Natural Resource Extraction: Modern Remediation Techniques in Response to Acid Mine Drainage

by

Matthew Horine

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ABSTRACT

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The solid and liquid wastes generated from modern and abandoned mine sites can contain materials that aid in the production of Acid Mine Drainage (AMD). AMD is a source of water pollution and environmental degradation for areas around the world with historic and modern natural resource extraction operations. As the formation and impacts of AMD are better understood, the development of site specific remedial methods continually evolves.

Currently in the United States there are several governmental agencies that tend to the management of active mines and the reclamation of abandoned or closed mine sites. With water quality limitations enforced, recommended management techniques are implemented using a range of remedies such as active (i.e., involving chemical and mechanical inputs), passive (i.e., utilize natural processes), and source control treatment methods. Active and passive methods tend to pool and remediate already impacted mine effluent, while source control methods avoid the creation of polluted discharge. As each mine will differ regarding physical characteristics, the criteria for deciding on a treatment method will vary greatly among site specific needs.

The intent of this project is to present a simple perspective on the advantages and disadvantages of modern techniques used to mitigate acid mine drainage. It will also contain a brief history of the governmental agencies created in response to abandoned and surface coal mines within the Appalachian region.

BIOGRAPHY

Matthew Horine is a graduate student at North Carolina State University fulfilling the requirements for the degree of Master of Environmental Assessment. He has a B.Sc. in Earth Science with a minor in Geology from the University of North Carolina at Charlotte. He has also worked in the professional fields of aircraft maintenance, environmental health & safety, environmental consulting, and iron ore/coal mining.

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INTRODUCTION

The impacts associated with disturbing ancient geologic formations can have devastating environmental and social consequences without proper governmental oversight. The modern globalization of resource extraction has left budding societies overwhelmed and unprepared for mining's environmental cost, while also leaving abandoned mines and societies overwhelmed and unprepared for environmental reclamation. Unfortunately, the damage caused by three centuries of large scale mining has only begun to be addressed within the last twenty-five years.

In the United States, as of 1977, the Surface Mining Control and Reclamation Act (SMCRA) has enforced state or federal limitations on coal mining effluent (OSMRE). Mandatory compliance with the limitations is conducted to minimize the disturbance to areas outside of the permitted zone. Enforcing the water regulations is paramount due to the acidic and metal dissolution concentrations in surface and groundwater being the most prominent threat created by active and abandoned mines (Johnson and Hallberg, 2005). The dissolved metals can raise heavy metal concentrations beyond harmful levels in organisms and plants living within affected areas. High concentration levels can negatively affect biota by means of bioaccumulation and eventually lead to toxicity. As fish and plants are consumed by humans, the bioaccumulation of heavy metals can pose a toxic risk to local communities and downstream populations.

However, the exposure of these heavy metals to the elements also causes a chemical reaction described as Acid Mine Drainage (AMD) or Acid Rock Drainage (ARD). This acid generating phenomena occurs due to the oxidation of pyrite, but the process becomes complex due to varying geochemical and physical characteristics of individual mine sites. Yet, the acidic waters continue to be problematic world wide as their low pH enables the dissolution and transportation of highly concentrated heavy metals to areas outside of mining zones.

In order to mitigate the problem of AMD, there have been several techniques developed to clean contaminated water. The techniques are generally broken down into active, passive, or source control treatment systems. Active treatment technologies will tend to involve the input of energy and chemicals within a treatment facility, whereas passive systems will tend to use only natural processes such as gravity, microorganisms, and vegetation systems. Source control methods are developed to inhibit the initial creation of AMD by diverting or neutralizing unaffected waters.

The type of treatment chosen at the mine will depend heavily on local environmental factors such as the climate, lithology, and area available. Other factors include the extent of contamination in the water, the type of contaminant that must be removed, the volume of water requiring treatment, and the required discharge water quality. Since no two mining sites will be identical, the steps towards water reclamation will require independent approaches per mining scenario.

BACKGROUND

History of the SMCRA

Prior to 1977, there were few states requiring environmental regulations on abandoned and active coal mining sites (EPA BMP, 2002). The Surface Mining Control and Reclamation

Act (SMCRA) was enacted in 1977 after the U.S. Congress recognized the need for federal regulation regarding coal mining activity, rehabilitation of abandoned mines, and protection of society and the environment from the adverse effects of mining operations. In order to help pay for this act, the SMCRA created a system requiring mining companies to contribute to bonds for land rehabilitation and environmental damages caused by the mining activities through a series of taxes on a per ton basis (OSMRE). The act simultaneously created a regulatory program, the Office of Surface Mining Reclamation and Enforcement (OSMRE) under the U.S. Department of Interior, to oversee the implementation of the SMCRA at coal surface mines.

The SMCRA program was designed to regulate surface mining operations, as well as controlling and reviewing state & tribal mining programs. It was also tasked with overseeing abandoned and surface mine land reclamation, while also conducting environmental regulation enforcement when necessary (OSMRE). However, as of today most coal producing tribes & states, with the exception of Washington and Tennessee, now self operate and enforce the regulations pertaining to active surface mining operations, while OSMRE focuses on an oversight role.

Abandoned Mine Lands Reclamation Program

Although OSMRE operates in an administrative role regarding active coal mining, the Abandoned Mine Land reclamation program (AML) continues to be OSMRE's primary focus and responsibility under the SMCRA. Since the signing of the SMCRA in 1977, the AML program has collected over $10.1 billion in fees (fees as of 2002, $0.315/ton for surface extraction & $0.135/ton for underground extraction) from coal production (EPA BMP, 2002). Of this money collected, the office has allocated upwards of $7.6 billion in grants to states, tribes, and the United Mine Workers of America. Additionally the money has been distributed to OSMRE's operation to reclaim and rehabilitate land and waters harmed by pre-1977 coal mining (OSMRE). Since the implementation of the Surface Mining and Control Act of 1977, the AML and coal industry have reclaimed or restored over 1.5 million acres of land disturbed by coal mining in the Mid-Appalachian region (OSMRE, 1997).

