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EFFECTIVE TREATMENT OPTIONS FOR ACID MINE DRAINAGE IN THE COAL REGION OF WEST VIRGINIA

A Thesis submitted to
the Graduate College of
Marshall University

In partial fulfillment of
the requirements for the degree of
Master of Science

in

Geography

by

Daniel Kirby

Dr. Anita Walz, Committee Chairperson
Dr. Godwin Djietror
Dr. Kevin Law

Marshall University
May, 2014

Acknowledgments

I would like to thank Dr. Anita Walz for all of her support and advice in the writing of this thesis and also as my graduate advisor. I would also like to thank Dr. Godwin Djietror and Dr. Kevin Law for agreeing to be on my committee and providing their unique insight to help in the improvement of this thesis. I would also like to thank everyone involved in the Geography Department at Marshall University for providing a great environment to learn and work in for the last two years.

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Abstract

Coal mining has a long history in the state of West Virginia and until recently mining was unregulated. Due to this history there are several legacy problems of the mining industry being dealt with today. Acid mine drainage (AMD) is one of the major legacy problems being combated today in the state. AMD is the product of oxidation in abandoned mine lands and runs into surface water. There are treatment sites all over the state to combat this problem. This thesis research looks the AMD problem in West Virginia and at the effectiveness of the treatment systems that are currently operating in the state. Data for each treatment site include treatment used, cost, load reduction of acidity, and metal load reduction. The data come from the various public and private agencies that manage that particular site. This data was used in GIS and statistical operations to show were AMD is a problem and the effectiveness, both overall and by cost, of the treatments that are being used by the state. AMD source data show that there is a widespread problem in the state that is not going away. It was found that in comparison to the other treatment types in use anoxic limestone drains, open limestone channels, and land reconstruction are the most effective for reduction of acidity and metals.

Keywords: mine drainage, load reduction, active treatment, passive treatment

Introduction

Coal mining is not a new phenomenon, nor is it a relatively new addition to human's impact on the planet. Since the industrial revolution the production and mining of coal has skyrocketed into a large scale industry on its own. Nowhere else embodies this fact more than the state of West Virginia, which as a state is wholly associated with coal mining more than any other feature. Coal mining has many good outcomes as a whole, and specifically for West Virginia. It provides heat and power to the world and provides West Virginia with a place in the economy.

There are also drawbacks to the mining of coal; these include both immediate and long term impacts. Immediate drawbacks include actions like mountaintop removal and deforestation. Longer term problems, or legacy problems, are impacts of coal mining that are still being dealt with today from mines long closed. Legacy problems refer to impacts like climate change; but also, being specific to coal mining one of the most prevalent legacy problems is acid mine drainage. Acid mine drainage is a condition where, as the name suggests, the water is made acidic. Acidic water is not the only issue caused by acid mine drainage. As the flowing water mixes with mine wastes and other mining leftovers it picks up metals and other substances that pollute the water to the point of danger to ecosystems. In addition to acidity there are elevated concentrations of materials like iron, aluminum, and magnesium along with other metals and materials in the water.

Acid mine drainage is a big problem in areas where there are abandoned mines. Active mines are monitored and drainage can be removed or treated at its source; or the drainage will be prevented from forming in the first place. With as many years as coal mining has been going on in West Virginia there are many mines that are no longer in use, or even monitored. It is these mines that typically become a source of acid mine drainage into rivers and streams in West Virginia.

The water that is impacted by acid mine drainage must be treated in order to stop any more problems from starting in the stream or river and to help reverse any effects that have already occurred in the area where the drainage is entering the water. There are systems today that are installed in the affected areas to manage the drainage that comes into the water flow. These systems are classified into either active or passive, and they either treat with chemicals or by using natural and biological processes. West Virginia has to treat a large amount of drainage and utilizes different systems at the numerous treatment sites throughout the state.

Governmental agencies dealing with the environment are in charge of managing and installing these systems, or have oversight of local groups. On the national level there is the Environmental Protection Agency (EPA) and the Office of Surface Mining Reclamation Enforcement (OSMRE). On the state level there is the West Virginia Department of Environmental Protection (WVDEP) and the Office of Abandoned Mine Lands and Reclamation. These organizations work together with private organizations, like watershed associations, to fund and complete projects in West Virginia’s impacted watersheds.

Objectives

Acid mine drainage will continue to be a problem in the future and treatment technologies will be important for everything from the health of the stream and wildlife in it, to human health of those near that water. This thesis research examines the current acid mine drainage problem and the technologies for acid mine drainage treatment in West Virginia. West Virginia has made a large effort to combat the problem and in this research the actions that have been taken at affected sites all over the state are examined for overall effectiveness. The treatment in use at each site is then compared to other affected sites in the state. This research aims to provide useful information for the present and future of the fight against acid mine drainage in West Virginia, showing what is effective and, after comparative analysis, where practices may need to change.

Literature Review

A. Acid Mine Drainage Formation and Chemistry

Today acid mine drainage is a fairly well understood phenomenon. It is primarily a legacy issue resulting from the days of coal mining when problems of this nature were not understood, and likely not even thought of. The chemistry and formation of AMD has been thoroughly documented through the years of dealing with this issue.

Acid mine drainage naturally forms with the oxidation of mine wastes; producing the low pH, high sulfate levels, and elevated levels of metals expected in mine drainage. It takes three main ingredients to create AMD; reactive sulfides in mine waste, molecular oxygen, and water. These come together and the mine wastes are oxidized, creating acid mine drainage (Kuyucak, 1999). Pyritic metals that are present in variable levels in all coal deposits are the main causes of AMD. Drainage high in metals comes from the oxidation of sulphidic minerals, in particular iron pyrite (Johnson and Hallberg, 2005).

Other factors may influence the rate of production of AMD from the site. These factors include bacteria, temperature, starting pH, and alternative oxidants like Iron or Manganese. The hazardous materials are mainly wastes that have reactive sulfides that are found in places like waste dumps, impoundments, leach pads, open cuts, pit walls, and other exposed areas (Kuyucak, 1999). These can be found on all kinds of mine sites, including both underground and open pit mines. Acid mine drainage is however time dependent, which is why new sources are continually being discovered. The drainage does not have to form while the mine is active. It could be, and often is, years later that the problem of AMD arises.

Not all waste materials, or areas, on a mine site cause acid mine drainage. Drainage can form if the material contains sulphide metals, including pyrite and pyrrhotite. These metals become oxidized when they come into contact with the atmosphere, meaning air and rain. After oxidation there is sulfuric acid production and the liberation of metals (Kuyucak, 1999). This leads to water that runs through the area to become acidic, pick up metals, and thus become acid mine drainage. The metals that are most commonly found in acid mine drainage are Iron, Aluminum, and Manganese. The only way to prevent AMD from forming at a mine site is to prevent the sulphide metals from oxidizing. Today there are many methods that are in practice on active mine sites to prevent this from happening. This includes capping waste piles, diverting water, and having on-site treatment with constructs like limestone trenches (Skousen and foreman, 2000). These practices are strictly monitored, at least in the US, so no drainage comes from current mining operations. The long term performance of these practices and monitoring is not yet certain.

There are also practices for when the mine shuts down, or for any abandoned mines that are found. A mine can be walled off, dry sealed, or sealed so that water can come out but no air can go in, known as a wet seal. Land reconstruction with drains and ditches is also practiced to keep water away from the pyrritic metals (Skousen and Foreman, 2000). These practices help sites to not have the mine drainage production scenario or to help diminish it if already present.

There are five different types of acid mine drainage during a period of treatment. Type 1 AMD is very acidic, pH less than 4.5, and has higher levels of metals and oxygen. The levels of the metals Iron, Aluminum, and Manganese are much higher in this form of AMD. Type 2 is less acidic, with a pH of more than 6.0. It also has high levels of dissolved solids, along with higher levels of ferrous iron and manganese. If this drainage becomes oxidized the pH will dramatically drop to that of type 1 AMD. Type 3 is actually more commonly known as alkaline mine drainage, the alkalinity is greater than the acidity. It does have moderate to high levels of dissolved solids with low to moderate levels of iron and manganese. Any acidity created by oxidation is generally neutralized by the alkalinity already present in this water. Type 4 is neutralized acid mine drainage, with a pH of more than 6.0. It has high levels of suspended particulates that must settle out of the water before it can become type 5 AMD. Type 5 is neutralized AMD with high totals of dissolved solids. Most metal hydroxides precipitated out before reaching this stage, leaving mainly dissolved calcium and magnesium with a few sulfates and bicarbonates. If alkalinity or oxygen is lacking in the treatment of the water it is unlikely to reach the qualifications of type 5 AMD. There are also other classifications for transitional stages where these types are mixed and a neutral stage, where acid and alkaline are balanced at near neutral pH (Skousen et al, 1998).

