BEST PROFESSIONAL JUDGMENT ANALYSIS FOR CONSTRUCTED WETLANDS AS A BEST AVAILABLE TECHNOLOGY FOR THE TREATMENT OF POST-MINING GROUNDWATER SEEPS[1]

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Abstract: The Pennsylvania Department of Environmental Resources (Department) performed a best professional judgment (BPJ) analysis to determine the best available technology economically achievable (BAT) for the treatment of postmining ground water seeps from surface coal mining operations. Acidity, Fe, and Mn were selected as the pollutants of primary interest to be removed. Data from 73 constructed wetlands, subcategorized according to the wetlands' influent net acidity or alkalinity, were analyzed. The sizing guidelines obtained from the data compare favorably with previous sizing guidelines presented by the U.S. Bureau of Mines. The sizing guidelines were applied to data from 794 postmining ground water seeps from the bituminous coal mining counties of Pennsylvania based on the median quantity and quality data for the seeps in five subcategories of net acidity or alkalinity. Costs to treat the seeps for 25 yr were determined for conventional treatment and for constructed wetlands treatment, both with and without anoxic limestone drain pretreatment, and both considering and not considering Mn removal. Based on the analysis, constructed wetlands treatment was found to be BAT for treatment of postmining ground water seeps, particularly for mildly acidic and alkaline seeps.

Additional Key Words: Best professional judgment, ground water seeps, constructed wetlands.

Introduction

When the U.S. Environmental Protection Agency (EPA 1982) developed its coal mining technology-based effluent limitations (40CFR434), it considered only discharges that occur during active mining. It did not establish limitations for ground water seeps that could occur after mining had been completed. Passive treatment systems were not in routine use when the effluent guidelines were evaluated. Since that time, constructed wetlands and anoxic limestone drains (ALD's) have emerged as potential alternative technologies. In the absence of federally promulgated guidelines, best available technology economically achievable (BAT) may be developed by means of a best professional judgment (BPJ) analysis. Section 304 of the Federal Clean Water Act specifies that the following factors are to be used to identify the BAT: (1) age of equipment and facilities involved, (2) the process employed, (3) process changes, (4) engineering aspects of the application to various types of control technology, (5) non-water quality impacts, (6) total cost of the application of technology in relation to the pollutant reduction benefits to be achieved, (7) the cost of achieving such effluent reduction, and (8) other factors deemed appropriate.

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The Department performed a BPJ analysis for postmining ground water seeps (hereinafter "seeps") as described above (Hellier 1993). Based on the analysis, the Department finds that for some categories of seeps, treatment with constructed wetlands (hereinafter "wetlands") is a cost-effective, environmentally sound alternative to more conventional treatment.

Performance data from 73 wetlands were used in this BPJ analysis. Cost information from several sources, including consultants, coal operators, and government agencies, was used to determine the capital, operation and maintenance, and amortization costs for wetlands sized according to guidelines developed below. The cost information was applied to actual seeps to determine the overall costs of using wetlands treatment. Costs for conventional and wetlands treatment were compared, and the BAT was determined.

Postmining ground water seeps may occasionally develop after reclamation. They are not caused or affected by the type, age, or condition of the mining equipment. The methods of mining do not affect the choice of treatment technology that would be used should a seep occur. Finally, there is no processing of material at a coal mine that will cause a seep. Seeps occur because of the hydrology and geology of the reclaimed mine site. The technology employed in treating seeps is independent of these factors.

Wastewater Characteristics and Performance of Wetlands

The Department characterized seeps on the basis of data taken from 794 postmining seeps arising from 406 different surface mine permitted areas in the bituminous coal mining counties of Pennsylvania. These seeps can be subcategorized according to their net acidity or alkalinity: (1) very acid seeps - net acidity >300 mg/L (as $CaCO_3$), (2) moderately acid seeps - $100 \leq$ net acidity ≤ 300 mg/L, (3) weakly acid seeps - $0 \leq$ net acidity < 100 mg/L, (4) weakly alkaline seeps net alkalinity < 80 mg/L, and (5) strongly alkaline seeps - net alkalinity ≥ 80 mg/L. Figure 1 summarizes the water quality of seeps in the five subcategories (Tukey 1977, Helsel 1987).