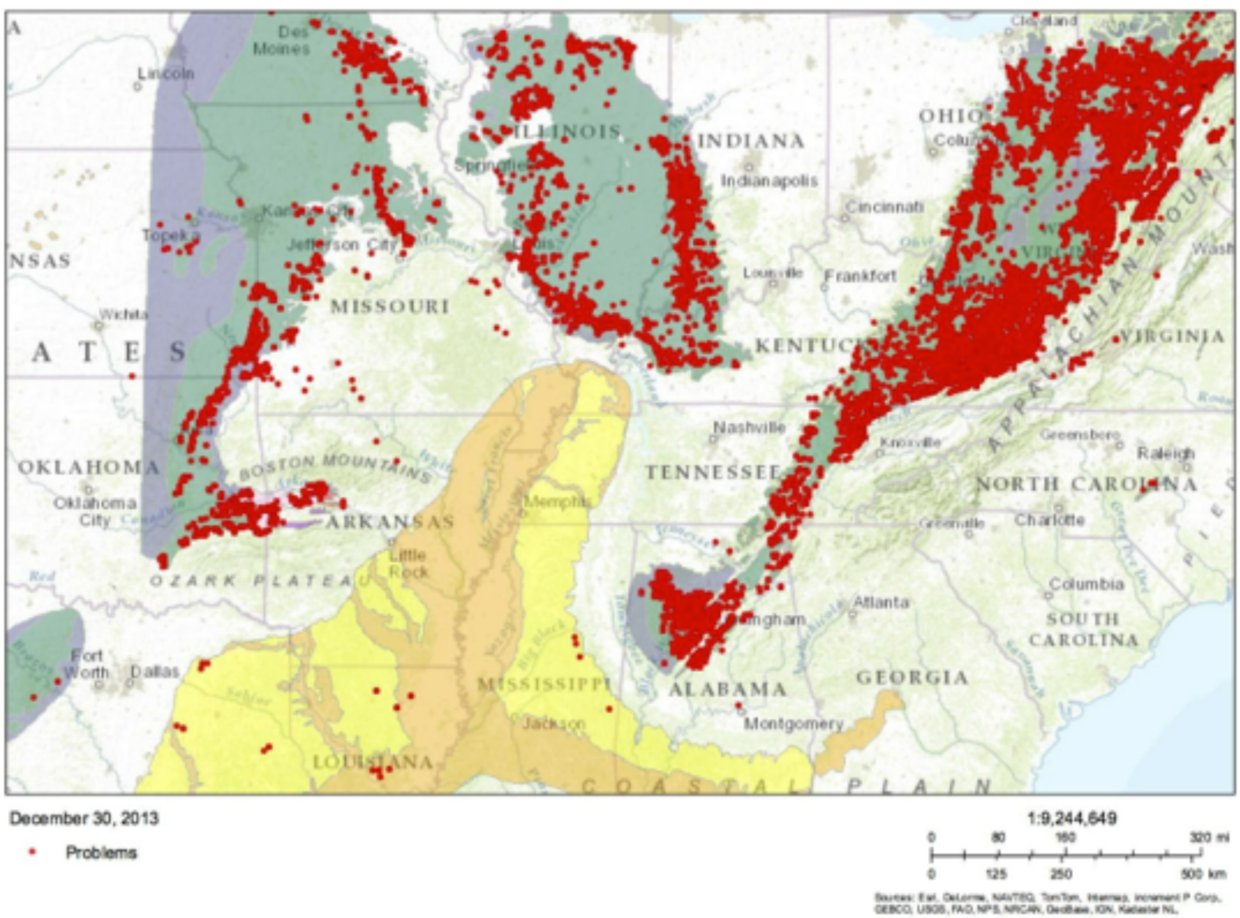


Fig. 1 Current abandoned mine sites (indicated with red dots) within the Midwest and Appalachian Region according to OSMRE's Abandoned Mine Land Inventory System.

Since the inception of the tax levy on coal production in support of the AML fund, many western states have worried that their coal production fund contributions would be used to finance reclamation and rehabilitation projects in the eastern U.S., where most abandoned mine reclamation projects take place (Costello, 2003). Due to this recognized inequality a compromise between the federal and state governments has recognized the need to allocate 50% of the collected fees generated by any particular state to be invested back into the rehabilitation and reclamation projects within the contributing state (Bamberger, 1997).

Despite progression in government regulation, industrial fee collection, and abandoned mine land reclamation efforts, there are more than $3 billion worth of high priority sites requiring reclamation in OSMRE's e-AMLIS inventory (Figure 1). In addition to the high priority sites, there are concerns with overlying deep mining sites that are not listed in OSMRE's e-AMLIS system. While it is believed that these areas are not currently posing a danger to life or property, they do have the potential to be reclamation priorities as they continue to degrade and intensify in the future (OSMRE). The Mineral Policy Center, a non-profit organization, estimates that roughly 557,000 abandoned mines are still located within the United States (Mineral Policy Center, 2003) and may need future financial assistance.

Addressing AMD

In a response to mitigating future overburdening costs for the government and mining companies, modern environmental regulations concentrate heavily on avoidance and reclamation in an attempt to curb AMD production during active mining operations. The methods utilized for operational mines tend to use active treatments involving aggressive chemical additives (Costello, 2003). The benefit of these methods allows a company to be flexible with treatments regarding varying mineral concentrations of effluent during the different stages of mining. Alternatively, passive treatment methods tend to be employed at abandoned or closed mines due to the more consistently homogenous mine effluent. The advantage of having chemically consistent mine effluent allows for methods requiring less maintenance and subsequently lower overhead costs.

Modern efforts have cut AMD affected streams by roughly 50% since the inception of AML in 1977 (Bandy, 2007). Table 1 summarizes the miles and associated areas of streams within the midwest and Appalachian regions that were still affected by AMD as of 1998 (EPA BMP, 2002). The stream miles are self reported by states, but given the massive amount of unaccounted for abandoned mines in the U.S., the table below might not represent the full extent of acid mine drainage.

State	Stream Miles (IMCC, 1998)	Stream Miles (State 303(d) lists, 1998)*
Alabama	65	50 + 444 acres
Illinois	NA	- -
Indiana	0	- -
Kentucky	600	141 + 219 acres
Maryland	430	- -
Missouri	139	- -
Ohio	1,500	- -
Pennsylvania	3,000	2,149

State	Stream Miles (IMCC, 1998)	Stream Miles (State 303(d) lists, 1998)*
Tennessee	1,750	726 + 510 acres
Virginia	NA	44
West Virginia	2,225	2,019
Totals	>9,709	>5,129 + 1,169
	*Includes lakes and reservoirs affected by AMD.	

Table 1. Stream miles affected by AMD within the United States.

ACID MINE DRAINAGE

Acid mine drainage (AMD) primarily affects surface water bodies and groundwater. These disturbed waters characteristically have lower (<6 pH) than normal pH levels (~6.5 - 8.5 pH), as well as containing high concentrations of sulfate, dissolved iron, and other metals (e.g., aluminum, manganese, copper, and lead) (EPA BMP, 2002). The low pH or high metal concentrated (total or dissolved) water conditions will generally not support fish or aquatic life due to the inherent toxicity of the water. Even if the acid is neutralized by carbonate minerals (typically calcite or dolomite), the dissolved metals will precipitate out of solution and line the stream bed in a solid form (EPA BMP, 2002). This scenario again doesn't allow for aquatic life to survive due to the blanketing of oxygen generating macrophytes. It also impacts the usable water supply for domestic, industrial, and recreational purposes.

Simply put, AMD forms from the oxidation of pyrite (FeS_2) and other sulphidic minerals being exposed to oxygen and water (Costello, 2003). Unfortunately for mining companies and local environments, pyrite happens to be the most abundant sulfide mineral on the planet (Johnson and Hallberg, 2005). In the case of the Appalachian coal industry, coal deposits will contain varying (normally 1–20%) amounts of "pyritic-sulfur" including organic sulfur (Johnson and Hallberg, 2005). The oxidation of these sulphidic minerals is a natural part of the weathering process. The process, however, is generally slow when in its natural unearthed state due to the undisturbed nature of the ore (lack of contact with air and water). Yet, the natural reactions leading to AMD will be exacerbated as resource mining tends to move massive amounts of underground earth to the surface. The unearthed orebodies will now have larger surface areas exposed to both air and water, and thus increasing their oxidation rates (EPA BMP, 2002).

The primary reactions managing the oxidation of pyrite are presented below (Behrooz, 2012, Singer & Stumm, 1970). However, the reactions have been labeled as somewhat misleading in that the primary oxidant involved in pyrite oxidation in most situations is ferric iron rather than molecular oxygen. Also, the multiple procedure process of pyrite oxidation involves an oxygen-independent reaction and also oxygen-dependent reactions (Evangelou, 1995).