AMD becomes a larger problem when it begins to violate the water quality standards of the state, which are set to protect aquatic life as well as drinking water. Acidity is an issue that would use the pH scale and needs to be at 6.0 or above to be considered non-acidic. According to the water quality standards of the state of West Virginia the levels where iron becomes an issue is at 1.5 mg/L. Manganese becomes a problem at levels exceeding 1.0 mg/L. Dissolved aluminum is considered an issue when the levels are higher than 87 µg/L (WVDEP Water Resources, 2011). When these levels are exceeded the state is required to pursue a solution to the problem with supervision from the EPA.

B. Active Treatment of Acid Mine Drainage

Active treatment, also known as chemical treatment, involves adding chemicals to the water to raise pH and precipitate metals. There are several different chemicals that are in use to combat acid mine drainage. This group of methods also involves the use of machinery to put the chemicals into the water. Active treatment can be very effective, as effective as any passive method, but treatment is determined on a site by site basis.

There are a variety of chemicals in use today and each one can be used in many different ways, differing delivery systems and set up of the sites. Commonly used chemicals include; limestone, hydrated lime, pebble quicklime, soda ash, caustic soda, ammonia, and steel slag. Each one of these chemicals has different properties, costs, and some differences in how they can be delivered.

To constantly deliver a chemical to the water without constant human monitoring there had to be an innovation in treatment technology. This innovation came with the Aquafix machine, which utilizes the water wheel concept. No power is required for this system and the flow of water is what adds the chemical to the water (Skousen and Jenkins, 1993). Other forms of this concept are simply referred to as dosers, such as those installed at Three Forks Creek in West Virginia. These dosers use a water powered mechanism to relay the chemical of choice from a nearby silo (WVDEP, 2011).

If the site has drainage that is not too acidic and contains few metals then limestone would be a good choice for active treatment of the site. This material is not very soluble and can develop a covering preventing any from getting to the water, so this is not a choice for extreme situations. For these minimal sites this could be an excellent choice, especially since it is cheap and easy to handle safely. For implementation of this system the limestone can simply all be dumped in or it can be metered in, added over time rather than all dumped at once (Skousen et al, 1996).

In areas of high flow or acidity there are several options for active treatment. Among these options hydrated lime may be the most effective option. This is the most popular chemical used to treat acid mine drainage worldwide. With this option there has to be a mixing plant on site to mechanically mix the powder that the hydrated lime starts as and then deliver it to the affected water (Skousen et al, 1996). These systems are distinguished by the silos that are on the site, this can be expensive but the cost is spread over time.

Pebble quicklime is used with the aquafix machine for areas that have periodic times of mine drainage. This system is used because it uses the water well concept, only adding chemical when the flow moves the water wheel. This can be adapted for harsher situations, the chemical is very reactive and is not used as much (Skousen et al, 1996).

Soda ash use is declining, in part because it is only used because it's convenient. Remote areas with only very slight problems may have a small system that delivers soda ash briquettes to the water periodically (Skousen et al, 1996). This system gives very little control to how much is added and when, but it is only used in remote areas with only slight AMD problems.

Caustic soda is added to the water using a gravity fed system, making this a good choice for areas that would be difficult and expensive to get electricity to. Caustic can raise the pH very quickly and is heavier than the water and can be applied even to ponds. It is however somewhat dangerous in handling and transporting, it is also more expensive than most other options. The caustic is stored in an onsite tank, which can freeze. This leads to changes in the chemical, to a 20% solution, or adding heaters or burying the tank (Skousen et al, 1996). This can lead to a higher price but still cheaper than the soda ash solution for remote locations.

Ammonia is a gas that is injected into the water and nearly immediately greatly raises the pH level. It is much cheaper than many of the other methods and ammonia is something that is natural, meaning living organisms produce it (Faulkner and Skousen, 1991). There are, however, several drawbacks. It can be hazardous to handle and operators must be very careful about how much is added to the water, an overload of ammonia could seriously harm the stream. This is why the use of this chemical is more regulated and could even require a change to a sites NPDES report (Skousen et al, 1996). It can be very effective and is cheaper than many other options but it must be determined on a site by site basis if this is the correct chemical to use.

Steel slag is a solid material that results from the processes of smelting and refining metals and can be found in piles at any site where steel was made (Ziemkiewicz and Skousen, 1998). This material is soluble and releases calcium and magnesium oxides, chemicals that raise pH. Unlike lime this slag material does not absorb CO_2 from the air and the slag also generates more alkalinity than the same weight in lime. But the slag can also contain heavy metals, though most do not test in high amounts, with the exception of nickel and manganese. There are many different kinds of slag, depending on how it was produced, some contain more metals while others have a higher potential for neutralizing AMD. Slag acts differently when combined with acid and perhaps that is why it is not used as often as lime, especially on sites with high acidity. As an active treatment the slag would be directly applied, dumped or metered into the water (Ziemkiewicz and Skousen, 1998). Slag does have the benefit of being abundant and cheap to obtain, though transport may be costly.

Treatment that involves the precipitation of metals has to have a way to remove precipitated metals from the water. This is normally completed through residence time in a settling pond or wetland. Metals dissolved from AMD form tiny masses, or flocs, that settle out of the water when it remains still (Brown et al, 1994). This material can either be left in the pond or wetland, pumped to refuse piles, or to sealed abandoned mines or pits (Skousen et al, 1996).

C. Passive Treatment of Acid Mine Drainage

Passive treatment uses natural processes to treat acid mine drainage. This often involves the diversion of water into a pond or wetland. Unlike active treatment chemicals are not added to the water. Instead in most of these systems the affected water is diverted through natural or biological treatments to achieve similar results as the chemical treatments.

One of the most used passive systems, as both stand alone and part of another system, are wetlands. There are three types of wetlands used in passive treatments; aerobic, anaerobic, and vertical flow. These wetlands are all constructed wetlands because it is against federal law to degrade natural wetlands. There are no such regulations for constructed wetlands. Aerobic wetlands are shallow, with depths no more than 30 cm. These wetlands are typically used when the incoming water is net alkaline. Their primary use is just for aeration and precipitation of metals from the water (Skousen and Ziemkiewicz, 2005). Anaerobic wetlands are deeper, any wetland that is more than 30 cm deep. These wetlands are used when the incoming water is net acidic. It has an organic rich substrate and utilizes plants and bacteria for treatment (Skousen and Ziemkiewicz, 2005).

Vertical flow wetlands utilize organic matter more than other wetland types. The wetland consists of layers of organic compost and limestone. The drainage is then driven through these layers where alkalinity is added and metals can precipitate. This type of wetland is a common part of the successive alkaline producing systems (SAPS) of passive treatment (Demchak et al, 2001).

Anoxic limestone drains are one of several passive systems that utilize the natural qualities of limestone to add alkalinity to the water as it dissolves. An anoxic limestone drain is a buried trench, lined with plastic and limestone, where the water is diverted to run through this trench. This is typically installed upstream of a wetland, so that metals can be precipitated out through residence time in the wetland (Skousen, 1991). When being used to best effect an ALD intercepts mine drainage before its exposed to atmospheric oxygen and is completely enclosed (Cravota III and Trahan, 1999). ALD's are useful by themselves in certain situations but are also used as part of other systems. The flow rate, dissolved oxygen, concentration of metals, and acidity must all be considered when looking at the possibility of using an ALD to treat acid mine drainage (Skousen, 1991).

Alkaline producing systems (APS), or successive alkaline producing systems (SAPS), are passive treatments that combine several different forms of treatment to completely remediate AMD. These systems utilize anoxic limestone drains and organic substrates to continually run diverted water through until the water has been completely treated. This is a system that is in use and is very effective at raising the pH of the water but there is some issue with removing metals from the water (Skousen, 1997).

