ECOLOGICAL BENEFITS OF PASSIVE WETLAND TREATMENT SYSTEMS DESIGNED FOR ACID MINE DRAINAGE: WITH EMPHASIS ON WATERSHED RESTORATION[1]

Eric C. McCleary and Douglas A. Kepler[2]

Abstract: Western Pennsylvania has been a large source of coal for much of the United States since the late 1800's. During the extraction of the coal resources, acid mine drainage (AMD) often resulted. AMD from abandoned discharges has effectively rendered thousands of kilometers of streams lifeless in the Appalachian coal region. Restoration of these streams has been limited in previous years primarily because of the lack of cost-effective treatment for AMD. Conventional treatment (i.e., chemical addition) can treat AMD effectively but is costly to operate and maintain and is effective only when receiving human attention. Passive wetland treatment systems have proven to be the only realistic AMD treatment strategy, in terms of watershed restoration activities. If ecosystem health is the reason for implementing effluent standards then it can be reasonably argued that passive wetland treatment systems supply the most effective overall treatment, even if they do not meet one or more of the current effluent standards. Recent advancements in passive wetland treatment system technology have provided a management tool that could be used to treat the majority of AMD discharges cost-effectively, and when used strategically could reasonably be employed to restore the thousands of kilometers of AMD-affected streams in the coal regions of Appalachia. Secondary benefits that have been observed with passive wetland treatment systems suggest that these systems may be providing for accelerated ecological recovery independent of regulated effluent standards.

Additional Key Words: acid mine drainage, passive wetland treatment system, watershed restoration.

Introduction

Water of a quality consistent with biological functioning is critical to all life. Increasing human populations and the resulting consumption of our resources have necessitated that human society divert more attention to the preservation and restoration of our water resources.

The water resources of the Appalachian coal region have been particularly impacted, in terms of water quality degradation. Western Pennsylvania, for example, has been a large source of coal for much of the United States since the late 1800's. As of 1986, Pennsylvania contributed roughly 6.9% of all coal produced in the United States (Keystone Coal Industry Manual 1987). The extraction of coal contributed largely to the economic development in the coal mining regions, while leaving chronic environmental debts. These environmental debts have taken two basic forms: (1) incomplete or absent surface reclamation and (2) acid mine drainage (AMD). Surface reclamation today is not a serious problem largely because of restoration programs enacted by both State and Federal entities. AMD has been and remains the largest contributor to water quality degradation in most coal mining regions. The formation and cause of AMD are well documented (Hedin et al. 1994, Brodie 1993, Brodie et al. 1993, and Stumm and Morgan 1970). Surface and subsurface mining has left thousand of untreated AMD discharges flowing into thousands of streams in this region. AMD and its associated high metal and high acid content have rendered approximately 12,000 km of streams and 12,000 ha of impoundments biologically devastated (Appalachian Regional Commission 1969).

In 1977 the Surface Mining Control and Reclamation Act (SMCRA) was enacted creating the Office of Surface Mining, Reclamation, and Enforcement (OSMRE) within the U.S. Department of the Interior. OSMRE is the Agency responsible for regulating coal mining and reclamation in the United States through SMCRA. Basically, SMCRA requires that coal operators treat point source discharges that are regulated by the National Pollution Discharge Elimination System (NPDES) permits.

---

[1]Paper presented at the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29, 1994.

[2]Eric C. McCleary, Restoration Ecologist, and Douglas A. Kepler, Restoration Ecologist, Damariscotta, Clarion, PA, USA

Proceedings America Society of Mining and Reclamation, 1994 pp 111-119
DOI: 10.21000/JASMR94030111

https://doi.org/10.21000/JASMR94030111

The Federal Clean Water Act of 1972 entitles the U.S. Environmental Protection Agency (EPA) to set standards that each AMD discharge from a coal mining activity must meet. These standards for mining Applications are between 6 and 9 for pH, 7 mg/L daily and less than 3.5 mg/L on a monthly average for Fe, 4 mg/L daily and less than 2 mg/L on a monthly average for Mn. State regulatory agencies may set more stringent standards.