Reaction 1.1 $FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$

Reaction 1.2 $Fe^{2+} + O_2 + H^+ \rightarrow Fe^{3+} + 0.5H_2O$

Reaction 1.3 $FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

Reaction 1.4 $Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$

Reaction 1.5 $2FeS_2 + 15/2O_2 + 7H_2O \rightarrow 2Fe(OH)_{3(s)} + 4SO_4^{2-} + 8H^+$

To summarize the reactions above, the ferrous iron in reaction 1.1 is produced by the oxidation of pyrite with dissolved oxygen, creating sulfate and a solubilized ferrous iron. The ferrous iron will then oxidize to produce ferric iron in reaction 1.2. The ferric iron will become an oxidant of pyrite, which creates a release of H^+ and subsequently lowers of the solution's pH in reaction 1.3. Reaction 1.4 shows the development of iron hydroxide via the hydrolysis of ferric iron. Finally, the reaction 1.5 shows the complete oxidation of pyrite, including the precipitation of iron hydroxide (Behrooz, 2012, Singer & Stumm, 1970).

The oxidation of sulfidic pyrite influences coal mining since operations typically leave some sulfide minerals (especially pyrite) in the waste spoil piles, tailing rocks, or unmineable coal seams (Costello, 2003). These wastes are often buried underground or left exposed at the surface once a mine has closed. Allowing water to pass through acid-producing, heavy metal concentrated material in the mining site can generate high acidity, while suspending or generating dissolved metals. This most notably causes streams and lakes to turn a red or yellow color from the precipitation of ferric hydroxide (reaction 1.5) which precipitates between pH levels of 2 - 4 (Figure 2). It also poses a threat to human health and natural ecosystems through its harmful characteristics. This visually observable effect of iron precipitate is known as "yellow boy".

Fig. 2 Ferric hydroxide (pictures a and b) gradually precipitates out of solution before confluence within another stream (picture c) (Behrooz, 2012).

BEST MANAGEMENT PRACTICES

1. Active Water Treatment

Active water treatment is the most common type of water treatment method at working mines (Zinck and Griffith, 2013). As mentioned earlier, active water treatment technologies will tend to involve the input of energy and chemicals to alleviate AMD associated issues. Such water treatment technologies typically include the addition of lime, limestone, or caustic soda to raise the pH of the mine effluent (Wolkersdorfer, 2008). Once the pH has been elevated from the addition of the appropriate amount of alkaline material, dissolved metals precipitate out of solution and sink to the bottom of settling or sedimentation ponds located on site. The concentration of metals allows for their easier removal in a solid state form.

Operational mine sites will expect changing conditions within their mine effluent due to the mineral makeup of varying geologic layers that are processed. Active treatment technologies allow companies to be responsive and precise to changes in water quality by utilizing immediate effective treatments, such as:

- chemical / (bio)chemical additions;
- aeration processing;
- sorption and ion exchange;
- membrane filtration processes.

Another benefit to active treatment technologies is its ability to process high water flow inside relatively small areas(Costello, 2003). Active treatment plants can also process high water flow situations quicker, while also allowing for accurate and active monitoring within an industrial setting.

A drawback to the utilization of active treatment is the eventual concentration of the sludge by-product produced during treatment. Unfortunately, the sludge has limited economic worth and will often be managed as waste. The costs associated with handling this waste increase dramatically in instances where the sludge by-product becomes highly composed of cadmium or arsenic (EPA BMP, 2002). In this case the sludge must now be classified as hazardous waste and will require special handling and disposal.

In addition to disposal costs, high costs associated with the maintenance of the treatment facility and supply of reagents needed for the reactions have warranted the exploration of various methods to reprocess the sludge for further use. Some methods have led to salvageable iron or other metal concentrations from mine effluent, whereas others have recycled neutralizing agents (alkaline material) for further active treatment methods. The benign material can also act as general fill for construction purposes around the mine, or within the agricultural industry (e.g., fertilizer) (Johnson and Hallberg, 2005).

1.1 Chemical Treatment

Among mine operations in North America, the prevailing method of active treatment concerning AMD is the addition of alkali reagents to the effluent (Zinck and Griffith, 2013). The created chemical solution converts the hazardous aspects of the water (low or high pH and metal concentrations) into a less environmentally damaging medium by precipitating out metals and neutralizing the pH level. However, since mines will have different types and amounts of metals being discharged due to varying lithology, and also considering metals precipitate at different pH levels, chemical treatments will vary according to each mine's mineral makeup and discharge limitations.

As the most often utilized reagent, hydrated lime is particularly useful and cost effective in high-flow, high-acidity situations. This is due to its low cost efficiency in solids/water separation, and high density waste sludge production (Skousen et al. et al., 1998). The initial capital investment cost of a hydrated lime treatment plant is often high due to the meticulous engineering / maintenance that must be done to the lime slurry piping, namely preventing the product from congealing on the sidewalls. However, once this engineering problem is alleviated, hydrated lime becomes a cost effective method of chemical treatment (Skousen et al. et al., 1999).

Estimated costs for hydrated lime are calculated by comparing the tonnage needed to neutralize a ton of acidity. In the case of hydrated lime, it requires roughly 0.74 ton / ton of acidity and has a cost estimate of $60 - 100 / ton of lime (Skousen et al., 1999). Skousen (1999) also gave an example of a stream with a flow of 1,000 gpm and an acidity concentration of 100 mg/L. The calculation took into consideration the maintenance costs, installation costs, and the net value from the treated waters. The calculation yielded an annual cost of roughly $54,200.

In instances where a short residence time is given for metal precipitation within settling ponds, chemicals known as coagulants or flocculants are also added in order to combine smaller particles into larger clumps by means of reducing net electrical repulsive forces at the particle surfaces or bridging particle spaces with additive chemicals (Skousen et al. et al., 1999). The additives hasten the settling process, and allow for smaller area settling ponds to be used on site due to the lowered residence time required for influent.

Depending on the regulated water quality (e.g., EPA limitations for wastewater treatment in Table 2), a mine may also use other active treatment technologies including ion exchangers, membrane filters, and reverse osmosis (Younger et al, 2002). Once the targeted semi-solid contaminant or sludge has been removed from the water, it is dried and processed as waste. Depending on the chemical makeup of the waste, it can be used further as a neutralizer in active treatments or stored within the mine (Wolkersdorfer, 2008).

Parameter	**Total Metal Concentrations** (30-day average)
Iron	3.5 mg/L
Manganese	2.0 mg/L
pH	6-9 pH units

Table 2. EPA limitations for treatment of wastewater from coal mines in 40 CFR 434.

1.2 Aeration Treatment

In the case of water containing low dissolved oxygen levels, active aeration treatment will be utilized predominantly for the oxidation of iron and manganese (Zinck and Griffith, 2013). Without the gravity driven or mechanical aeration (rotating blades positioned under the water in an aeration basin), ferrous iron's conversion to ferrous hydroxide wouldn't allow for precipitation until pH ≥ 8.5 (Skousen et al., 1999). The delayed precipitation would require larger quantities of alkaline reagents to raise the water's pH for stabilization and precipitation. Whereas in the presence of dissolved oxygen, ferrous iron will oxidize to ferric iron, which then forms ferric hydroxide. As discussed earlier, ferric hydroxide has the ability to precipitate at pH ≥ 3.5. The accelerated oxidation of ferrous iron to ferric iron will require less alkaline loading material to precipitate iron and other metals from the AMD (Johnson and Hallberg, 2005).