Conventional treatment was considered as a candidate technology for the treatment of seeps. The conventional treatment process described in the EPA development documents for the Coal Mining Point Source Category is a proven technology. Treatment consist of using alkaline compounds such as CaO, $Ca(OH)_2$, Na_2CO_3, $NaHCO_3$, NaOH, or NH_3 to neutralize any acid in the discharge, to give it a positive net alkalinity, and to raise its pH to a value in the range $6.0 \leq pH \leq 9.0$. In the process, Fe and Mn compounds are converted to less soluble oxides or hydroxides. The treated discharge is then detained in one or more settling basins for 24 h or more. The metal oxides and hydroxides are removed in the settling basins by sedimentation, sometimes assisted by application of a coagulant. Typically at least two settling basins are built in series to minimize solids carryover at the outfall. BAT regulations, 40CFR34, describe the effluent quality achievable using conventional treatment. These requirements are summarized in Table 1.

These BAT limitations apply to discharges in existence as of October 1985. "New source" discharges occurring after that time must also comply with these limits, except for Fe limits, which are 3 mg/L (30-day average) and

Table 1. Pennsylvania's BAT limitations.

Pollutant parameter	30-Day average	Daily (24 hr.) average
Iron (Fe)...........	3.5	7
Manganese (Mn) mg/L.	2	4
Suspended solids mg/L.	35	70
pH*.................	6-9	6-9

*Between 6 and 9 at all times.

6 mg/L (daily average). For all practical purposes, BAT and "new source" effluent requirements are equivalent in terms of the technology needed to achieve compliance. Although not part of EPA's BAT requirements, the Department's regulations require that alkalinity > acidity at all times.

A commonly used passive treatment system is the constructed wetland. Both aerobic and anaerobic processes occur in wetlands. Aerobic processes remove Fe and Mn by oxidation, hydrolysis, and settling of the resulting oxides and hydroxides. Al is removed by hydrolysis and settling. Hydrolysis of metals consumes OH^- and liberates H^+. To prevent this additional acid contributing to pollution of the receiving waters, one relies on (1) alkalinity originally present in the seep, (2) pretreatment by an anoxic limestone drain, or (3) a rock and organic substrate that generates alkalinity under anoxic conditions.

Anaerobic conditions develop in the substrate. Bacteria, using the substrate as a carbon source, reduce SO_4^{-2} to S^{-2}, thereby removing acidity. Part of the S^{-2} escapes to the atmosphere as H_2S, while part precipitates metals in such forms as FeS. The bacteria incorporate C into HCO_3^-, thereby generating alkalinity. Because HCO_3^- from limestone also contributes alkalinity, the rock incorporated into the substrate is often limestone (Anderson and Schiff 1987).

Alkalinity may also be added by means of an anoxic limestone drain (ALD). The limestone is buried in a trench, forming a drain through which the water to be treated is passed in the absence of O_2. Anoxic conditions are supposed to prevent coating of the limestone by $Fe(OH)_3$. The limestone dissolves, imparting alkalinity and neutralizing part or all of the acidity. The treated water is directed into a settling basin or constructed wetland, where the cations are removed by oxidation, hydrolysis, and settling, as above.

The Department examined wetlands that were used in the treatment of 73 of the 794 postmining ground water seeps, subcategorizing the wetlands in the same manner as it subcategorized the 794 seeps. Figs. 2-4 show the performance of the five subcategories of wetlands as grams per day of pollutant removed per square meter of wetland area. A mass flow per unit time per unit area is called a flux. The removal is therefore the difference between the influent and effluent fluxes of pollutant. Figure 2 shows that when the influent was originally acid, the effluent net acidity has been significantly reduced relative to the influent net acidity; however, when the influent net acidity > 100 mg/L wetlands with acid influents have acid effluents. Wetlands whose influent net acidity <100 mg/L tend to have alkaline effluents. Wetlands tend to have effluent [Fe] that is substantially lower than their influent [Fe] (Fig. 3). Wetlands are not as effective in terms of Mn removal (Fig. 4).