Coal operators, while operating, have generally met the criteria set forth by the EPA. However, in cases where treatment ceases either temporarily or permanently the aquatic environment receiving the AMD discharge once again receives degraded water, adversely affecting the biota. With the prevailing economic situation, coal operations once thriving are now experiencing economic hardship. Because of this hardship, many coal operations have ceased and many more are in the process. This has left the States and Federal Government with the ultimate responsibility of AMD abatement under he Clean Streams Law of 1972. While bonds were allocated for each permitted coal extraction activity, the bond remaining after forfeiture is insufficient to allow for AMD treatment in perpetuity with conventional treatment (i.e., chemical). Thus, abandoned discharges, both those with bonds and those created prior to bonding requirements (1977), are flowing into the streams and rivers of the United States unabated.

Water affected by AMD require various forms of treatment before it can be considered an acceptable resource for most aquatic biota and human uses. In an effort to meet the standards imposed by the EPA, two types of treatment have emerged: active and passive. active treatment commonly consists of chemical addition in the form of soda ash briquettes, hydrated lime, quick lime (CaO), or sodium hydroxide. Being inherently acidic, AMD generally possesses low pH and elevated Fe and Mn concentrations. Chemical addition effectively raises pH, causing the chemical-physical precipitation of typical metals dissolved in AMD. Chemical treatment is effective but costly, in terms of the chemicals, maintenance of the treatment system, and the overall effects to the receiving aquatic environment (Hedin et al. 1994, Brodie et al. 1993). Passive treatment generally includes systems that are designed around constructed wetlands that require little in terms of operation and maintenance costs. These systems are generally less effective at meeting effluent criteria than chemical treatment but possess the secondary benefits of perpetual, year-around treatment, minimal operation and maintenance costs, and great potential for ecological restoration.

Restoration of AMD-affected waterways has been limited primarily because of insufficient funds allocated for such purposes, acceptability of passive treatment system technology by the controlling regulatory agencies, and the foresight of these agencies to predict the cost of chemical treatment to the coal industry and the environment. There are currently talks underway to appropriate existing funding, within the State and Federal Governments, to allow for treatment of existing AMD discharges; however, two questions will have to be answered: (1) who will ultimately pay for the abatement and how will it be prioritized and (2) what type of abatement will achieve the most cost-effective results.

This paper is intended to support the contention that passive wetland treatment systems can be used to successfully mitigate the effects that AMD has had on the ecology of the Appalachian coal region streams. Passive wetland treatment systems appear to provide the most cost-effective treatment of AMD discharges, with secondary benefits of providing for increased ecological recovery (Williams and Dalby 1993). The approach of this paper is to elucidate on the various passive treatment systems that can effectively provide a solution to the above second question. If the intent of the original law regarding effluent standards is the maintenance of overall ecosystem health, then it can be reasonably argued that passive wetland treatment systems would supply the most effective overall treatment, even if they do not meet one or more of the current effluent standards.

Discussion

Cost Comparison Rationale

One of the purported advantages of passive wetland treatment systems is the supposed costs savings in terms of perpetual treatment. The following example should illustrate the potential for cost savings, when properly designed passive wetland treatment systems are implemented site specifically:

The R.E.M. Orcutt/Smaill wetland was constructed in 1987 to deal primarily with the high iron loadings (>20,000 g/d). The initial design consisted of an aerobic wetland that was sized to the available area (roughly 0.12 hectares). The source AMD discharge was net acidic (possessing acidity values greater than 200 mg/L) allowing for little abiotic precipitation of Fe. Removal rates did not meet expectations, and in the spring of 1992 revisions were made to the system that incorporated an anoxic limestone drain (ALD) and a successive alkalinity producing system

Table 1. Water quality data for R.E.M.Orcutt/Smaill site, Union County, Jefferson County, PA.

Monitoring location	pH[1]	Fe, (mg/l)	Acid, (mg/l)	Acidity loading, (g/d)	Fe loading, (g/d)
L1 (ALD)...	6.18	155.0	213	31,561	22,967
L2..........	4.00	46.3	161	23,856	6,860
L3..........	3.75	29.8	152	22,523	4,416
L4..........	3.33	25.8	146	21,634	3,823
L5(Effluent)	3.98	9.0	64	9,483	1,333

[1]Field Measurements
Note: Flow measured at 102.9 L/min.
Source: U.S. Bureau of Mines laboratory data, January 18, 1993.