Although this process will allow for a significant portion of iron to precipitate out of the water and effectively mitigate the creation of acid mine effluent within a controlled setting, there are metals that will need a higher pH level for precipitation. Table 3 shows the varying pH levels at which metal hydroxides will precipitate while at a certain concentration, notice the 10+ pH for manganese. Again, the chemical dosage needed for AMD reclamation will adhere to the site specific chemical make-up (e.g., pH levels, metal concentrations) and will also depend on the effluent metal composition and the regulatory discharge limits of those metals.

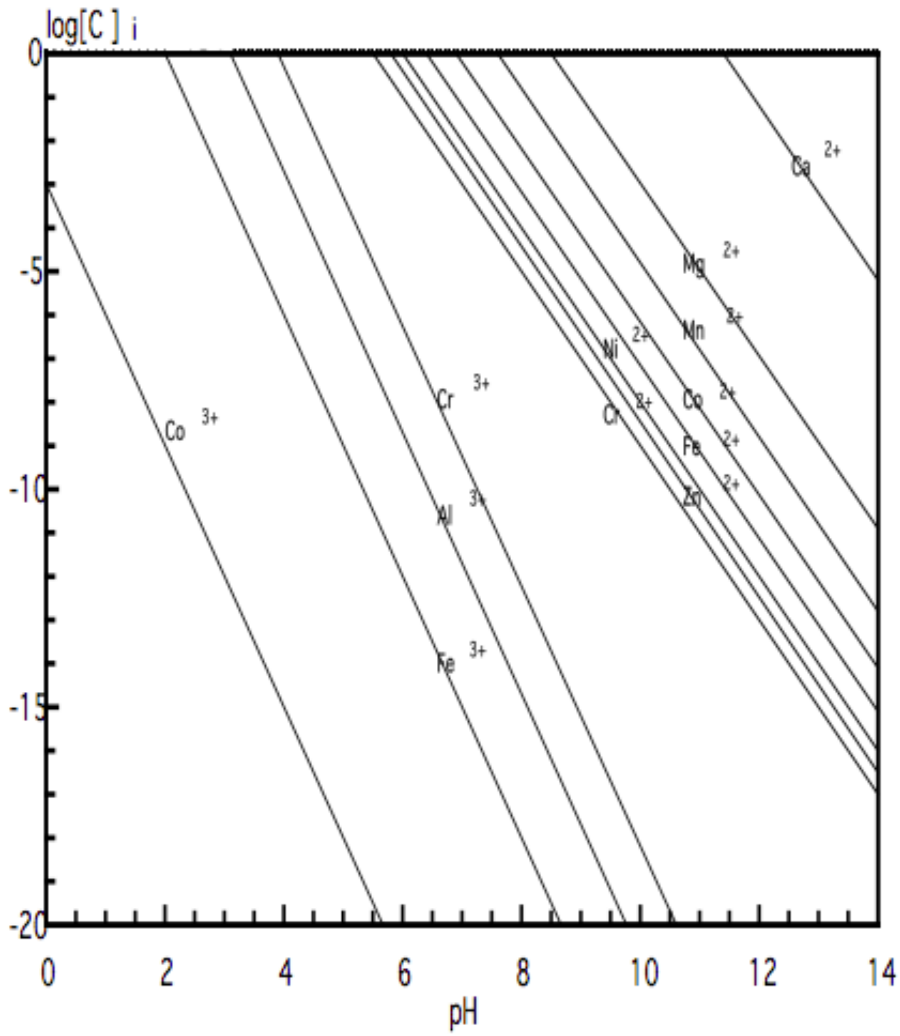


Table 3. Theoretical pH level for metal hydroxide precipitation.

2. Passive Water Treatment

Passive water treatment methods are techniques that treat acid mine drainage without the continual and active additions of biological/chemical reagents or the application of external energy (Zinck and Griffith, 2013). Passive water treatment methods are best known for their extensive and successful application in the treatment of municipal wastewater and urban runoff. However, passive treatment's utilization and development in the mining industry is still new and unfolding due to a series of challenges, namely treating highly acidic or high metal concentrated effluent in remote areas with varying climates. Despite these challenges, relatively low operational and maintenance costs continue to generate interest in passive water treatment.

Capital costs of a treatment system like a passive wetland are estimated to be roughly $0.32 - $0.46 per kilogram of metal removed as compared to an active method at $0.66 - $0.89 per kilogram of metal removed (Ford, 2003). Between the cost savings, low required maintenance, and ability to process homogenous effluent, passive treatment technologies can be the ideal scenario for abandoned or closed mine sites.

Of the passive water treatment methods, constructed wetlands are the most frequently utilized form of bioremediation technology. The most common abiotic method is anoxic limestone drains (Younger et al, 2002). Other forms of passive technologies include:

- aerobic wetlands;
- anaerobic wetlands;
- natural aeration;
- settling ponds;

- limestone drains.

As with active water treatment technologies, passive treatments must also account for maintenance, treatments, and evaluations (Wolkersdorfer, 2008) such as dredging, waste disposal, and water body monitoring. Passive systems will also generate hazardous and benign materials that will need eventual storage and disposal. In addition to these costs, passive water treatments require large surface areas and topographically stable environments to accommodate structures such as wetlands. This may be problematic to mining companies that are based within mountainous regions, as large amounts of flat land or stable climate conditions might be difficult to obtain.

2.1 Wetland Ponds

The goal of using a wetland is to decrease the acidity, dissolved metals, and sulfate concentrations in mine effluent by using microorganisms to generate alkalinity and immobilize metals. The processes generating the alkalinity are generally reductive processes, including denitrification, methanogenesis, sulfate reduction, and iron & manganese reduction (Johnson and Hallberg, 2005). These bioremediating processes are broken down into aerobic and anaerobic wetlands.

<u>*2.1.1 Aerobic Wetlands*</u>

The aerobic wetland is predominantly used with waters having net alkalinity (Costello, 2003). It is designed to encourage the oxidation of ferrous iron and hydrolysis of ferric iron (see reactions below) by allowing the effluent long detention times and water aeration. The reaction of the oxidation and hydrolysis event produces acidity and lowers the pH of the effluent water in the wetland, allowing for the precipitation of ferric hydroxide and other metals (Johnson and Hallberg, 2005).

$4Fe^{2+} + O2 + 4H^{+} > 4Fe^{3+} + 2H_2O$

$4Fe^{3+} + 12H_2O > 4Fe(OH)_3 + 12H^{+}$

The surface-flow system is a wetland design that inhibits the water's interaction and permeation with the wetland soil (Skousen et al. et al., 1999). To stabilize surface flow and prevent channeling within the wetland, typha are planted in the shallow system. Aerobic systems typically have a total depth of less than 30 cm (Ford, 2003). Not only do wetland plants help encourage uniform flow of the water movement and aeration, but they also act as a filter regarding the accumulation of ferric and other metal precipitates (Johnson and Hallberg, 2005). Additionally, some macrophytes are able to circulate oxygen from their aerial parts to their root systems, which in turn may accelerate the rate of ferrous iron oxidation due to the increase in the water's dissolved oxygen (Johnson and Hallberg, 2005).

The conceptual design of an aerobic wetland is done by estimating the loadings of metals or acidity in grams per square meter per day. Aerobic wetlands are built to withstand 10 g/m^2/day Fe and 0.5 g/m^2/day Mn to achieve the EPA effluent limitations of 3 mg/L Fe and 2 mg/L Mn over a 30 day average period (Ford, 2003). As an example, if the Fe influent concentration was 300 g/day, one would divide 300 g/day by 10 g/m^2/day to get 30 m^2. This 30 m^2 area is the required size an aerobic wetland in order to effectively treat mine effluent with such an incoming daily concentration.