The U.S. Bureau of Mines has initially made an empirical estimate for minimum sizes for wetlands (Hedin and Nairn 1992). For a net alkaline water the minimum size based on Fe loading is

$$A(m^2) = Fe\ (g/d)/(20\ gd^{-1}m^{-2}) \tag{1}$$

and for Mn loading

$$A(m^2) = Mn\ (g/d)/(0\ .5\ gd^{-1}m^{-2}) \tag{2}$$

The Bureau also suggests that an anaerobic wetland could be designed on the basis of

$$A\ (m^2) = [\text{net acidity}]\ (g/d)/(5\ gd^{-1}m^{-2}) \tag{3}$$

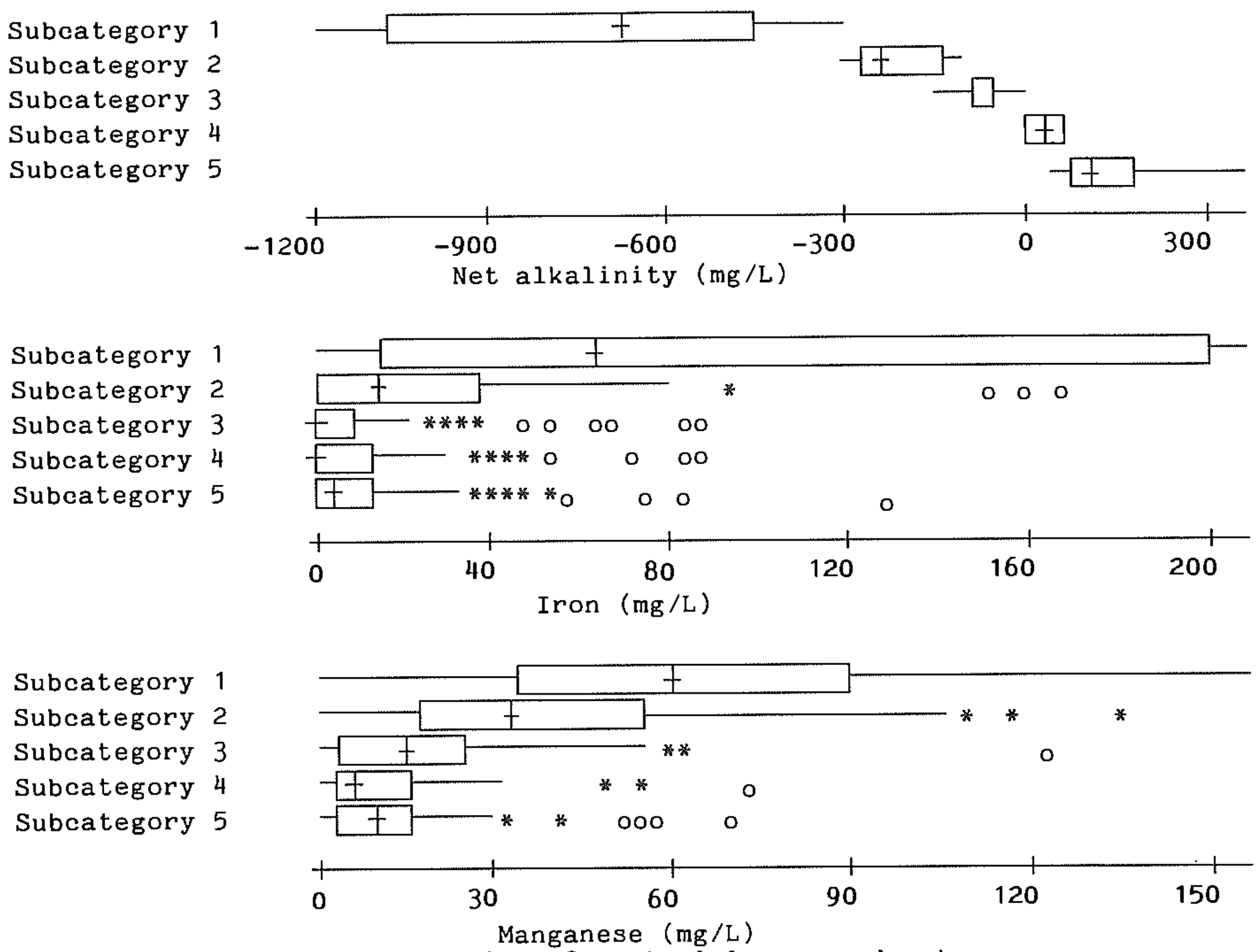

Figure 1. Water quality of post mining ground water seeps.