Limestone ponds are simply ponds that are lined with layers of limestone in the bottom. The purpose of these ponds is for treatment of AMD at the point where it is upwelling and allows the water to filter up through the layers of limestone and into the pond (Skousen, 1997). This has obvious physical limitations and may not be useable in all areas, or all situations. It does have the benefit of being an above ground method, meaning upkeep and maintenance of a limestone pond is easier than on systems that are buried (Skousen, 1997).

Open limestone channels are a basic form of treatment where a channel is constructed and lined with limestone; this is effective with both armored and unarmored limestone, though the unarmored limestone is slightly more effective than the armored limestone (Ziemkiewicz et al, 1994). This is basically a well constructed trench the water is diverted through. This being the case there are many factors in the construction and use of this system of passive treatment (Ziemkiewicz et al, 2003). This includes the type, or severity of the drainage, the slope of the area, and any other physical limitations of the site in question.

Limestone leach beds are a commonly used part of passive treatment. The leach bed is a normally shallow pit that is filled with limestone chips and stone, which naturally add alkalinity to the water that passes through. The water to be treated must be diverted, likely through a culvert, into the leech bed and then out of it, after sufficient resident time, and back to where it should flow naturally (Black et al, 1999). The leach bed is fairly easy to construct and a wooden fence is more than enough to protect it, since the bed is just stone and not something deeper or more sensitive, like a wetland.

One issue when using limestone is when it comes into contact with mine drainage that contains aluminum and iron(III) the limestone can develop armor. The AMD that generally causes this tends to be more highly acidic and contain higher levels of these metals. Armor forming means that the hydroxides that are created when the limestone mixes with these metals, particularly Iron, can coat the limestone and reduce its ability to treat the drainage. This is not to say that unarmored limestone cannot be used to treat drainage but it is somewhat less effective than its unarmored counterpart. In laboratory testing the armored limestone has proved to be anywhere from 2 to 45 percent less effective than unarmored, depending on the specific circumstances of each site (Ziemkiewicz et al, 1997).

The leach bed concept can also utilize steel slag, rather than limestone. This proves to be very effective, producing alkaline water of up to a 9 pH (Simmons et al, 2002). This is most effective if the water being treated for acidity and is not impacted by iron, aluminum, or manganese (Ziemkiewicz et al, 2003). This has all the same benefits of the limestone leach bed; that is easy construction and maintenance.

Bioreactors are a different form of passive treatment that doesn’t involve diverting water as much as the other passive methods. They utilize microorganisms for treatment, as is used in some forms of wetland treatment, to help accelerate metal precipitation. With a bioreactor the treatment is generally applied to the site producing the drainage, rather than diverting the water and treating it there. This treatment is generally applied to spoil backfill on mining sites, where AMD does originate in many cases (Skousen, 1997).

Similar to active sites precipitated metals have to be dealt with in passive systems. If they aren’t going to be allowed to remain in ponds or wetlands then a flushing procedure is necessary. Most passive systems have mechanisms that either automatically flushes the system with water to clean metals out or have easy access for managers to flush the system (Skousen, 1997). Flushed metals are then moved or pumped to the same locations where precipitated metals from active sites are stored.

Methodology

Data

Due to the long history of coal mining there are many places in West Virginia that have been impacted by mining. OSMRE maintains a database of abandoned mine lands, or AML sites. The abandoned mine lands inventory system is an electronic database, called e-amlis. This database includes all AML sites for the US and the system can be searched through by geographic region and date. AML sites include all problems relating to mining; such as highwalls, portals, subsidence, and acid mine drainage. The sites in the e-amlis system are added after inspection by OSMRE, or the state agency that has been given that authority. Obviously all new sites are not new drainage that just started that year. There are two ways, other than new drainage, to bring data into e-amlis. One way is that there was already a slight problem that was known but it did not qualify for funding the year before but has changed in a big enough way to now qualify. The other way is that individual sites are inspected, either a routine inspection or requested by a third party. There are ways for anyone, including independent citizens to report potential problems that will then be investigated by OSMRE, or another agency with authority and added to the system if qualified. The acid mine drainage sites in were found by searching through the site names and descriptions in e-amlis.

These sites producing AMD have to be treated when and if they begin to cause problems in the water ecosystem of streams and rivers. Many of the areas that are impacted receive some form of treatment to mitigate the AMD impacts. The sites investigated for this study are distributed all over the state in six major watersheds; the Cheat, the Lower New, the Monongahela, the Tygart Valley, the Upper Kanawha, and the West Fork. Data comes from several different sources, from local to national agencies. The largest source of data came through the EPA. This data was obtained through the Grants Reporting and Tracking System (GRTS) for nonpoint source projects. This site is maintained by the EPA and the agencies responsible for each site report to this database. Each project report includes information such as cost, treatment system used, acid and metal load reduction, timetable for the project, and location. The information provided to this database and other sources of information come from the organization that is managing a particular site. These organizations include the WVDEP, the WVU National Minelands Reclamation Center, the Friends of the Cheat, the Friends of Deckers Creek, and the Plateau Action Network. The state Office of Abandoned Mine Lands and Reclamation also deals with AMD remediation and some data on active treatment in the state was obtained from this office.

Analysis

The e-amlis data are used in two ways to show the scope and scale of the AMD problem in West Virginia. First, ESRI ArcMap was used to show where the abandoned mine lands and mine drainage sources are in West Virginia. Secondly the increase in mine drainage sites present in e-amlis per year was put into a chart. This chart as well as information about how new sites are added to the system show the nature of the problem; whether it is increasing, decreasing, or staying at about the same level. For treatment over the same time period the number of projects listed in the GRTS database and from WVDEP was charted; this will show if the state is increasing or decreasing their efforts to combat AMD.

Data for individual sites were put into a spreadsheet and used for statistical measures. For forty-six sites investigated there is average cost, average reduction of acidity, average reduction of aluminum, iron, and manganese. Data were also split up by watershed and treatment type, with the same statistical analyses being performed. Open limestone channels were used to show the change in effectiveness based on project size, length of the channel in this case. Charting this data show how effectiveness, or removal rates, change when the physical size of the project changes.

Overall treatment in the state was shown in two ways, by watershed and treatment system. A chart showing load reduction per $1000 spent gives a cost effectiveness measure for each treatment system used frequently in the state. ESRI ArcMap was then used to show the treatment in the major watersheds; by type, total cost, and total load reduction. This was done by adding fields into the watershed attribute table to correspond with each variable and then creating a choropleth map of each variable for the state. This shows the overall impact of the treatment and suggests which treatments could be applied to improve the waters of West Virginia.

Results

West Virginia's AMD Problem

Figure 1A shows all abandoned mine land sites in the state as found in the e-amlis database maintained by OSMRE. Figure 1B shows data from the same source but only those entries that specifically, in the name or description, mention mine drainage. Both Figures 1A and 1B show priority for these sites. Priority 1 and 2 are required to be in the database and represent areas that pose threats to the well being of the people in the region. These are the sites that must be treated and monitored until such time as there is no more problem. These are the sites that federal oversight is concerned with, wither the EPA or OSMRE. Priority 3 sites are not required to be reported and are those that are not considered threats but are still problem areas. These less important sites are not as important and can be treated when there is time and money available, unless it changes to become a priority 2 or 1 site. These sites are those that are being funded under the Surface Mining Control and Reclamation Act (SMRCA) of 1977 or can qualify for SMRCA funding under to rules of the law.