(SAPS). These passive system additions significantly affected water quality; Fe removal went from 70%-75% to 95%. Acidity values associated with this discharge were also reduced from source values out of the ALD of >200 mg/L to the effluent acidity of 50-60 mg/L (associated mostly with Mn).

The costs to reduce the acidity values were calculated for both the passive system and a hypothetical chemical treatment system that would reduce the acidity to the same level. A 25% level of error was calculated into each treatment scenario. Values (U.S. Bureau of Mines, laboratory data 1993) for this particular discharge, referred to as L1 are shown for one date (18 January 1993) in table 1. This date was chosen as representative of a date on which passive treatment systems are considered to be at their theoretical lowest effective treatment level.

To calculate the cost of treatment for the passive treatment system, the alkalinity value of 125 mg/L out of the ALD was utilized as the $CaCO_3$ equivalent for alkalinity production with a 25% error to allow for greater alkalinity production than observed. Assuming 90% $CaCO_3$ content of the limestone, approximately 21 kg of limestone is dissolved daily at this site. With a cost of $15 per ton of limestone delivered, the annual treatment cost for this discharge is $125 per year. The installation costs of the ALD and SAPS were roughly $10,000 for materials and labor.

The costs to chemically treat this discharge to the same effluent acidity can be calculated by determining the acidity loading and inserting the value 149 mg/L (from table 1; subtract L5 acidity from L1 acidity) into a common equation utilized by the chemical treatment industry to determine the amount of chemical needed to neutralize the AMD discharge acidity:

> g/d of acidity ($CaCO_3$) x 0.80 ($CaCO_3$ equivalence conversion factor) x 1/0.99 (% pure) x 1/0.90 (% reactive) x 1/0.75 (% effective) = g/d of NaOH required to neutralize specified amount of acidity.

To neutralize the same 149 mg/L of acidity chemically that is neutralized in the passive system roughly 33 kg of NaOH would be required per day. Sodium Hydroxide currently costs $0.40/lb, on average, which translates to approximately $29/day and $10,600/year for chemical treatment alone. Additional funds would be required for staff to operate the treatment equipment.

Brodie et al. (1993) quoted figures similar to these for the chemical treatment of a discharge that had been converted from chemical to passive. While these are a few examples, it can be seen that passive treatment systems possess the ability to literally pay for themselves within 2 to 3 years (1 year in the R.E.M. Orcutt/Smaill system). Passive treatment systems, with this type of payoff and little or no operation and maintenance, can, when properly designed, operate at or below standard effluent criteria 365 days/year.

Table 2. Passive wetland treatment systems, construction dates, and the average influent and effluent characteristics from implementation to present.

Site	Construction year	Influent Effluent	Sample Size, n	pH	Fe, mg/L	Mn, mg/L	Acidity, mg/L	Alkalinity, mg/L	Flow, L/min
Somerset	1984	I	43	4.4	162	50	373	0	47
		E	40	5.5	18	33	69	NG	---
Donegal	1987	I	29	7.1	5	8	NG	202	501
		E	28	7.4	<1	2	NG	NG	---
Emlenton	1987	I	40	4.7	89	77	320	15	55
		E	40	3.2	15	73	271	0	---
Latrobe	1987	I	43	3.5	125	32	617	0	86
		E	43	3.7	56	29	343	NG	---
Piney	1987	I	39	5.8	1	15	NG	60	468
		E	39	5.8	1	15	NG	NG	---
FH	1988	I	73	2.6	153	9	929	0	15
		E	73	2.9	137	10	674	0	---
Blair	1989	I	12	6.2	52	30	NG	166	11
		E	8	7.0	<1	5	NG	NG	---
Cedar	1989	I	26	6.3	92	2	NG	336	156
		E	27	6.4	41	2	NG	NG	---
Keystone	1989	I	28	6.3	37	<1	NG	142	8,606
		E	28	6.4	32	1	NG	NG	---
Shade	1989	I	20	6.0	<2	23	NG	31	10
		E	20	6.8	<1	10	NG	NG	---
Morrison	1990	I	34	6.3	150	42	NG	271	7
		E	24	6.6	<1	11	NG	NG	---

Source: Hedin et. al. 1994.
FH Friendship Hill National Historic Site.
NG Not Given