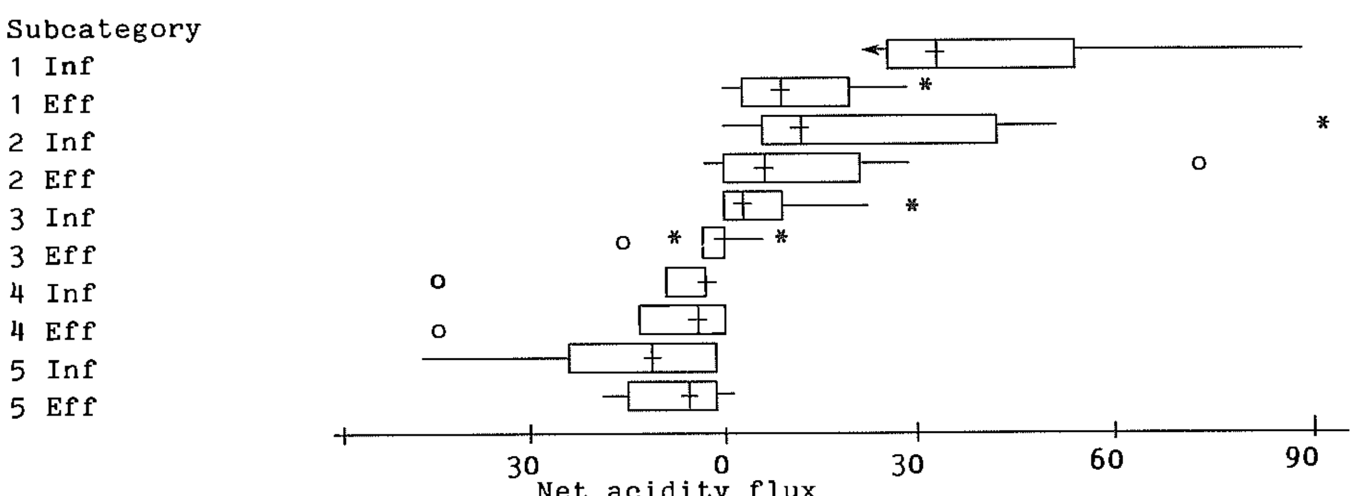

Figure 2. Comparison of influent (Inf) and effluent (Eff) acidity fluxes for the five subcategories of constructed wetlands.