2.1.2 Anaerobic Wetlands

As opposed to the aerobic wetland, the anaerobic wetland is generally used to neutralize net acidic waters and reduce metals to the sulfide form. Aerobic wetlands are also commonly referred to as compost bioreactors (Johnson and Hallberg, 2005). The compost bioreactor is a generic term given to a closed system that is below ground level and does not provide a livable environment for macrophytes.

The anaerobic wetland is designed to have effluent pass through a relatively deep (~1 m), permeable and anoxic organic substrate (compost) as seen in Figure 3 (Johnson and Hallber, 2005). The breakdown of the compost materials acts as a substrate for the native iron and sulfate reducing bacteria. This bacteria will also reduce dissolved oxygen as AMD moves through the compost layer. The anoxic conditions favor the growth of sulfate reducing bacteria (e.g., desulfovibrio and desulfotomaculum) which convert sulfate to hydrogen sulfide gas (Cook, et al. 2008). The conversion produces net alkalinity, which aids in the precipitation of the dissolved metals (Cook, et al. 2008).

The conceptual design of an anaerobic wetland anticipates processing daily acidity loadings of roughly 3.5 - 7.0 $g/m^2/day$, and is on average 6 times larger than an aerobic wetland (Ford, 2003). Though the acid loadings rate are noticeably less than that of the iron loading rates in an aerobic wetland, a modern variant to the traditional compost bioreactor has included an aggregate layer of limestone (Johnson, 2005). The process of the traditional bioreactor stays the same as the AMD will still flow through the compost. However, afterwards, the AMD will move through a limestone gravel bed to induce further alkalinity, as shown in Figure 3. Though the calculation for daily loadings regarding the alkaline bed will become more complex, the additional support of the aggregate should increase the designed acidity loading rate and inversely decrease the needed area of the anaerobic wetland.

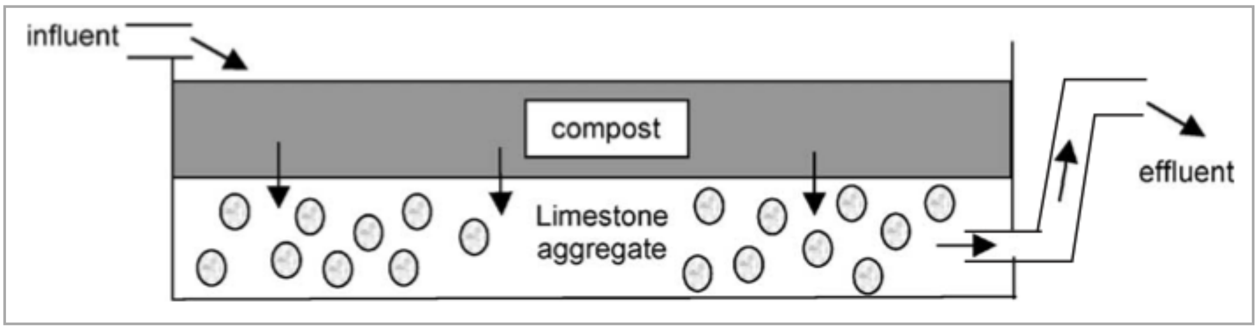


Fig. 3 Simplified schematic of a anaerobic wetland / compost bioreactor using limestone aggregate to lower effluent pH (Johnson and Hallberg, 2005).

2.2 Anoxic Limestone Drains

A common form of abiotic passive water treatment is the anoxic limestone drain (ALD) system. ALDs are constructed as buried channels of limestone through which anoxic water is passed (Ford, 2003). The limestone will dissolve in the acidic water, which subsequently adds alkalinity. The alkaline water will suspend iron in its reduced form (Fe^{2+}) while also avoiding the oxidation of ferric iron due to anoxic conditions. The mitigation of precipitating ferric hydroxide will avoid the covering or armoring of the limestone with the iron or aluminum precipitate. The armoring of the limestone would critically impact the potency of the neutralizing agent (Johnson and Hallberg, 2005). Also, to further increase the development of alkalinity concentrations, the partial pressure of carbon dioxide within the drain is raised above atmospheric levels. This increased rate of dissolution consequently increases the concentration of alkalinity to levels above 100 mg/L (Skousen et al., 1999).

As seen in Figure 4 (Kirby, 2009) within an ALD system, mine effluent should flow over a bed of limestone gravel, which has been constructed within a drain and is kept impermeable to both air and water. The drains dimensions will vary with widths from 1.0 - 20 meters, depths of up to 1.5 meters, and lengths of roughly 30 meters (Johnson and Hallberg, 2005). Drains adhering to low dissolved oxygen (D.O.) and low aluminum water influent will have an effective lifespan of 25 - 30 years with minimal costs during this period of time (Skousen et al., 1999).

2.2.1 ALD Case Study

The Brandy Camp site in Pennsylvania utilized an ALD to treat AMD waters. The influent had a pH of 4.3, acidity of 162 mg/L as $CaCO_3$, Fe of 60 mg/L, Mn of 10 mg/L, and Al of 5 mg/L (Skousen et al., 1999). Once the water passed through the ALD, the effluent had a pH of 6.0, net alkalinity of 10 mg/L as $CaCO_3$, Fe of 50 mg/L, Mn of 10 mg/L, and Al of <1 mg/L. From the numbers, one can see that iron and manganese passed through the system at near full concentrations of the influent, but later precipitated in subsequent wetlands, which was planned. PH levels were raised to a near neutral level and aluminum precipitated inside the ALD. The precipitation of Al inside the drain is expected to armor the limestone pore spaces and decrease the lifespan of the ALD (Skousen et al., 1999).

As seen in the Brandy Camp example, most modern reclamation trends will need to brace for successes and failures in order to find a system that works well for their needs. However, the process of cleaning polluted water can be quite complicated and no treatment is guaranteed given the complexity of mining sites (Johnson, 2005).

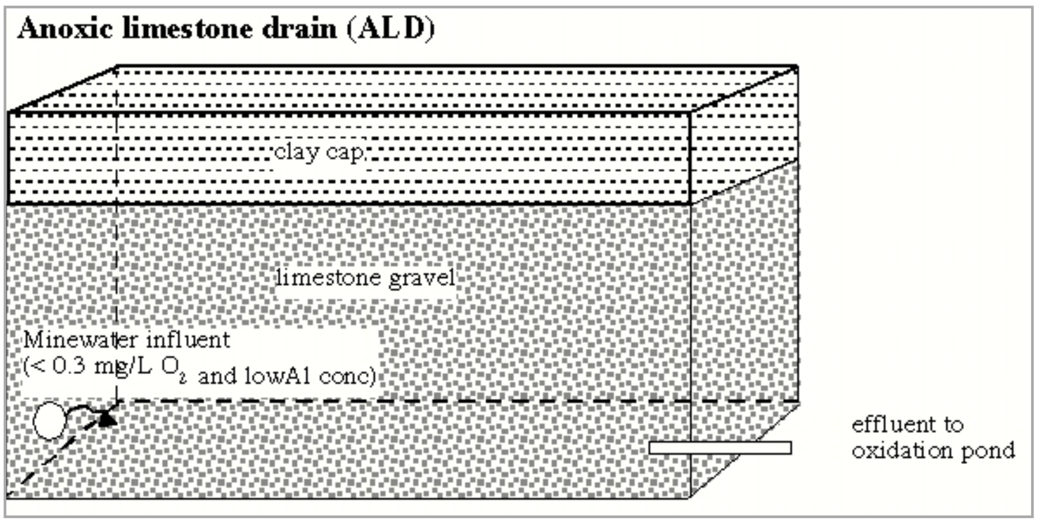


Fig. 4 Simple schematic of an anoxic limestone drain (Kirby, 2009).