Other Concerns

When the financial aspect of treatment is addressed, it is apparent that passive treatment systems are relatively inexpensive to construct, operate and maintain. Time or longevity of the passive treatment system operating life is a question that often follows. Longevity, however, is a question that remains theoretical at this point, because the oldest passive treatment systems still functioning effectively are generally less than 10 years old (Hedin et. al. 1994). Passive systems show no signs of physically failing and should operate well into the future. Table 2 gives a list of systems, when they were implemented, and average water quality data over their life span. The longevity of passive wetland treatment systems can be calculated for all components of the systems (ALD's, aerobic portions, and SAPS') but provides little comfort to those financially responsible for treatment. However, when chemical treatment is examined in this light the longevity question is just as applicable. Where passive treatment systems are limited by natural physical constraints (e.g., plugging of substrates and limestone, accumulation of Fe and other metals), chemical treatment systems are limited directly by operation and maintenance costs. Chemical treatment has been in place for about 16 years under the mandate of SMCRA. Generally, the only surviving treatment systems are those that are being operated by corporations able to withstand the economic burden of operating such systems. Total water treatment costs for the coal mining industry are estimated to exceed $1 million per day (Kleinmann 1989). The number of corporations that are still able to generate the funds necessary to operate and maintain their systems is rapidly dwindling. Operation and maintenance of these systems would then ultimately become the responsibility of the State and Federal Governments. Very little funding has been allocated for treatment systems by either of these entities, and the realization that chemical treatment would be cost prohibitive is apparent (Fabian 1993). Thus, while chemical treatment does provide the theoretical optimum treatment scenario the lack of funds necessary to maintain operation and the inability of most operators to treat to theoretical effectiveness with chemicals result in less than optimum AMD treatment.

A question that often follows the longevity concern is of passive wetland treatment limitations: What types of AMD discharges can be effectively treated? The quality of the AMD and the area relative to flow and quality have been the limiting factors in the past. Available area for passive wetland construction (as it relates to AMD flow and quality) is now the only real limiting factor. In situations where large flows of severe quality must be treated, physical limitations in regard to area must be considered. In some cases there is no recourse but to either combine chemical and passive treatment or utilize chemical treatment alone. Cases in which AMD flow and quality are actually limiting are relatively rare. In most instances, passive treatment systems will provide the proper solution to the AMD problem.

Quality of the AMD discharge was a significant factor in the past when only net alkaline and low metal contaminated waters were dealt with adequately (Burris et al. 1984). Recent technological advancements have allowed the treatment of net acidic, low pH, and high dissolved metal concentration AMD (see table 3). While these examples are relatively recent, the technology that has allowed these systems to function are based on well-known chemical, physical, and biological processes (Hedin et al. 1994, Stumm and Morgan 1970, Brodie et al. 1993).

The quality of some AMD discharges can still produce limitations when considering a passive treatment system design. Some AMD source qualities have yet to be incorporated into successful designs (i.e., high ferric iron and aluminum concentrations and high flows of fair to poor-quality AMD). The lack of successful treatment designs when dealing with certain AMD discharges is probably due more to the concentrations of past treatment efforts than to actual treatment limitations (Hedin et al. 1994). Through the perseverance of research-oriented institutions (e.g., U.S. Bureau of Mines and the Tennessee Valley Authority) and individual groups that are concerned with the restoration of waters affected by AMD, AMD that could not be treated passively a few years ago is now being treated effectively with passive systems (see table 3, Hedin et al. 1994). Passive treatment system technology is 15 to 20 years old, and large advancements have been made in the last 3 years. Significant water quality improvements in AMD discharges seem to be directly related to passive treatment system design (Brodie et al. 1993, Hedin et al. 1994, Kepler and McCleary 1994). Designs that rely on " black boxes," "magical " microbes, and "special" additives, or are implemented by individuals or organizations not familiar with the fundamentals of AMD treatment mechanisms are less reliable and have seriously affected the advancement of scientifically designed passive treatment systems.

Wieder (1989) examined 146 wetlands to determine if trends could be uncovered that would allow for *a priori* predictions as to the constructed wetland treatment efficiency. No trends were noted, which led Wieder to question the reliability and predictability of wetlands as acceptable treatment mechanisms. He was a spokesperson

Table 3. Water data and locations of three recently constructed passive wetland treatment systems.