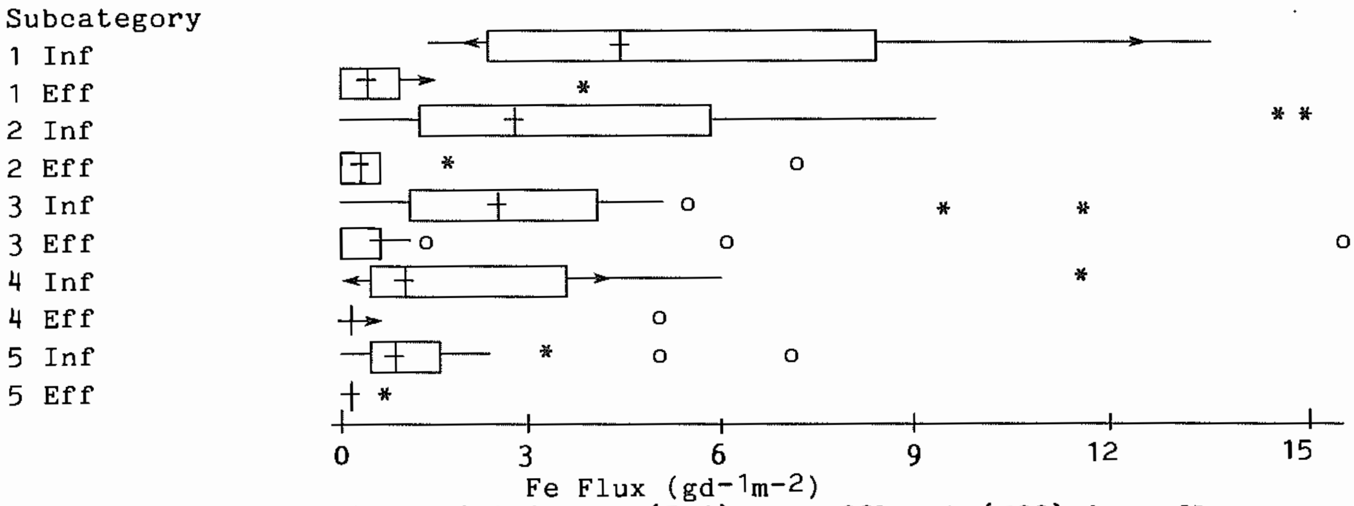

Figure 3. Comparison of influent (Inf) and effluent (Eff) iron fluxes for the five subcategories of constructed wetlands.

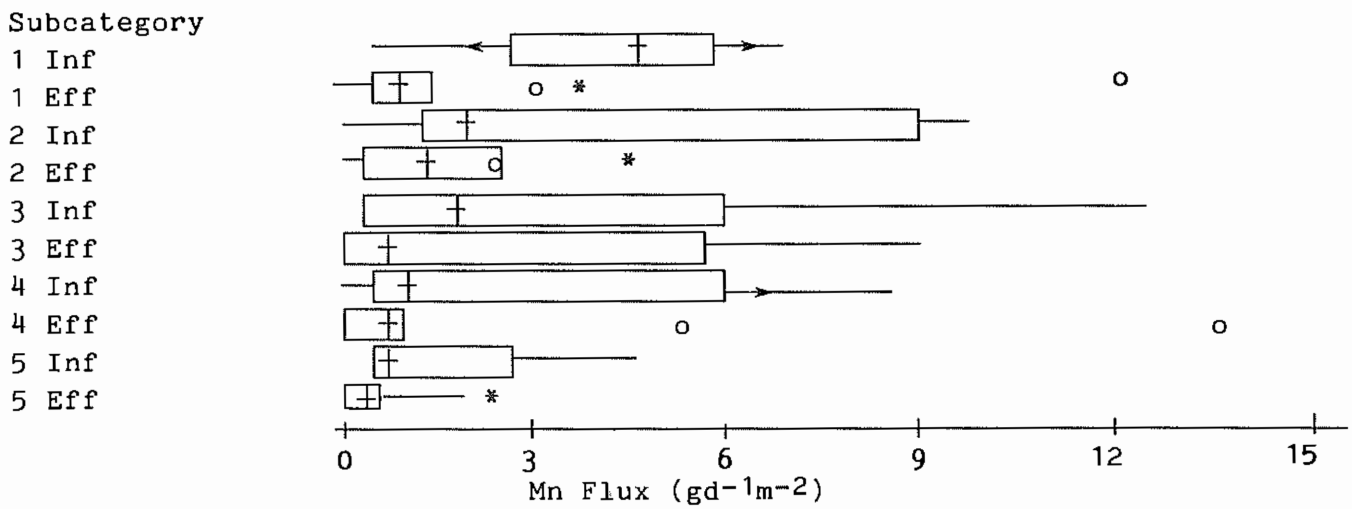

Figure 4. Comparison of influent (Inf) and effluent (Eff) manganese fluxes for the five subcategories of constructed wetlands.

to remove excess acidity. Because acidity is neutralized by alkalinity produced under anaerobic conditions, whereas Fe and Mn are primarily removed by oxidation under aerobic conditions, the area necessary for Fe and Mn removal cannot necessarily be considered a part of the area needed for acidity removal. One design suggested by the Bureau of Mines is removal of Fe and Mn in a wetland designed to take advantage of aerobic conditions, following in series a wetland that has been designed to take advantage of anaerobic conditions, generate alkalinity, and remove acidity. Because the wetlands are in series, the required area is the sum of the area of the acidity removal wetland and the Fe and Mn removal wetland.