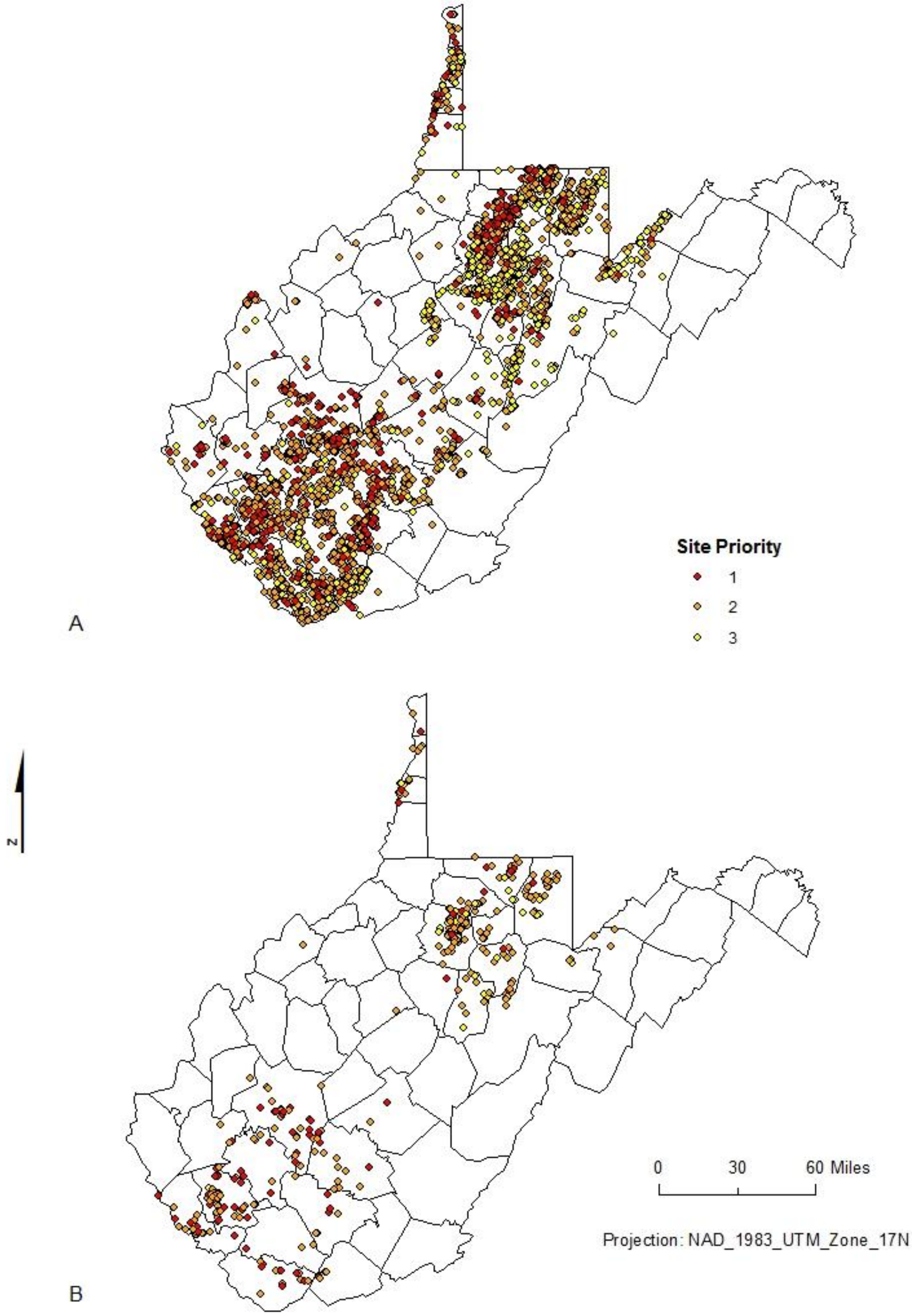

Figure 1: (**A**) Entire current e-amlis database; 1326 priority 1 sites, 2002 priority 2 sites, 1064 priority 3 sites. (**B**) All sites in database featuring mine drainage; 107 priority 1 sites, 271 priority 2 sites, 48 priority 3 sites.

Figures 2 and 3 represent the sources that are added and projects that are undertaken each year. These figures show data from two different sources, nonpoint source projects and data from the e-amlis system. These figures are only to show the trends in the number of sites being treated, or new sources or projects being added.

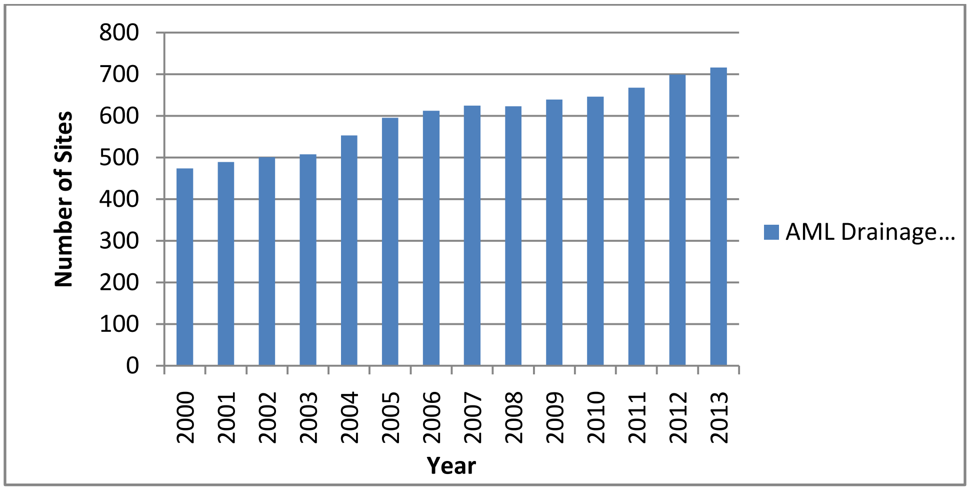

Figure 2: All abandoned mine land sites involving mine drainage in the 4th quarter of each year. (2010 and 2011 only recorded through the 3rd quarter)

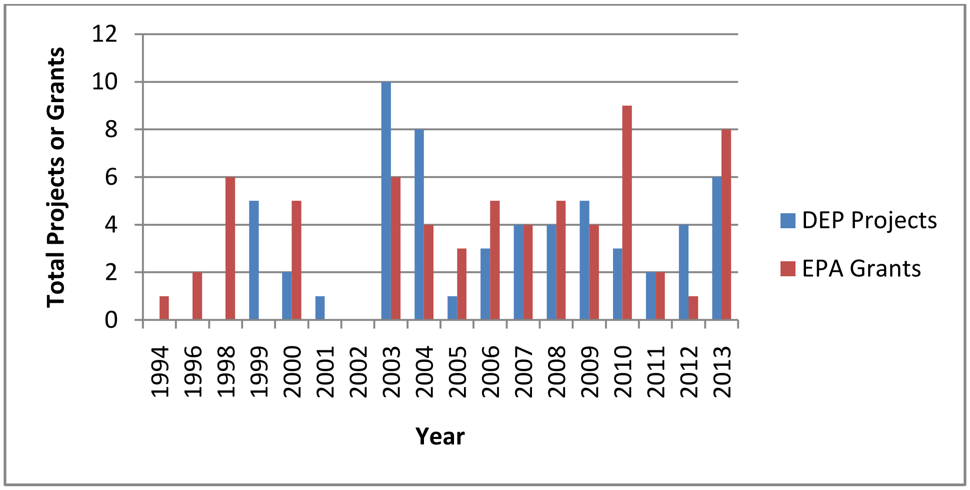

Figure 3: Non-point source projects begun by West Virginia Department of Environmental Protection in calendar year (January-December) and grants for projects from the Environmental Protection Agency in the fiscal year (July-June).

Treatment in West Virginia

Acid mine drainage is actively being treated in many sites across the state. There are different systems used to treat the mine drainage and these systems are all variably successful. Table 1 shows the averages of cost, acidity reduction, aluminum reduction, iron reduction, and manganese reduction for 46 projects that were recorded in the EPA GRTS system. It is important to note that one treatment project is not just for one source; one project treats multiple sources up to an entire watershed.

Table 1 Average Cost and Load Reduction Per Project

Average Budget	Average Acidity Reduction (lbs/yr)	Average Aluminum Reduction (lbs/yr)	Average Iron Reduction (lbs/yr)	Average Manganese Reduction (lbs/yr)
$247,671	113423	13550	41957	5942

Table 1 includes all projects both passive and active in the averages.

Historically West Virginia has used mainly passive treatments. Currently there are multiple forms of passive treatment being used in the state. Table 2 shows the different passive treatment methods included in the 46 projects investigated.

Table 2 Passive Treatment Technologies

Passive Treatment	Number of Projects that Include Treatment
Land Reconstruction	7
Open Limestone Channels	32
Limestone Leachbeds	21
Wetlands	18
Steel Slag Treatment	7
Sulfate Reducing Bioreactor	4

These systems are used either singularly or in conjunction with each other in certain projects to treat the mine drainage. Table 3 shows the singular projects and the two most used multiple treatment projects.