Site location[1]	Sampling location	Flow, L/min	pH	Alkalinity, mg/L	Acidity, mg/L	Iron, mg/L
Damariscotta:[2]						
Schnepp Road....	Influent	54.5	3.2	0	300	45
	Effluent	---	7.0	56	0	2
USBM:[3]						
Howe Bridge[4]....	Influent DRI	137.0	5.87	32.0	507	307.12
	Influent PO	84.5	6.10	40.0	344	227.61
	Effluent	---	6.49	75.0	<10	47.68
USBM:[3]						
Orcutt/Smaill[4]....	Influent L1	135.6	5.84	107.0	275	199
	Influent R1	105.7	5.19	48.0	895	508
	Effluent	---	5.48	37.0	109	37.3

[1]All sites in Union Township, Jefferson, PA.

[2]Data from Damariscotta, 23 August 1993.

[3]U.S. Bureau of Mines laboratory data (4 May 1993, Orcutt/Smail; 27 July 1993, Howe Bridge).

[4]Two source discharges are present at both Howe Bridge, DRI and PO; and Orcutt/Smaill, L1 and R1. These discharges combine for one effluent discharge at both sites.

for OSMRE at the time of this publication, and his conclusions led regulatory agencies to question passive wetland treatment system approaches. The failure of this study to partition out designs that were based on sound scientific principles from those that were implemented by those unfamiliar with the basic principles led Wieder to the correct conclusions; namely, that a high degree of variability exists within the designs of passive treatment systems and as a result the predictability of such systems prior to implementation is small. Hedin et al. (1994) and Stark et al. (1990), in contrast to Wieder found that a great deal of predictability does indeed exist when passive treatment systems are examined that were designed on well-known principles. Kepler and McCleary (1994), when applying these basic principles in atypical fashion to AMD considered untreatable (passively), produced results consistent with these principles (see table 3). These recent advancements in wetland treatment system design indicate that passive wetland treatment systems are capable of treating a wide variety of AMD discharges to higher degrees of success than were previously believed possible (Hedin et al. 1994) and that the systems efficiency is predictable (Hedin et al. 1994, Kepler and McCleary 1994). A modification (fig. 1) of a U.S. Bureau of Mines flow chart provides *a priori* criteria necessary to predict passive wetland treatment system behavior. With these advancements in passive wetland treatment system technology, attempts are being made to apply these treatment devices as tools for watershed restoration.

Watershed Restoration of AMD-Affected Waters

The intent of water treatment in the past has been to preserve the quality of the receiving aquatic resources (Clean Water Act of 1972). The means through which this was to be accomplished were the chemical parameters set as standards by the EPA. These standards when met would theoretically preserve the quality of the receiving waterway. Under ideal conditions this goal would have been achieved; however, with limitations on funds