The Department's data for subcategory 1 discharges show a substantially higher median acidity removal of 29.16 $gd^{-1}m^{-2}$. Long-term removal of such high amounts of acidity may not occur, and the data may be indicative of a transient condition based on high initial rates of alkalinity generation in the substrate. The median removal rate falls to 10.59 $gd^{-1}m^{-2}$ for subcategory 2. Wieder et al. (1993) initially found high acidity removal rates for subcategory 1 wetlands, but the rates of acidity consumption declined over time.

For subcategory 3, the median acidity removal rate of 6.01 $gd^{-1}m^{-2}$ is close to the threshold value of 5 $gd^{-1}m^{-2}$ suggested by the U.S. Bureau of Mines. The influent net acidity flux for this subcategory is low; the wetland removes substantially all of the acidity. The Bureau of Mines data are based on wetlands with higher influent net acidity loadings, whereas the wetlands examined by the Department were sized based on perceived "worst-case" conditions, i.e., high acidity, [Fe], and [Mn]. The Department's data suggest that the Bureau of Mines 5 $gd^{-1}m^{-2}$ is an acceptable conservative design guideline.

The data for Fe removal suffer from the same limitations: influent Fe loadings in $gd^{-1}m^{-2}$ are low, and the wetlands have relatively large areas. The U.S. Bureau of Mines gathered data from wetlands that had high [Fe] in both influent and effluent. From these wetlands' data, the Bureau (Hedin and Nairn 1993) found a design removal rate of 20 $gd^{-1}m^{-2}$. Most of the wetlands in the Department's study had influent loadings substantially < 20 $gd^{-1}m^{-2}$, as a consequence, the Department cannot determine empirically whether 20 $gd^{-1}m^{-2}$ of Fe would have been removed had it been present. The median removal rate was 4.24 $gd^{-1}m^{-2}$ for very acid influent. While the Department's data cannot be used to corroborate the Bureau of Mines' 20 $gd^{-1}m^{-2}$, the Department accepts the Bureau of Mines' conclusions but recommends design based on an iron removal rate of 5 $gd^{-1}m^{-2}$ for influent pH <6.5. For influent pH >6.5, 20 $gd^{-1}m^{-2}$ may be used.

The Department's data agree closely with the Bureau of Mines' suggested design criterion for Mn removal. Hence, a removal rate of 0.5 $gd^{-1}m^{-2}$ is suggested for all net acidity and alkalinity ranges.

Sizing Recommendations

It would appear reasonable that wetlands should be designed on the basis of summing the areas from equations 1, 2, and 3 for conditions of influent pH>6.5:

$$A(m^2) = (\text{net acidity loading g/d})/(5\ gd^{-1}\ m^{-2}) + (\text{Fe loading g/d})/(20\ gd^{-1}m^{-2}) + (\text{Mn loading g/d})/(0.5\ gd^{-1}m^{-2}). \quad (4)$$

For less alkaline conditions or for acid conditions, the sizing could be based on

$$A(m^2) = (\text{net acidity loading g/d})/(5\ gd^{-1}\ m^{-2}) + (\text{Fe loading g/d})/(5\ gd^{-1}m^{-2}) + (\text{Mn loading g/d})/(0.5\ gd^{-1}m^{-2}). \quad (5)$$

Removal of up to 85% of the Fe present in the influent is achievable, as is removal of up to 50% of the Mn when the influent is alkaline (but only about 25% if the influent is acid). Wetlands designed to take advantage of anaerobic processes should produce alkaline discharges for subcategory 3, 4, and 5 influents. Wetlands designed to take advantage of anaerobic processes should remove most of the acidity for subcategory 2 influents. Wetlands remove much acidity for subcategory 1 influents, but the effluent remains acid.

Potential Merit of ALD's

ALD's can be considered as ancillary treatment to either diminish the influent net acidity to <100 mg/L or make the influent alkaline, so that the wetlands can take advantage of the more favorable net acidity or alkalinity ranges for Mn removal and for the discharge of an alkaline effluent. At present, because the technology is relatively new, the Department does not possess sufficient data to assess the effectiveness of ALD's. Pretreatment with an ALD reduces the design size of the wetlands, but the operator bears the responsibility for any needed wetland expansion should the ALD provide unsuccessful. ALD's are thought to be self-supporting pretreatment units for subcategory 2 and 3 seeps. For acidity in subcategory 2, they may be the treatment of choice owing to economic considerations. For subcategory 3, wetlands tend to remove the acidity without the need for pretreatment by an ALD. ALD's may be installed as precautionary measures for subcategory 3 and 4 influents. For subcategory 4, it is reasoned that the hydrolysis reactions that remove the cations may remove most or all of the alkalinity if it was initially too low. For subcategory 5 influents, an ALD is unnecessary.