2.3 Composite Passive System Example

Typically the use of wetlands is a multiple step process that can include a combination of aerobic, anaerobic, or anoxic limestone drains (Ford, 2003) as pictured in Figure 5. For example, a simplified sequence of events would begin with the highly acidic and low dissolved oxygen / low metal concentrated AMD waters passing through an anoxic limestone drain to induce alkalinity. Once passing over the ALD, the water will then flow through a settling pond to allow for the precipitation of metals induced from the higher or lower pH. Afterwards, the water will be directed into an aerobic (net alkaline water) wetland or anaerobic (net acidic water) to further oxidize or reduce metals, namely iron and manganese, and aid in the precipitation of remaining metals and sulfides (Johnson, 2005). The final stage of the effluent should have a neutral pH and lowered amount of total and dissolved metals.

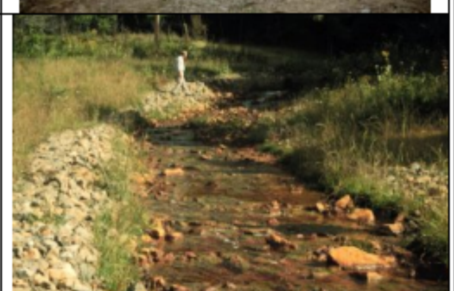
Aerobic Wetland		Anoxic Limestone Drain photo credit: www.wvu.edu/ ~agexten/ landrec/land	
Aeration and Settling Pond		Sulfate Reducing Bioreactor (AKA Bio-chemical Reactor – [BCR])	
Successive/ Reducing alkalinity producing systems (SAPS/ RAPS) photo credit: www.wvu.edu /~agexten/ landrec/		Open limestone channels (OLCs) photo credit: www.wvu.edu/ ~agexten/ landrec/	
Limestone beds		Limestone Sand (semi-passive)	

Fig. 5 Main components of selected passive treatments (EPA BMP, 2002).

3. Source Control

Another best management practice used on active and abandoned mine lands is the source control method (Cook et al. 2008). The core concept of source control is eliminating at least one factor (water, oxygen, or sulfidic minerals) in the reaction process of AMD by using a series of water diversion tactics. Other source control methods work to neutralize the potential acid causing materials in situ by combining acid producing and acid consuming materials to create a neutral substance.

Unfortunately regarding source control, the initial investment capital needed to implement methods such as the land pile cover is generally very expensive given the large amount of land that must be addressed. Even then the buffering soils or man-made cover has the potential to breakdown due to natural elements such as root intrusion or reactions with the atmosphere. Though source control can be an effective short term solution, the methods aren't practical for long term (+1,000 years) mitigation needs.

3.1 pH Neutralization

Areas within underground mines and open surface mines have spaces that are generally backfilled to increase stabilization, able traffic infrastructure, and simply pile and store refuse. It is found that many times this refuse or backfill is a contributor to acid mine drainage. However, not all refuse is chemically enabling the production of AMD, but instead has the chemical makeup to inhibit the AMD reaction process, and can actively contribute to the restoration of discharging waters.

Perhaps the best way to explain this process is to highlight the scenario that took place in Boone County, West Virginia. The current mining company encountered small valley fills composed of overburden from old coal seams. These fills were constructed during mining operations from the 1960s - 1970s (Cook et al., 2008). This was before overburden analysis was required to anticipate acid-producing potential, as is now mandatory by the SMCRA and was often used with disregard to likely negative consequences (Cook et al., 2008). Using an acid based accounting procedure, it was found that the earlier fills contained acid producing materials, and in fact, they did produce acidic drainage. When the Black Castle Mining Company (BCMC) acquired the coal mined land, they also inherited the environmental liability that was linked to the parcel.

BCMC then began operating in the area during the late 1980s. Throughout the process of removing coal from deeper within the geologic column, they encountered alkaline sandstone. Using this net alkaline resource, the sandstone spoils were used to construct valley fills around and below the pre-existing fills that were discharging AMD. The two drainage areas that were being examined started with high acidity/high metal effluent (pH 3.5 - 4.5 with 100-200 mg/L as $CaCO_3$ acidity) (Cook et al. 2008). Remarkably, the placement of the alkaline material in the extended valley fills eliminated the need for chemical treatment of the mine discharge. The water quality in the tributaries of the local creek had been improved to a pH greater than 6.2 and acidities less than 1 mg/L (Cook et al. 2008).

The outcome had a net result of improved water quality within the major stream of each drainage area. The measured results have exceeded the prediction of a "slight decrease in acidity, along with a possible decrease in aluminum" (Cook et al. 2008). Even with this, the watershed is in far better shape chemically than it was prior to the addition of alkaline fills. This has effectively eliminated the need for chemical treatment of acid mine drainage from the pre-existing valley fills, while allowing the mining company to use spoils as a natural buffer and save potentially millions of dollars in remediation efforts (Cook et al. 2008).

3.2 Water Diversion

Another common source control tactic is diverting surface water flow overhead/around a mining site in order to limit the amount of water entering the mined area. This process can manipulate water volume and direction within the open pit or deep pit mining areas while effectively minimizing the consequences of acid mine drainage on groundwater or downstream bodies of water. The strategy of diverting surface level runoff involves establishing a series of drainage channels to direct surface water off the site prior to its mine infiltration or restricting its ability to permeate into backfill piles. The diversion is constructed on the uphill boundary of a surface mine which allows for a complete channeled bypass of the hazardous area (Cook et al. 2008). Typically the channels will be constructed using impermeable soils and directed into corresponding settling pools, ponds, or wetlands.

Though water diversion is considered a source control method, the term water diversion itself is broad and is used in a variety mining engineering tactics. One such practice, alkaline loading, utilizes both active and passive treatment techniques while still aiding in source control. This particular process diverts surface water flow into pooling areas of alkaline material, namely slag or lime substances, in order to raise the alkalinity of the water (Cook et al. 2008). The now net alkaline surface water will be channeled into pyritic rich coal spoils or underground deep mines that will eventually produce acid mine drainage. This alkaline loading method is a diversionary tactic that increases the pH of upgradient water by diverting channeled water over chemicals or natural fill before coming into contact with mining backfill or mine zones (Cook et al. 2008).

Similarly to channeling water past source areas, another water diversion strategy employed in AMD reduction is simply dewatering a mine. The notion of dewatering a mine stems from the basic concept of removing the water source, typically groundwater, that would cause pyrite oxidation in deep and open pit mines (Skousen et al., 1999). Since removing large volumes of deep water from around complex mining sites is not entirely feasible outside of a controlled setting, dewatering proposals will reduce but not eliminate the quantity of water that meets pyritic material through a series of pumping wells (Skousen et al., 1999, Norton, 1987).