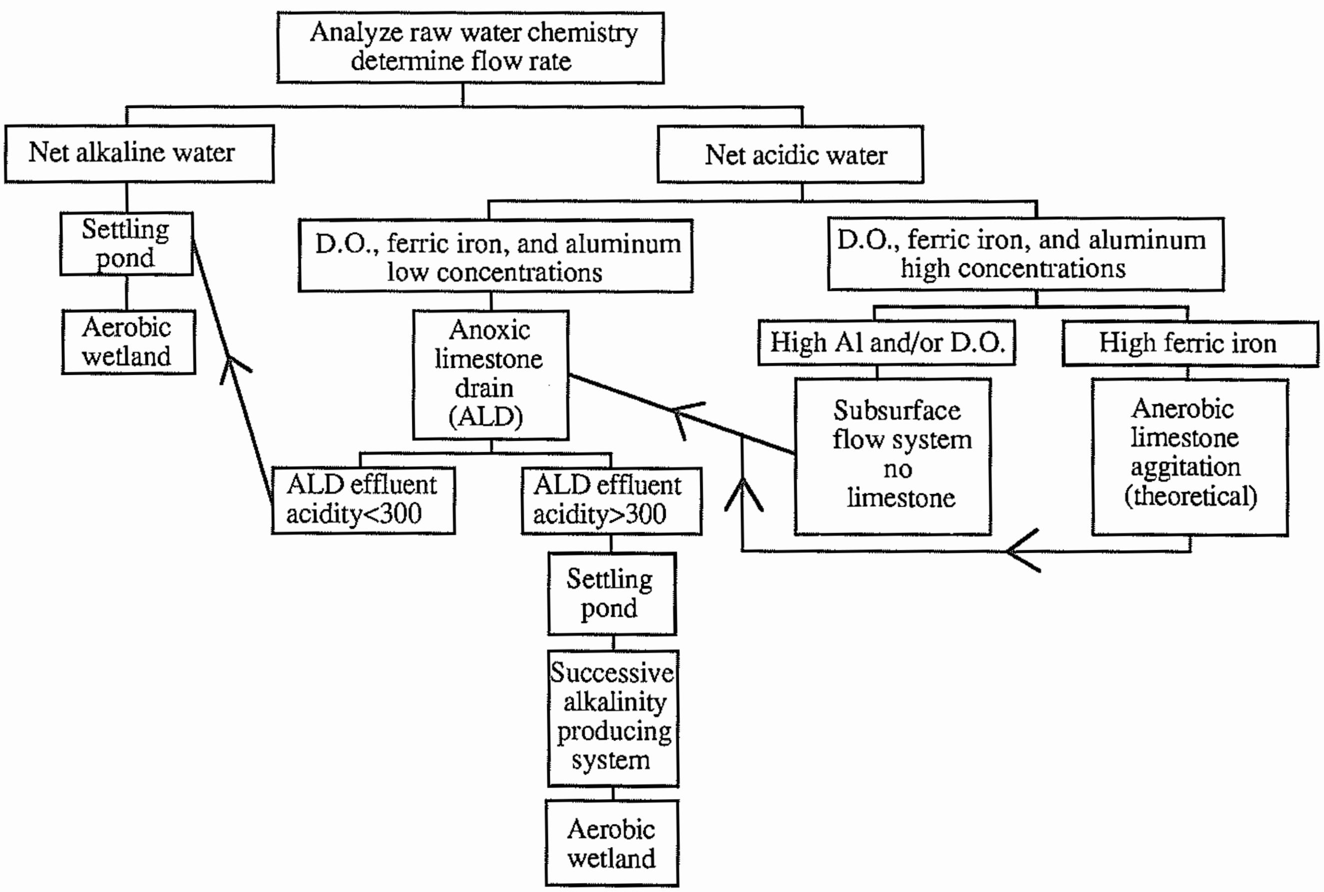

Figure 1. Flow chart showing dichotomous determinations necessary for design of passive wetland treatment systems. Adapted from Hedin et. al. (1994). D.O. dissolved oxygen.

necessary to implement and maintain treatment, these objectives were not met. In fact, the inability to react to the problem associated with these standard effluent criteria has arguably done more to negatively impact riparian health than it has to preserve the ecological health of existing waters (Environmental Protection Agency 1987, 1988a, 1988b, 1989a, 1990, General Accounting Office 1987).

Effective watershed restoration plans are being implemented by several watershed organizations in Pennsylvania, but the support from the regulatory agencies is instrumental in accomplishing the goals of these groups. This support is contingent upon the approval of treatment mechanisms that will be effective (cost and treatment) in abating AMD. The information presented in this paper suggests that passive treatment systems hold promise for such restoration efforts in terms of cost-effective, perpetual treatment. Passive treatment system efficiency can be predicted *a priori* (Hedin et al. 1994, Kepler and McCleary 1994), which can led to estimation of overall watershed impacts (McCleary and Kepler 1992).

A critical component of obtaining approval and implementing successful restoration programs is the ability to define success. Success is currently defined as the ability of the treatment mechanism to meet the Federal Clean Water Act (enacted 1972) mandate that all coal mining point source discharges meet water quality standards set by the EPA. While this definition of success seemingly incorporates an ecological component by proxy, the generality of the criteria does not account for local geographic variations, biological sensitivity, and/or cumulative impacts. Thus, treatment success is limited to the effluent of the treatment system with little regard for the receiving waterways.

Chemical and physical indicators have been the standard by which most forms of water pollution have been assessed (Karr 1991). AMD has not been an exception to this policy and despite massive regulatory efforts, continual declines in water quality and quantity have prevailed (Environmental Protection Agency 1987, 1988a, 1988b, 1989a, 1990, General Accounting Office 1987). A paradigm shift appears necessary in the monitoring and assessment of water resources from the chemical and physical to one that incorporates more of the biological component (Environmental Protection Agency 1984, 1987, 1988a, 1989b, 1989c) if watershed restoration is to become a reality. Some (Van Putten 1989) call directly for the development of biological criteria to protect water resources from negative impacts.

