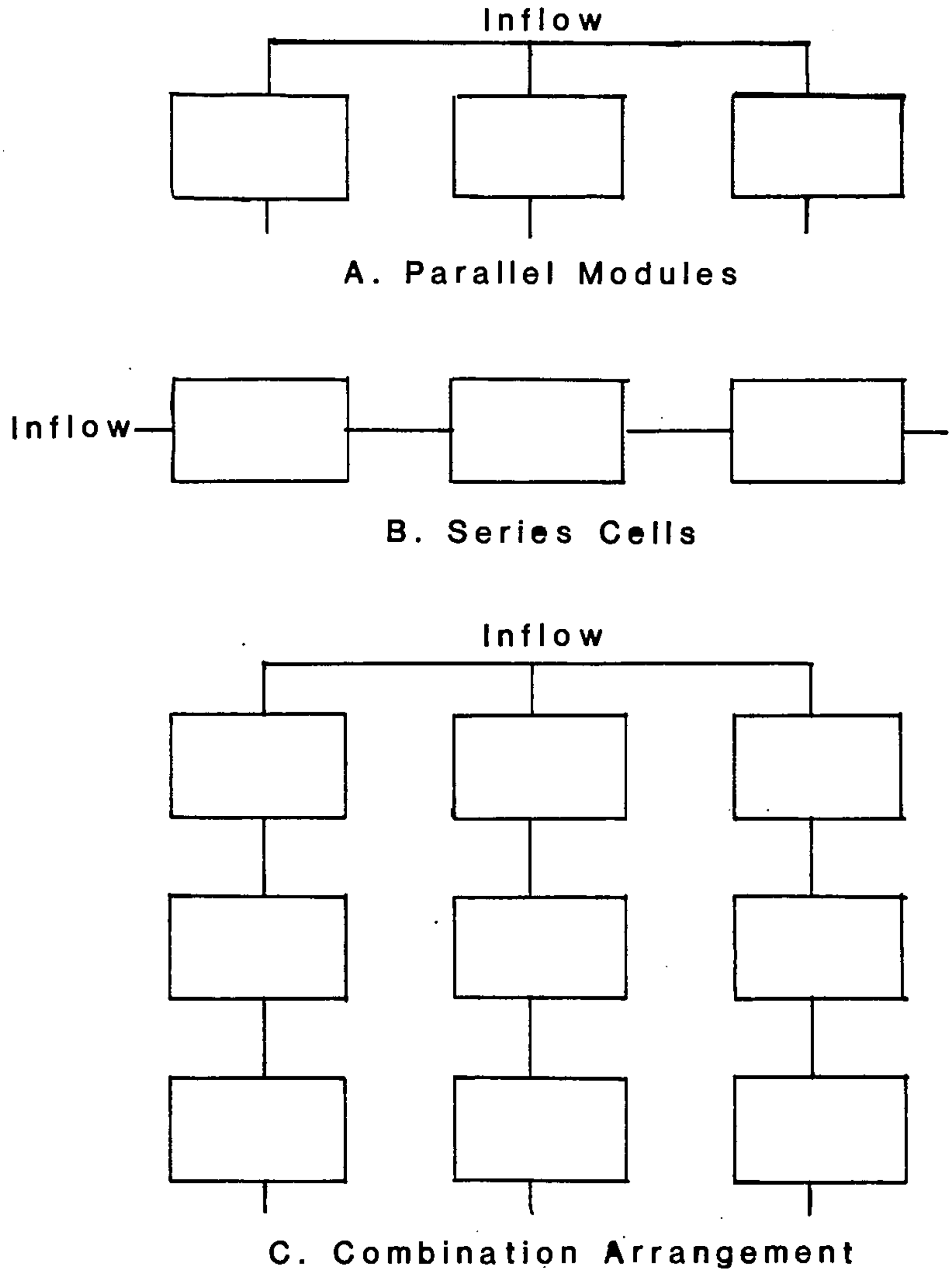

Figure 2. Wetland System Configurations.

Emmerick, J.C., Huskie, W.W. and D.J. Cooper. 1988. Treatment of discharge from a high elevation metal mine in the Colorado Rockies using an existing wetland. In Proceedings of a Conference on Mine Drainage and Surface Mine Reclamation Vol. I: Mine Water and Mine Waste. U.S. Department of the Interior, Bureau of Mines Information Circular IC-9183, p. 345-351.

Guertin, deF., Emerick, J. C. and E. A. Howard. 1985. Passive mine drainage treatment systems: a theoretical assessment and experimental evaluation. Unpublished report submitted to the Colorado Mined Land Reclamation Division, Cooperative Agreement No. 202-317.

Hammer, D. A. and R. K. Bastian. 1988. Wetlands ecosystems and wastewater treatment. Presented at the International Conference on Constructed Wetlands for Wastewater Treatment. (Chattanooga, TN, June 13-17, 1988).

Hedin, R. S., Hyman, D. M. and R. W. Hammack. 1988. Implications of sulfate-reduction and pyrite formation processes for water quality in a constructed wetland: preliminary observations. In Proceedings of a Conference on Mine Drainage and Surface Mine Reclamation Vol. I: Mine Water and Mine Waste. U.S. Department of the Interior, Bureau of Mines Information Circular IC-9183, p. 382- 388.

Hiel, M. T. and F. J. Kerins, Jr. 1988. The Tracy wetlands: a case study of two passive mine drainage treatment systems in Montana. In Proceedings of a conference on Mine Drainage and Surface Mine Reclamation Vol. I: Mine Water and Mine Waste. U.S. Department of the Interior, Bureau of Mines Information Circular IC-9183, p. 352-358.

Holm, J. D. 1983. Passive mine drainage treatment: selected case studies. In Medine, A. and M. Anderson (eds.) Proceedings, 1983 National Conference on Environmental Engineering, ASCE.

Howard, E. A., Emerick, J. E. and T. R. Wildeman. 1988. The design, construction and initial operation of a research site for passive mine drainage treatment in Idaho Springs, Colorado. Presented at the International Conference on Constructed Wetlands for Wastewater Treatment. (Chattanooga, TN, June 13-17, 1988).

Kleinmann, R. L. P. 1983. A low-cost, low-maintenance treatment system for acid mine drainage using sphagnum moss and limestone. Symposium on Surface Mining, Hydrology, Sedimentology and Reclamation. (Lexington, KY: University of Kentucky).

Sencindiver, J. C. and D. K. Bhumbla. 1988. Effects of cattails (Typha) on metal removal from mine drainage. In Proceedings of a conference on Mine Drainage and Surface Mine Reclamation Vol. I: Mine Water and Mine Waste. U.S. Department of the Interior, Bureau of Mines Information Circular IC-9183, p. 359-366.

Stillings, L. L., Gryta, J. J. and T. A. Ronning. 1988. Iron and manganese removal in a Typha-dominated wetland during ten months following its construction. In Proceedings of a conference on Mine Drainage and Surface Mine Reclamation Vol. I: Mine Water and Mine Waste. U.S. Department of the Interior, Bureau of Mines Information Circular IC-9183, p. 317-324.

Wildeman, T. R. and L. S. Laudon. 1988. The use of wetlands for treatment of environmental problems in mining: non-coal mining applications. Presented at the International Conference on Constructed Wetlands for Wastewater Treatment. (Chattanooga, TN, June 13-17, 1988).