Table 3 Single and Multiple Passive System Sites

Type	Number of Projects	Average Cost	Average Acidity Reduction (lbs/yr)	Average Aluminum Reduction (lbs/yr)	Average Iron Reduction (lbs/yr)	Average Manganese Reduction (lbs/yr)
All Single Systems	11	$257,762	88,164	11,866	37,781	3,181
Open Limestone Channel (OLC)	3	$160,743	271,404	18,668	17,229	2,508
Wetlands	2	$204,268	54,144	14,270	19,060	1,775
Land Reconstruction (LR)	4	$528,615	18,380	12,401	89,378	32,360
Limestone Leach Bed (LLB)	1	$67,972	15,000	2,400	200	560
Anoxic Limestone Drain (ALD)	1	$14,796	40,231	84	4,011	0
All Multiple Systems (max 4)	33	$236,052	62784.15	13682	43254	1184
Open Limestone Channel and Limestone Leach Bed	10	$279,340	48,786	3,512	7,669	10,200
Open Limestone Channel and Wetlands	6	$284,064	69,874	5966	19,271	0

Open limestone channels are the most often used form of treatment in West Virginia. They are also easy to compare to each other when the length of the channel is reported; a longer channel results in more reduction in acidity and metals, this is however site specific. Figure 4 shows the change in reduction of acidity, iron, aluminum, and manganese when the length of the limestone channel is increased. This gives a sense of how the size, or area, of a project or system can affect the outcome.

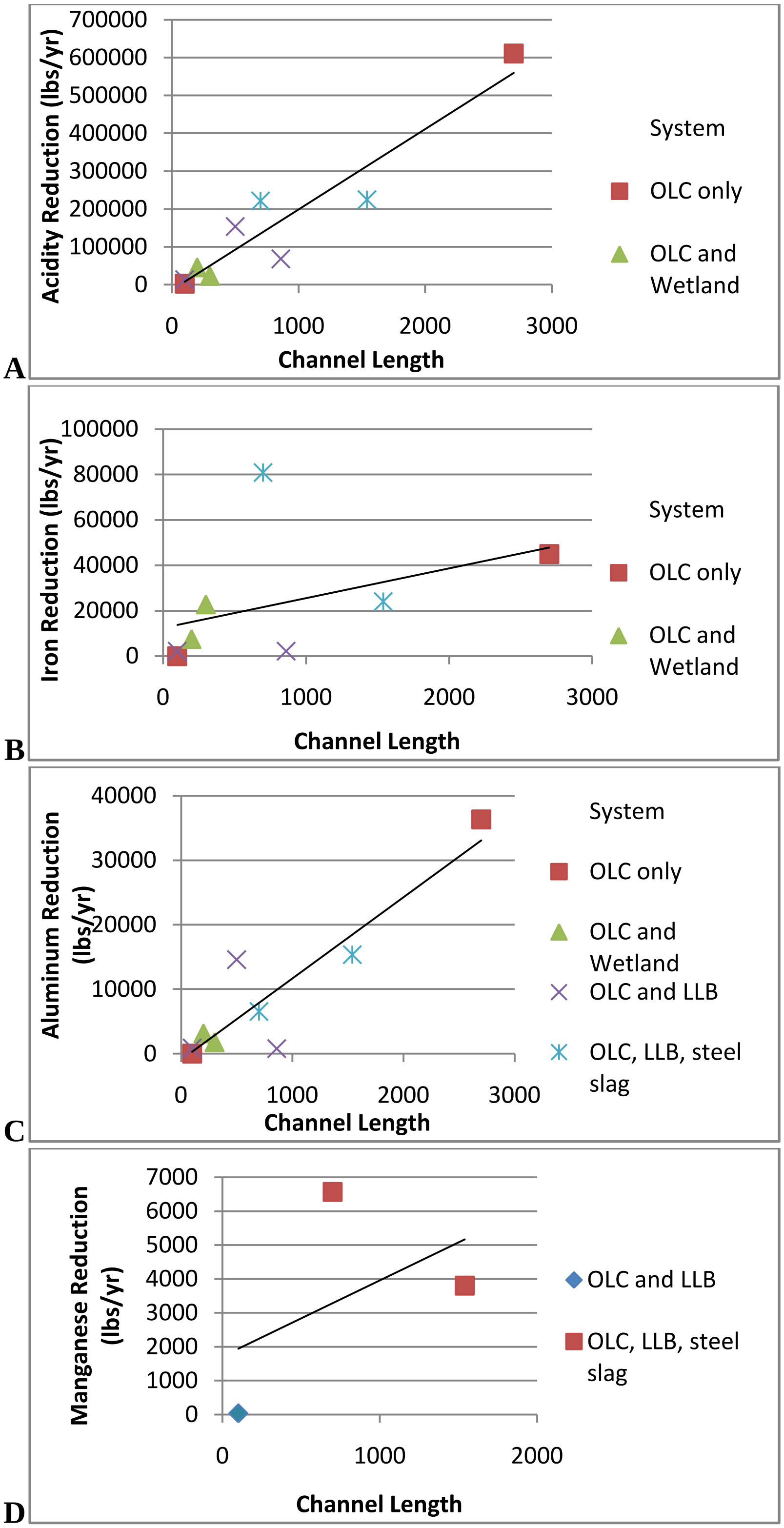

Figure 4: Acidity (**A**), Iron (**B**), Aluminum (**C**) and Manganese (**D**) reduction based on the length of open limestone channels used in treatment.

Figure 4 shows that as the size of the project, length of channel in this case, goes up the reduction in acidity and metals increases as well. This shows that the size or area of the project being used for treatment has an impact on the effectiveness of the system.

Passive treatment does seem to be changing somewhat in the state as either new or improved methods are being used. This includes the use of steel slag, bioreactors, and targeted treatment of specific problems at the treatment site. Steel slag treatments are being used as passive systems, often in leach beds. A comparison of similar waters shows the change in effectiveness with steel slag. The results of this are shown in Table 4.

Table 4 Steel Slag Use in Passive Systems

GRTS Project Name	**Total Cost**	**Acid Reduction** lbs/yr (per $1000)	**Iron Reduction** lbs/yr (per $1000)	**Aluminum Reduction** lbs/yr (per $1000)	**Manganese Reduction** lbs/yr (per $1000)	**Treatments Used**
Roaring Creek Portal 5 Project	$248,905	54	9	4	< 1	Limestone Leach Bed, Open Limestone Channel, Aerobic Wetland
Roaring Creek	$315,302	704	257	21	21	Limestone Leach Bed, Open Limestone Channel, Steel Slag

The addition of steel slag has some associated costs but also seems to positively impact the effectiveness of the system; load reductions with steel slag included are much higher. This is not the only factor but is certainly one of the reasons for the increase.

Targeted treatments, as well as bioreactors, are best shown in the projects being undertaken at the Summerlee site. Table 5 shows several projects on the site and the beginnings of projects suited to remove only one of the mine drainage associated issue.

Table 5 Targeted Treatment at Summerlee

GRTS Project Name	**Total Cost**	**Acid Reduction** lbs/yr (per $1000)	**Iron Reduction** lbs/yr (per $1000)	**Aluminum Reduction** lbs/yr (per $1000)	**Manganese Reduction** lbs/yr (per $1000)	**Treatment systems**
Summerlee Bioremediation	$90,760	992	337	54	40	Sulfate Reducing Bioreactor, Terracing, Aerobic Wetland
Summerlee Phase 1.2	$95,853	Not monitored	485	Not monitored	Not monitored	Open Limestone Channel, Enhancing current Wetlands and Iron Terracing

This shows the lower cost of doing this type of treatment, each issue that needs to be targeted could be taken care of without the cost of features needed for other issues. There is a system in planning for aluminum reduction and in the future there may also be a system installed for reducing manganese at the Summerlee site.

Though the main form of treatment is passive there are projects in the state that are using active treatment technologies. There is only one example of active treatment in the 46 sites examined however. A system of limestone dosers is operating in Kanes Creek. Table 6 shows the active treatment beside a passive system, both in operation on Kanes Creek.

Table 6 Active Versus Passive Treatment at Kanes Creek

GRTS Project Name	**Total Cost**	**Acidity** lbs/yr (per $1000)	**Iron** lbs/yr (per $1000)	**Aluminum** lbs/yr (per $1000)	**Treatment Used**
Kanes Creek South #3 and Morgan Mine Road AMD	$510,000	90	14	5	2 Limestone Dosers
Kanes Creek #3 and Valley Point 12 Remediation	$528,265	87	6	14	Open Limestone Channel and Aerobic Wetland: 2 rounds

The active treatment is very effective here, especially with acid loads and iron load reduction. Two limestone dosers cost nearly as much up front as two rounds of this passive treatment but the active treatment is just as effective, or even more so in the case of iron load reduction.