Restoration efforts require that all aspects of the environment associated with the water resource be measured in some capacity to provide an objective assessment of the restoration success. In some cases meeting a pH of 6.0 may not be necessary for the ecological recovery of the ecosystem, especially when background waters are typically less than 6.0. In other cases the addition of alkaline materials in sufficient quantities to neutralize the effects of the contaminants may actually contribute more to the receiving stream degradation than is easily observable.

Importantly, since restoration efforts are generally considered from a holistic standpoint, a measurement that incorporates many different types of parameters from the affected system should provide a more robust measurement of treatment success. The reduction of the definition of success to a few water quality parameters that may or may not reflect regional geographic and biological differences is not ecologically sound and may actually have contributed to the degradation of the riparian ecology in coal regions of Appalachia.

A primary concern of passive wetland treatment systems for AMD treatment is the ecological recovery of the streams affected by AMD. Recent data suggest that passive wetland treatment systems not only provide for water treatment, but can act to increase ecological recovery of the immediate area and when used strategically may act as an effective watershed management tool in areas affected by AMD (McCleary and Kepler 1992, Hedin et al. 1994, Williams and Dalby 1993) The restoration of the ecology in these devastated watersheds would provide positive impacts associated with the aquatic resources in these areas.

We are at a junction in AMD abatement that requires a definitive decision as to types of treatment mechanisms and scope of overall treatment. With the number of waterways that have been negatively impacted by AMD the scope of the problem is seemingly monumental. The cost of treatment is unrealistic if conventional chemical treatment is considered alone (Kleinmann 1989), and passive treatment cost is significant if all problems are considered collectively. For example, if each AMD discharge averages $20,000 to implement passive treatment and there are 1,000 discharges in the affected watershed then $20 million would be necessary to implement an abatement program for this watershed. Recent projections (U.S. Army Corps of Engineers 1981) have estimated restoration of AMD affected waters in the Clarion River Basin, located in western Pennsylvania, at $120 million (this study did not account for water treatment, only surface reclamation, which would have increased this figure easily twofold.) Restoration programs would necessarily have to examine the benefit-to-cost ratio of the restoration before funds could be allocated for such projects. Recent conversations with the U.S. Department of Agriculture (Duncan 1993) suggest that the cost-benefit ratio for AMD watershed restoration would easily be higher than that normally required to initiate remedial actions (1.2 to 1.0).

Summary

The all-or-nothing response from the regulatory agencies in the coal mining regions of Appalachia must be reevaluated if ecological restoration is our goal. Years have passed with little being done to abate the AMD problems of this region, yet the technology exists that can positively impact streams receiving AMD. Passive wetland treatment systems , while not currently a solution for 100% of the AMD problems, hold the greatest promise for the effective, long-term treatment of such waters. While passive treatment systems may not always be consistent with current effluent criteria, their application as a tool for watershed management and restoration is great. Recent activities utilizing passive treatment systems as an approach to watershed restoration have met with great success. The restoration of thousands of kilometers of streams and hectares of impoundments in the Appalachian coal regions, affected by AMD, is dependent on the success of these early restoration efforts. The ability to objectively demonstrate that these restoration attempts will significantly enhance the quality of the receiving environment is imperative. Success must not be indicated by a few chemical parameters but a consideration of the intent of the Clean Water Act (1972), which includes secondary ecological benefits associated with passive wetland treatment systems. The secondary benefits associated with these systems include water resource recovery, wildlife habitat and restoration, and educational values.

Literature Cited

Appalachian Regional Commission. 1969. Acid mine drainage in Appalachia. U.S. Congressional House Document No. 91-180. Volumes I-III, Appendix C.

Brodie, G. A. 1993. Staged, aerobic constructed wetlands to treat acid drainage: case history of Fabius Impoundment 1 an overview of the Tennessee Valley Authority's program. p. 157-167 . In G. A. Moshiri (ed.), Constructed Wetlands for Water Quality Improvement. CRC, Florida.

Brodie, G. A., C. R. Britt, T. M. Tomaszewski, and H. N. Taylor. 1993. Anoxic limestone drains to enhance performance of aerobic acid drainage treatment wetlands: experiences of the Tennessee Valley Authority. p. 129-139. In G. A. Moshiri (ed.), Constructed Wetlands for Water Quality Improvement. CRC, Florida.