Selection of Pollutant Parameters

Under current regulations, Pennsylvania technology-based effluent requirements currently apply to the parameters pH, net acidity, Fe, and Mn for discharges that occur during active mining. The same parameters were considered for seeps. Acidity has several adverse effects on the environment, including but not limited to damage to aquatic life, damage to bridges and other structures, and potential damage to drinking water treatment and distribution facilities. Therefore, the Department finds that seeps must be treated such that the final discharge has a residual alkalinity; i.e., acidity <0. This will generally mean pH > 6.0.

The oxides and hydroxides of Fe, especially FeO(OH), precipitate from solution and form a sediment that settles out on the bottoms of receiving streams. The sediment produces an unsightly condition and smothers benthic life, usually making the stream unsuitable as a fishery. In addition, dissolved iron in the receiving stream can generate added treatment costs should the stream be used as a drinking water supply source. For this reason, Fe in seeps should be removed.

Under alkaline conditions Mn is present primarily as MnO_2. This compound causes black staining on rocks. In drinking water, Mn can cause taste problems in some food and beverages, as well as laundry stains. It has not been shown to be present in biologically harmful amounts in alkaline discharges. Because of the historic technology-based effluent limits currently applied to Mn for discharges from active sites, Mn is also considered as a pollutant parameter for seeps.

In considering discharges occurring during active operations, EPA 1982 determined that technology-based effluent requirements for 114 organic pollutants and for the inorganic pollutants CN^-, Sb, Be, Cd, Ag, Tl, As, Cr, Cu, Pb, Hg, Ni, Se, and Zn were unnecessary. The Department has determined from analysis of several seeps that these pollutants are not present at levels of concern. Furthermore, the Department finds that Al limits are unnecessary, because Al is not present in appreciable concentrations in wetland effluents with pH > 6.0. In summary, the pollutant parameters selected for consideration are pH, net acidity, Fe, and Mn.

Cost Considerations

The capital costs of a wetland are directly dependent on the required area, based on equations 4 or 5. To arrive at a construction cost per unit area, the Department interviewed several persons who have built wetlands to determine a cost per unit area. The median cost is $32.29 per square meter in 1992 dollars. Wetlands bear a small monthly operation and maintenance cost (about $100) for such tasks as minor repairs and fertilization. The Department considered the 25 yr operation and maintenance costs as constant from site to site. The amortized annual capital replacement costs are determined by the formula

$$\text{Cost}=(\text{capital cost})\ (i)(1=i)^{n}/[(1=i)^{n-1}] \qquad (6)$$

This figure is multiplied by 25 to arrive at the 25 yr cumulative amortization costs. The total 25-yr cost is the sum of the initial capital costs, the 25-yr operation and maintenance cost, and the cumulative amortization costs. Twenty-five years is an estimate of the operational lifespan of the wetlands before replacement is needed. Conventional treatment costs were also calculated on the basis of 25 yr of operation.

Once the total costs have been determined, the unit costs (i.e., costs per kilogram of pollutant removed) can be obtained by dividing the total costs by the total amount of pollution removed in 25 yr (kg net acidity+kg Fe+kg Mn). The choice of equation 4 or equation 5 has only about a $0.20 per kilogram effect on the unit cost. With the exception of subcategory 5, the cost per kilogram of pollution removed increases progressively as one procedure from strongly acid water to less acid water to alkaline water. This is due to the division by the quantity of pollutants removed, which becomes less as the water becomes more alkaline. This trend applies whether a wetland or conventional treatment is used.