Due to some successes with active treatments in the early 1990's in the Middle Fork and Blackwater rivers there is a pilot project, from the office of surface mining, of in-stream dosing in the Three Forks River. Table 7 shows some results of the Three Forks project.

Table 7 In-stream Dosers at Three Forks

	Cost	**Acidity (pH)**	**Iron**	**Aluminum**	**Manganese**	**Treatment System**
Three Forks Overall Treatment	$750,491 and $18,296 per month after	4.4-5.1 before 6.9-7.08 after	Increased after treatment	Significant reduction at all dosers	Significant reduction at all dosers	In-stream dosing

The project uses 9 limestone dosers to treat the entire Three Forks watershed. There is a more definite long term price tag associated with this but it has been very successful so far, with the exception of an issue where iron has flocculated without precipitating out of the water.

Overall State Treatment Trends

One way to see what the state is doing is to look at the funding that is being spent on various programs. According to data found in the e-amlis database West Virginia has spent, up to December 2013, $1,779,235,964 on abandoned mine land reclamation. This includes all forms of AML projects, including acid mine drainage. Water Problems in this cost summary is listed at $26,059,868 which includes all forms of water problems. The state has set aside tens of millions of dollars, along with grants from other various agencies, to combat this problem that is costing millions of dollars each year. The 46 projects used in this study from the GRTS database combined to cost $11,392,859.

One thing that must be considered in treatment is the cost effectiveness of the treatment. Figure 5 shows the effectiveness of the systems in use based on the cost of treatment. The cost effectiveness is shown by the reduction in acidity, iron, aluminum, and manganese per $1000 that is spent on the project. Figure 6 goes on to show the total cost and how much acidity, iron, aluminum, and manganese are being removed from the impacted watersheds that these projects are present in. These 46 projects are not the only ones present in the state, there are more projects that are using the same types of systems in these and other affected watersheds.

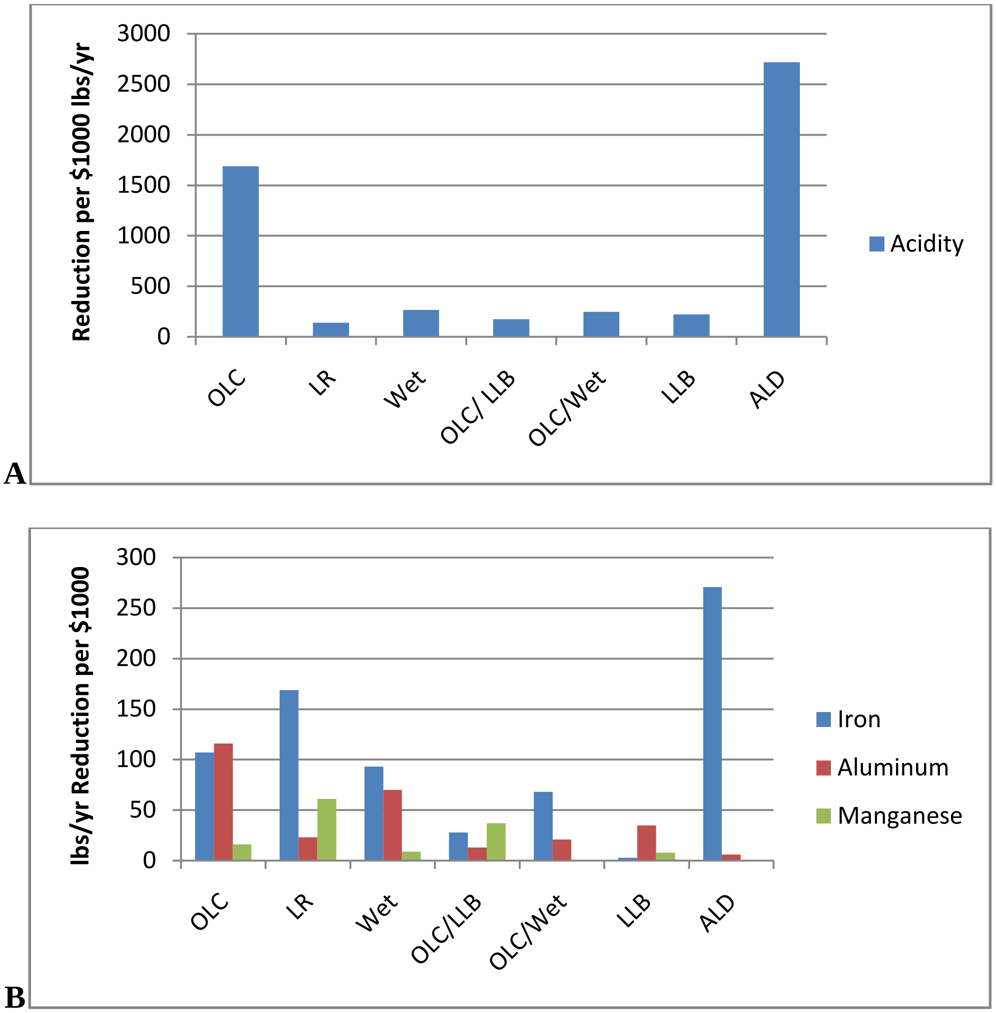

Figure 5: Cost effectiveness for **(A)** acidity reduction and **(B)** metal reduction for treatment systems per $1000 spent. Open Limestone Channel (OLC), Land Reconstruction (LR), Wetlands (Wet), Limestone Leach Beds (LLB), Anoxic Limestone Drain (ALD).

Figure 5 shows that for acidity and iron anoxic limestone drains are the most cost efficient. For aluminum reduction the most cost effective option is an open limestone channel. For manganese the most cost effective option is land reconstruction. Open limestone channels are effective in all categories but manganese, being the second most efficient for acidity and third for iron after land reconstruction.