As an example, a dewatering project was introduced at a surface mine in England. A series of outlying deep water wells were positioned contiguous to the existing surface mine allowing for uncontaminated water to be pumped to the surface and discharged effectively without being treated (Skousen et al., 1999, Norton, 1987). The case is significant because this particular mine is one of the largest open pit mines in the United Kingdom, and the chemistry of the water removed from the wells had a slightly higher than neutral pH and metal concentrations were below regulatory levels (Skousen et al., 1999, Norton, 1987). These conditions granted the mining company the ability to release the pumped water into local streams without further treatment. The process also effectively inhibited the flow of groundwater into their open pit and slowed the rate of pyrite oxidation produced at the mine.

Dewatering a mine is done for a variety of productive reasons, but namely to create dry conditions benefitting the operation as a whole. These benefits include keeping a workable site (secure material excavation), geotechnical strength considerations (e.g., roadways, mine walls), health and safety of the workers, and reducing the amount of groundwater that would come into contact with mined waste material. As in the dewatering case study, during active mining the water table with access to open or deep mines is kept at artificially low levels within the surrounding subsurface. This is generally done by utilizing a series of ongoing pumping operations. Though the pumping is seen as a responsible act, there are social and long term environmental concerns about drawing down the water table. Socially the local populations might have their water source or recharge source for local surface water bodies eliminated. Long term environmental concerns include the water table rebound to pre-mining levels and introduction of exposed mine walls to water and dissolved oxygen. This scenario can provide a source of AMD for thousands of years (EPA, 2002).

3.3 Land/Pile Covers

To further water diversion tactics, land or pile covers will encapsulate acid producing materials with natural, usually impermeable soil layers or man-made (PVC liner) materials (Johnson and Hallberg, 2005). The soils or PVC liner will create a low hydraulic conductivity layer, and subsequently limit the acid producing material's exposure to air and water. These acid producing materials refer to the spoils or backfill from the mine, and are generally removed from the bottom of the pit, compacted, and placed in a dry area away from the highwall (Skousen et al., 1999). The concentrated material, however, is left exposed to the elements and is a source for AMD.

This source control tends to become expensive when dealing with spoil piles that can be in excess of 100 acre areas. The impermeable natural soils are susceptible to eventual mineral degradation and also to natural vegetative processes that can root into the natural seal and expose the acid producing materials to water and air. Plastic liners are also used infrequently due to the high cost of covering large volumes of material. However, there is documented success with the encapsulation of small piles of acid-producing material (Skousen et al., 1999).

For instance, the method involving the blanketing of AMD material was utilized at the Upshur Mining Complex in West Virginia. There it was reported that an 18-ha spoil pile and overburden site were covered with a 20-mil continuously seamed PVC liner (Skousen et al., 1999, Norton, 1987). The liner was placed over the surface of the backfill and covered with roughly 0.5 m of soil. However, due to the sloping nature of the site, roughly 3 ha were not able to be covered with the liner. The infiltration rates and groundwater fluctuation levels from another comparable site on the mine's land was contrasted to the covered area. The comparison showed a reduction in groundwater recharge under the covered backfill. Most notably, this treatment reduced potential acid loads of drainage from the pile by up to nearly 63% by decreasing infiltration rates and diverting water over the refuse (Skousen et al., 1999, Norton, 1987). Similarly, in Illinois, an encapsulating soil technique was designed for a coal refuse disposal area. This method incorporated a graded and compressed refuse pile, and also a compacted clay liner and protective soil cover (Gentile et al. 1997), similar to the simple design in Figure 6. Initial permeation was determined to have decreased by roughly 18% when compared to an average unreclaimed refuse site. The belief is that once the material in the cover consolidates and becomes vegetated, the encapsulating material will reduce infiltration by 80% or more.

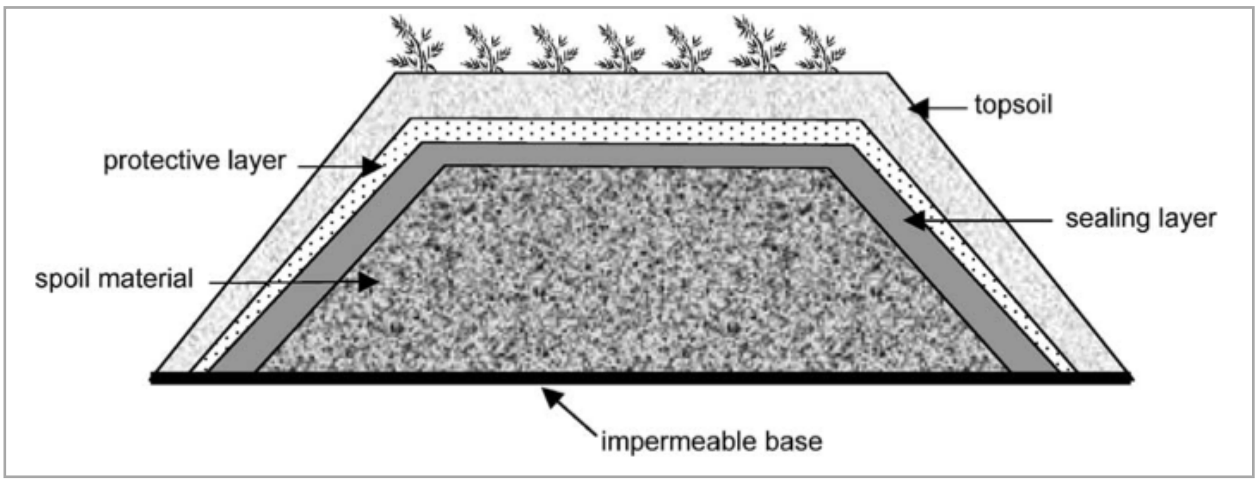


Fig. 6 Design of a dry cover for reducing the production of mine refuse effluent (Johnson and Hallberg, 2005).

TREATMENT SYSTEM SELECTION

For a company or government to decide on the best possible action and treatment system, they will take into account the local and effluent water quality limitations, costs of the proposed system, local weather and climate, amount of area available, and lithological makeup of the mine. The entities will also take into consideration the three main forms of treatment discussed earlier, along with each of their positives and negatives.

The real-time benefits of active treatments allows governments or companies to effectively influence the chemical composition of mine effluent. However, the high cost associated with these treatment methods makes the long term viability out of reach for low budget projects. As passive treatment technology has developed, the viability of implementing a low cost and effective treatment system for low budget abandoned mines has become realistic. Perhaps combining passive treatment technologies with simplistic water diversion techniques would be the best route for such projects.

Helping choose the right passive treatment system, Skousen (Figure 7) created a simplified flowchart. The chart bases a treatment scenario simply off of chemistry and water flow. As one can see, these suggested treatment systems are engineered with specific water characteristics (e.g., net acidic or alkaline, high or low flow, metal concentrations, dissolved oxygen content) in mind. Again, the results of this flowchart might not be fully attainable to some companies or governments due to land area restrictions, but the basic flowchart shows treatment methods used in combination with one another. This implies that certain methods could compensate for other processes and effectively limit the overall area needed for treatment.

However, selecting the proper treatment technique for an individual mine will continue to be based on the physical need and monetary abilities of a company or mine. Emerging and innovating technologies are evolving that may address the array of concerns and needs specific to many areas. Most passive techniques will fall into the emerging technologies category. This is due to their status as still developing and not fully proven within mining. Other innovative technologies that are also primarily passive treatment techniques include bioremediation, phytoremediation (phytoextraction, rhizofiltration, & phytodegradation), and vitrification (EPA BMP, 2002).