The costs for conventional treatment were determined by adding the capital cost of the treatment facilities to 25 times the sum of the annual operation and maintenance cost and the annual cost to amortize the capital cost for the treatment facilities (DER et al. 1988). A value of 8% is assumed to be the "true" interest rate for both wetlands and conventional treatment. The costs for conventional treatment are compared with the costs for wetlands treatment in table 2. The figures in the table are used in the conclusions below. The table shows that as the influent becomes less acid, or more alkaline, passive treatment becomes increasingly cost effective.

Table 2. Median Comparative Unit Costs of Several Modes of Treatment.

Subcategory	Conventional treatment removing acid, Fe, and Mn	Wetland removing acid, Fe, and Mn	ALD/wetland removing acid, Fe, and Mn	Wetland removing acid and Fe but not Mn	ALD/wetland removing acid and Fe but not Mn
1	$1.24	$4.18	$3.43	$2.36	$1.82
2	5.56	6.64	5.21	2.65	1.42
3	23.06	11.31	11.23	4.37	6.18
4	114.34	28.38	33.96	10.20	81.00
5	95.99	25.01	does not apply	9.09	does not apply

The BPJ analysis can now be conducted as follows:

1. Age of equipment and facilities involved, the process employed, and process changes. These factors are primarily associated with the manufacturing sector of industry and relate to the difficulty which some manufacturers may have in retrofitting BAT technology. The relative merits of conventional treatment and wetlands with or without an ALD are independent of these factors.

2. Engineering aspects of the application to various types of control technology: Conventional treatment and treatment by wetlands, either with or without an ALD, are technologically feasible. Conventional treatment requires less space but much more operational supervision than passive treatment systems. On the other hand, passive treatment systems can achieve substantial reductions in net acidity, iron, and manganese when subjected to a variable influent loading, while for optimum performance, conventional treatment feed rates must be continually adjusted.

3. Consideration of non-water-quality impacts: Wetlands at least partly replace a valuable natural resource that has been significantly damaged by past practice. Wetlands are anesthetically pleasing features of reclamation, and they provide wildlife habitat. They help conserve energy and mitigate the greenhouse effect. They are safer than conventional facilities and cause less of a sludge disposal problem. Conventional treatment, on the other hand, often occupies less land space.

4. Total cost of the application technology in relation to the pollution reduction benefits to be achieved and the cost of achieving such pollutant reduction: These are summarized in table 2. As influents become less acid or more alkaline, passive treatment becomes increasingly cost effective compared to conventional treatment.

Conclusions and Recommendations

The use of passive treatment technology is a cost-effective, environmentally sound alternative to the use of conventional mine drainage treatment for many postmining seep situations. The technology offers the added advantage of operational reliability while requiring minimal operational control.

Data on the 73 better-designed constructed wetlands systems (figs. 2-4) indicate that this technology can produce an effluent quality that is similar to, and in some cases better than, EPA's BAT effluent requirements (40CFR 434) for active mining. The data do not support, however, that a standardized set of BAT effluent limitations can be developed for such technology.

Section 122.44(k) of EPA's National Pollutant Discharge Elimination System (NPDES) regulations allows for "best management practices" to be specified in lieu of technology-based effluent requirements when numerical effluent limits are infeasible or when such practices are reasonably necessary to carry out the purposes and the intent of the Federal Clean Water Act. Passive treatment technology seems to fit in well with the "best management practices" concept.

With this concept in mind, and based upon the results of this BPJ analysis, the following recommendations are made:

1. BAT for post mining seeps from surface mining activities should be achieved through the use of passive treatment technology as a "best management practice" in lieu of numeric effluent limitations.

2. Where the use of passive treatment technology is not feasible (due to the size and poor quality of the seep), then conventional treatment should be considered BAT. This would generally be the case when the net acidity of a seep exceed 300 mg/L as $CaCO_3$.

3. Because of the significantly higher costs to remove manganese in post mining seeps, it is recommended that the design and sizing of passive

treatment for manganese removal be required only when needed to achieve the water quality standards for [Mn] in the receiving stream.

4. The Department should continue investigating the mechanisms of pollutant removal using passive treatment technology in order to refine the design and operational requirements for this technology.

At the time this paper was prepared and submitted, the Department had not yet begun regulatory changes to implement the recommendations. The final outcome may not totally reflect the results of this BPJ analysis.

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