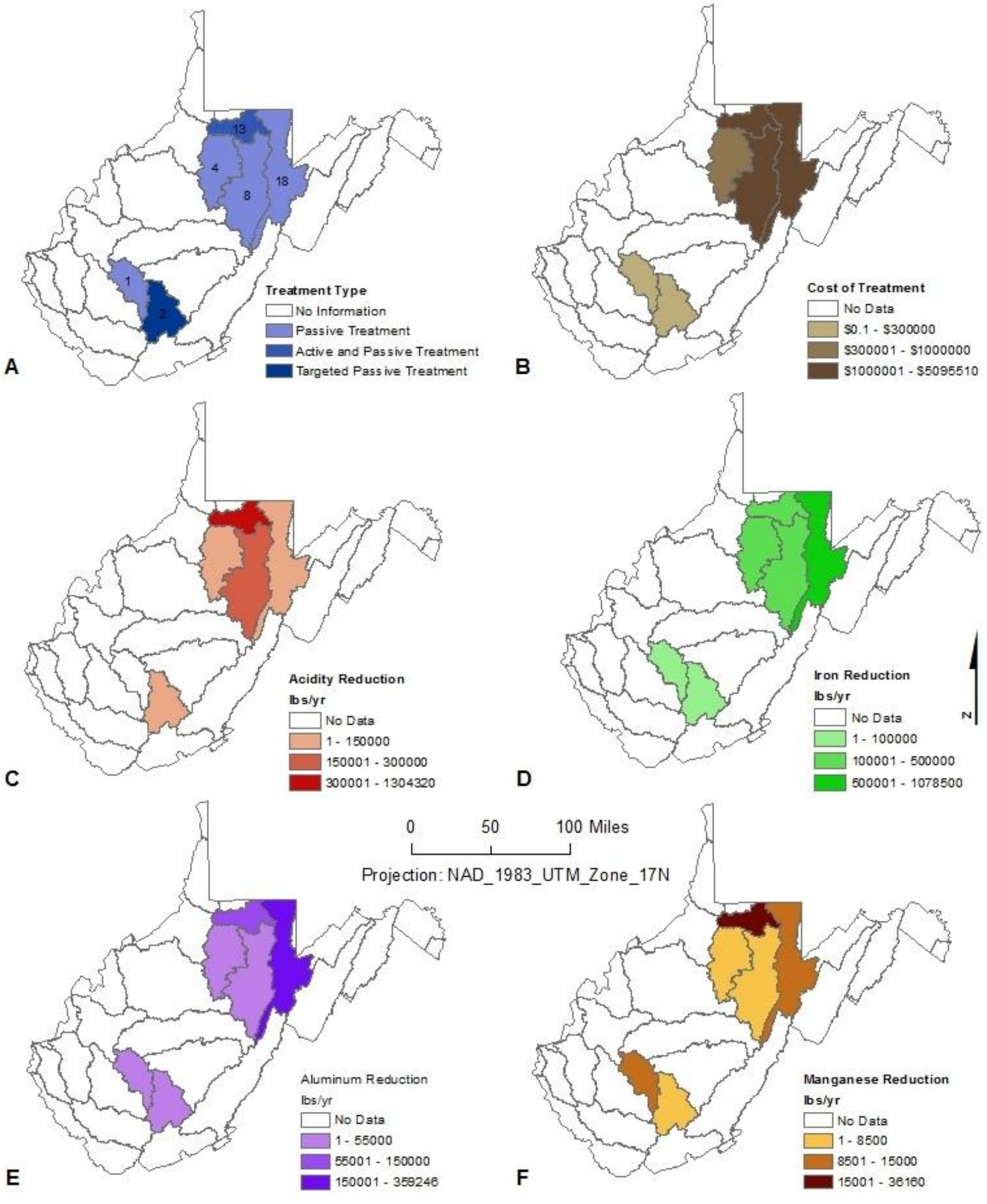

Figure 6: (**A**) Treatment type by watershed, labeled with number of projects. (**B**) Total cost of projects. Total reduction of mine drainage by projects in watershed; Acidity (**C**), Iron (**D**), Aluminum (**E**), and Manganese (**F**).

Figures 5 and 6 show the effectiveness of the treatment systems installed in the six watersheds that were investigated. Anoxic limestone drains, land reconstruction, and open limestone channels are shown to be very effective based on their individual cost of treatment. The effectiveness, based on cost or total reduction, of a project is influenced by the treatment used but also by other factors that could influence treatment at the site. These factors include terrain, land owners, and the amount of metals and acidity available to be removed in the first place. Terrain becomes a factor because some systems needs large flat areas, while other need areas with certain slopes available. Land owners can become an issue when the state has problems getting landowners to agree on the use of their land in the treatment projects. The amount of pollutants in the waters can determine how much can be removed in the first place. This information is available to some extent, but is mainly delivered on a by river or stream basis and in the case of treatment you would need the levels directly at the treatment site.

Discussion

The abandoned mine lands in West Virginia (Figure 1) will continue to create mine drainage but it is clear from looking at the trend (Figure 2) that the problem is not exponentially increasing, that is to say that there will not likely be a year where huge amounts of land and water have to be added to the inventory for potential treatment. There will be some new sources of AMD but the biggest issue for the state will be treating the large inventory that is already impacted, as well as monitoring these sites far into the future as shown in Figure 3. Reclaiming AML lands before drainage starts is also part of the solution the state must address. This issue was caused by many years of coal mining without thought of the consequences and the solution to the problem may well take as long to find as it was to create, or there may always be some form of treatment going on in West Virginia to keep the waters of the state safe for humans, wildlife, and the general ecosystem.

Treatment of AMD in the state progresses year by year, consuming a lot of time and money attempting to clean up the past legacy of the state. Most treatment in the state comes in the form of passive treatment systems. There are several different forms of passive treatment bring used (Table 2) and are successful being used in several ways. Table 3 shows that projects can be successful using a single system or multiple systems working together, though each shows advantages in certain areas. Open limestone channels are used very frequently due to their cost effectiveness, particularly with acidity (Figure 5). Figure 4 shows the reduction in acid and metal loads increase with the length of the channel; though this depends on the site, the physical conditions, and how much of the pollutants there are to be removed. Land Reconstruction is often used as well (Figure 5); it is costly but very effective in reducing metal loads in the water. Anoxic limestone drains are the most effective in this dataset for iron and acid, though this was based only on one anoxic limestone drain site.

Passive treatment in the state tends to use the same systems over and over but there are some new treatments that are in use that are proving to be beneficial. Steel slag use increases the load reduction while having no problems armoring, as limestone does. There is also the targeted treatment going on at Summerlee that is cheaper and can focus on the reduction of a specific pollutant, such as iron reduction.

Passive treatment is the preferred method in the state but there are several active systems in place. The system in Kanes Creek shows that 2 dosers can have the impact of two rounds of a multiple passive system, or the water being treated twice. The project at Three Forks shows that it may be possible to treat an entire watershed with one active project, though it has monthly costs that passive systems do not have.

There are many legitimate reasons for relying on passive treatment so heavily. There are initial conditions, aesthetics, property owners that may not want active treatment on their land, and total cost of the system. The total cost of the system includes future maintenance; passive systems do not require a large amount of future maintenance if working properly. There are, however, two drawbacks of passive systems. One is that it is harder to treat a larger area with these systems, without a large amount of construction. The other concern is with durability and maintaining the system. There are several recent projects that are just improvements or maintenance to an already existing system. With these issues in mind active treatment deserves at least more consideration and perhaps more use in the state.

The biggest limitation of this study is in the lack of standardized data for treatment sites in the state. The information compiled for this study is by no means all encompassing, meaning that there are other sites that are not included in this work. The reasons for this include lack of data, multiple groups keeping data in different ways, and the rather large AMD problem that is being combated in the state today and in the recent past. This work is not an authoritative work on acid mine drainage treatment in the state, especially in light of the data limitations, but it does serve to show the current state of treatment in West Virginia.

Conclusion

One thing that should be created is a centralized database of standardized data from all treatment sites, regardless of its funding or management. This would be a huge step in helping either academic or scientific research, as well as aiding in treatment choice for new sites. This would provide a way for easy mapping using GIS software, such as ESRI ArcMap. This data could then easily be used for research and to give site managers more help in choosing a treatment method, based on what has worked in similar conditions in the past.

The agencies in charge of the treatment of AMD in the state use software to help in choosing a treatment system but there are other things that must be considered as well. The reality of the situation in the state must be considered, in which a work such as this would be helpful. The reality of the physical situation on the ground, including landowners in the area must also be considered. Developing a better model specifically for areas of West Virginia would prove to be an invaluable asset.

The legacy of coal mining hangs over the state of West Virginia more than maybe any other place in the world. This mine drainage problem is not something that is just going to go away. Effective methods of dealing with the problem must be continued until there is a major innovation that could fix the problem or enough time has passed that AMD is no longer an issue threatening our water ecosystems.

Future research into this area could build upon this work. There are ways to expand on this work to better show effectiveness of systems. The best way would be to find the initial conditions at the project site and express the reduction as a percentage. This would remove any problems with comparison when the levels of pollutants there are to be removed are not the same. Another way to expand on this work would be a more intensive use of GIS software;

obtaining precise coordinates for treatment sites and AMD sources and then using the hydrology tools available to create better data and more powerful results.