Burris, J. E., D. W. Gerber, and L. E. McHerron. 1984. Removal of iron and manganese from *Sphagnum* moss. p. 1-13. In J. E. Burris (ed.), Treatment of Mine Drainage by Wetlands. Contribution 264. Dept. of Biology. PSU, University Park, PA.

Fabian, T. 1993. personal communication. Deputy Secretary, Department of Environmental Resources. Harrisburg, PA.

Duncan, R. 1993. personal communication. Pennsylvania Director, USDA. Harrisburg, PA.

Environmental Protection Agency. 1984. Water quality standards handbook. Office of Water Regulations and Standards. U.S. EPA. Washington, D. C., USA.

Environmental Protection Agency. 1987. Surface water monitoring: a framework for change. Office of Water, Office of Policy Planning and Evaluation. U.S. EPA. Washington, D. C., USA.

Environmental Protection Agency. 1988a. WQS draft framework for the water quality standards program. Draft 11-8-88. Office of Water, U.S. EPA. Washington, D. C., USA.

Environmental Protection Agency. 1988b. Future risk: research strategies for the 1990s. SAB-EC-88-040.Science Advisory Board. U.S. EPA. Washington, D. C., USA.

Environmental Protection Agency. 1989a.Water quality standards for the 21st Century. Office of Water. U.S. EPA. Washington, D. C., USA.

Environmental Protection Agency. 1989b. Impact of regulatory programs. U.S. EPA. Washington, D. C., USA.

Environmental Protection Agency. 1989c. Nonpoint sources: agenda for the future. Office of Water. U.S. EPA. Washington, D. C., USA.

Environmental Protection Agency. 1990. Biological criteria: national program guidance for surface waters. EPA-440/5-90-004. Office of Water Regulations and Standards. U.S. EPA. Washington, D. C., USA.

General Accounting Office (GAO). 1987. The nation's water: key unanswered questions about the quality of rivers and streams. GAO/PEMD-86-6.

Hedin, R. S., R. W. Nairn, and R. L. P. Kleinmann. 1994. The passive treatment of coal mine drainage. USBM IC, in press.

Karr, J. R. 1991. Biological integrity: a long-neglected aspect of water resource management. Ecological Applications 1(1): 66.

Kepler, D. A. and E. C. McCleary. 1994. Successive alkalinity producing systems (SAPS) for the treatment of acidic mine drainage. In Proceedings of the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage. (Pittsburgh, PA, USA, April 24-29, 1994). http://dx.doi.org/10.21000/JASMR94010195

Keystone Coal Industry Manual. 1987. 1987/1988 Coal mine directory (United States and Canada). McGraw-Hill. New York.

Kleinmann, R. L. P. 1989. Acid mine drainage. Engineering and Mining Jour. 190:16I-16N.

McCleary, E. C. and D. A. Kepler. 1992. The use of constructed wetlands as a tool for watershed restoration. In Proceedings of the Society of Wetlands Scientists 13th Annual Meeting. (New Orleans, LA, USA, May 23-31, 1992).

Stark, L., E. Stevens, H. Webster, and W. Wenerick. 1990. Iron loading, efficiency, and sizing, in a constructed wetland receiving mine drainage. p. 393-401. In J. Skousen, J. Sencindiver, and D. Samuel (ed.), Proceedings of the Mining and Reclamation Conference and Exhibition: Volume II. http://dx.doi.org/10.21000/JASMR90020393

Stumm, W. and J. J. Morgan. 1970. Aquatic chemistry. Wiley, New York. 583 p.

U. S. Army Corps of Engineers. 1981. Clarion river basin: acid mine drainage abatement program. Phase I General Design Memorandum October 1981. Volume 1, Main Report.

Van Putten, M. 1989. Water quality standards for the 21st century. p. 175. In G.H. Flock (ed.), Office of Water, U. S. Environmental Protection Agency. Washington, D.C., USA.

Williams, J. and P. Dalby. 1993. personal communication. Biology Dept., Clarion Univ. of PA. Clarion, PA, USA.

Wieder, R. K. 1989. A survey of constructed wetlands for acid mine drainage treatment in the eastern United States, Wetlands 9(2):299-310. http://dx.doi.org/10.1007/BF03160750