Some of these technologies are already being used in modern reclamation efforts, like bioremediation to help stabilize water by producing alkaline by-products. Whereas phytoremediation tools are used commonly in other industries, such as agriculture, to extract metals or pollutants through means of plant uptake and recycling or incinerating the harvested plant. Both bio- and phytoremediation offer a promising and natural alternative to helping stabilize affected areas (EPA BMP, 2002).

In the case that a government or company chooses to implement the improper or structurally inefficient treatment technique, serious environmental and social consequences are possible. For instance, a site named the Iron-Duke Mine in Zimbabwe uses a series of retention ponds to mitigate the effects of AMD after their permit to discharge effluent directly into a local river ended in 1990. The mine was originally pumping nearly 19,000 gallons of wastewater into the local river, but after implementing mandated environmental practices, the water was routed through retention ponds (Mapanda et al, 2007). The original idea was to have the ponds use an impermeable thin clay lining to prevent contaminated water from leaching further into the local groundwater, while allowing suspended solids to settle. However, it was found that the high concentrations of pollutants and pH changes from the AMD diminished the capacity of the

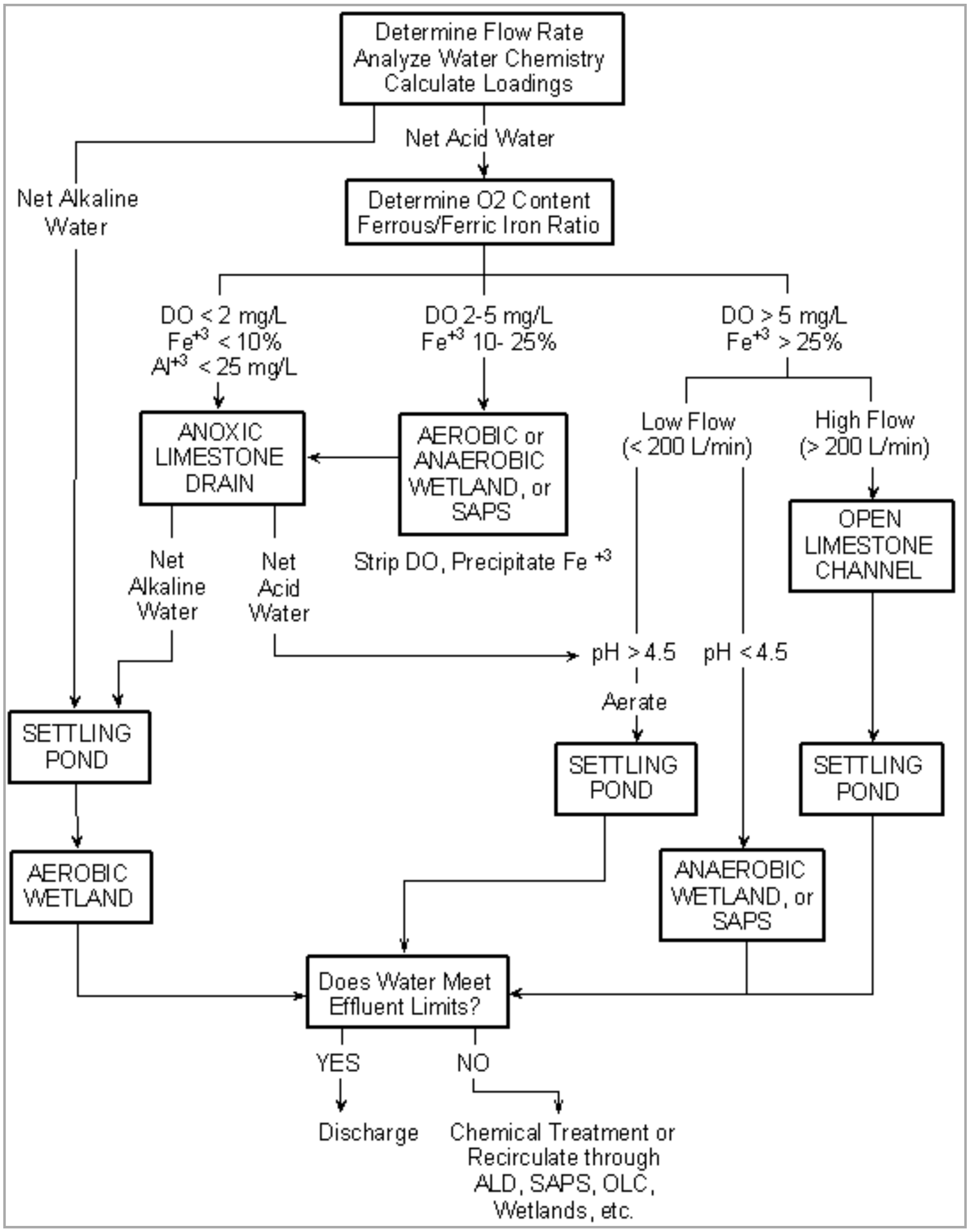


Fig. 7 Flowchart indicating the proper passive treatment system based off of water flow and chemistry (Skousen et al., 1999).

aluminosilicate clay materials (Mapanda et al, 2007). Once the impermeability of the clay soil was reduced beyond a working capability, the contaminated water was free to move into local water bodies without resistance.

Eventually it was found that the soils surrounding the ponds had a pH range from 2.4 - 5.8, with levels of pH being directly related to the distance from the retention pond or mine site (Mapanda et al, 2007). Those with the lowest pH levels were all within 15 meters of the retention ponds. Water and soil samples showed a chief source of contamination to be iron, sulphates, nickel, arsenic, salts, and acidity.

The example described above shows the maintenance and subsequent heavy costs associated with preserving settling pond reclamation activities. A simple settling pond without the correct engineering and basic structural materials can advance the degradation of its structure and surrounding environment by allowing for the permeation of contaminated water further within local groundwater and surface water bodies. The settling pond was incorrectly placed at the end of a high metal concentrated, high acidity stream. As figure 8 directs, the effluent required prior treatment to the settling pond and additional maintenance to it's impermeable layer. The government failed the local Zimbabwe community by not implementing strong regulations, but also the responsible company proved its disregard for the environment. Both scenarios could have been avoided by following and choosing to implement simple investigation techniques outlined by many of the world's leading mining producers.

CONCLUSION

The massive reach and significant implications of acid mine drainage consequently advance societies toward developing reasonable and effective treatment options. The technologies reviewed in this paper offer stories of success and growth, but often times have large drawbacks due to high costs and situational effectiveness. The differences between varying sites' geology, hydrology, climate, and chemistry make general application of any method nearly impossible. Yet as innovative technologies are implemented, analyzed, and improved, their effectiveness should increase while inevitably reducing costs.

Unfortunately the advancement in modern AMD knowledge and research has been nearly limited to the United States until 1993 and more specifically to the Appalachian region (EPA, 2002). As countries around the world begin to deal with problems associated with AMD, their efforts will also need to be specific to local environments and take into consideration the particular needs of their people. It is believed that with open lines of communication exemplifying successes and failures within geographically similar regions, the burden of trial and error will slow. The budgeting of similar AMD reclamation projects will be able to appropriately account for regional specific costs and proven effective treatment methods.

As of today within the U.S., the high number of abandoned mines compared to the limited government funds available for reclamation will ultimately dictate the foreseeable ecological future of coal and hard rock mining areas. However, the push towards innovative technologies utilizing natural treatment techniques with long term viability and minimal costs proves that near self-sustaining remediation is slowly becoming a practical choice. A choice that many in the U.S. must be prepared to make, because the problems with AMD will continue to haunt our land for the foreseeable future.

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