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Appendix A

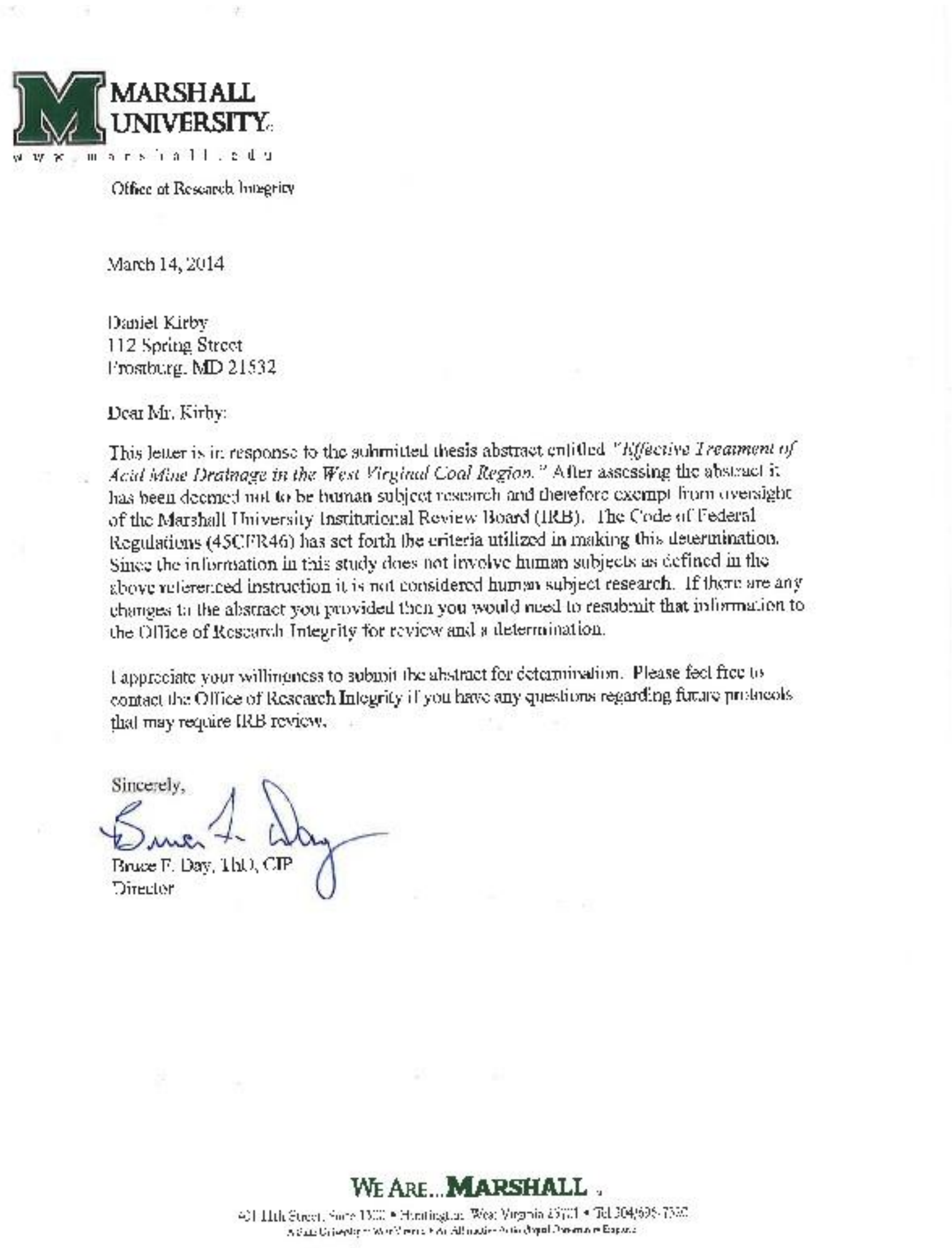
Listing of Projects Used from GRTS database

Project	Sub-project	Watershed	Cost	Fiscal year	Acid Redux	Al redux	Fe redux	Mn redux	treatment	complete	start	finish
Roaring Creek - Portal 5		Tygart Valley	$248,905	2013	13443	882	2174	33	OLC (100ft), Aerobic Wetland, Limestone leachbed	no	2013	2018
Upper Muddy Creek 2.1 (Schwab)		Cheat	$371,182	2013	153600	14580	0	0	OLC (500 ft), Wetland, Limestone leach bed	no	2013	2018
Ingrand Mine Remediation - Valley Highwall upgrades		Upper Mononhahela	$498,200	2013	26400	3000	3800	0	Vertical Flow System, Aerobic Wetland, Limestone leachbed	no	2013	2018
Summerlee AMD - 1.2		Lower New	$95,853	2013	0	0	46491	0	OLC, Wetland enhancements	no	2014	2018
Roaring Creek		Tygart Valley	$315,302	2012	221952	6560	80912	6560	OLC (700ft), Steel slag treatment, Limestone leach bed, Pond	no	2012	2016
Slabcamp AMD remediation		Upper Mononhahela	$459,815	2011	82200	7700	4700	0	2 OLC, 2 Limestone leach beds	no	2012	2016
Lamberts Run Site 7		West Fork	$156,622	2011	97808	0	30000	0	OLC, Lined outlet, Aerobic wetland	no	2012	2016
Upper Muddy Creek improvements		Cheat	$67,972	2010	15000	2400	200	560	Passive	no	2013	2014
Sandy Run of Kanes Creek improvements		Upper Mononhahela	$14,796	2010	40231	84	4011	0	ALD	yes	2012	2013
Smooth Rock Lick		Tygart Valley	$45,730	2010	2867	3.97	3.95	0	OLC (100ft)	yes	2012	2013
West Run Phase 1		Upper Mononhahela	$73,849	2010	225000	15360	24000	3800	OLC (1540ft), 4 Limestone leach beds, Steel slag treatment	no	2012	2014
Summerlee Bioremediation		Greenbrier, Lower New	$90,760	2010	90072	4880	30682	3583	Aerobic Wetland, Land Reconstruction, Sulfate Reducing Bioreactor	yes	2010	2013
Jeff Eanes Beech Run Road		Cheat	$5,145	2010	60860	7197	1841	972	Aerobic Wetland, 2 Sulfate Reducing Bioreactors	yes	2010	2013
Slabcamp Run mainstem AMD		Upper Mononhahela	$145,376	2010	82000	9000	5300	0	2 Anaerobic wetlands, OLC, Vertical Flow system	yes	2010	2013
Kanes Creek South 3 - Valley Point 12		Upper Mononhahela	$528,265	2009	46162	3165	7516	0	OLC (200ft), Aerobic Wetland	yes	2009	2013
Lamberts Run Site 6 Guinn Portal		West Fork	$250,000	2009	23800	1800	22820	0	OLC (300ft), 3 Aerobic wetlands	yes	2009	2013
Reed Mine and examination and repair of valley point 12		Upper Mononhahela	$528,265	2008	99600	9900	3500	0	2 OLC, Aerobic wetland	yes	2011	2013
Pringle Run Passive Treatment		Cheat	$250,000	2008	200606	19700	6682	2508	OLC	yes	2008	2011
NF Greens Run Passive (Dinkenberger)		Cheat	$250,000	2008	68141	810	2165		OLC (860ft), 2 Limestone leach beds	yes	2008	2012
Upper Muddy Creek Passive (Phase II)		Cheat	$192,535	2008	54144	15140	20020	1775	2 Aerobic Wetlands	yes	2008	2013
Smooth Rock Lick #1/2		Tygart Valley	$204,884	2008	40403	839	686	0	Passive Treatment	yes	2008	2012
Kanes Creek South #3 and Morgan Mine Road AMD		Upper Mononhahela	$510,000	2007	45994	2330	7301	0	2 Limestone Dosers	yes	2007	2011
Albert highwall enhancements		Cheat	$216,000	2007	0	13400	18100	0	Aerobic Wetland	yes	2007	2008
Raccoon Creek West End Portal #1		Tygart Valley	$147,550	2007	0	45436	71584	0	Land Reconstruction	yes	2007	2008
Smooth Rock Lick #3	Upper Buckhannon	Tygart Valley	$107,335	2007	0	288	2464	0	Passive Treatment	yes	2007	2012
	Smooth Rock Lick	Tygart Valley			4401	348	511	0				
Lamberts Run site #5		West Fork	$243,948	2006	0	1000	17600	8200	OLC, Limestone leach bed, Anaerobic Wetland	yes	2006	2008
Sovern Run site 62		Cheat	$250,000	2006	65300	37520	38200	2700	Land Reconstruction, OLC	yes	2008	2011
Valley Highwall 3 and Kanes Creek South #1		Upper Mononhahela	$399,469	2006	0	1600	4400	0	2 OLC, 2 Aerobic wetlands, sulfate reducing bioreactor	yes	2006	2010
Muddy Creek/ Dream Mountain AMD		Cheat	$288,391	2005	416000	39400	646000	4000	ALD, OLC, Aerobic wetland	yes	2005	2010
South Fork Greens Run AMD		Cheat	$129,293	2005	0	1024	1952	0	Land Reconstruction	yes	2005	2009
Lower Cheat watershed passive	MF Greens SWS 244	Cheat	$656,083	2004	0	45592	151215	0	OLC, Limestone leach bed, Steel Slag	yes	2005	2008

	Morgan SWS 304	Cheat			312000	137906	109060	0				
	Pringle SWS 314	Cheat			0	3521	1201	0				
Muzzleloader Club AMD		West Fork	$106,663	2004	0	34800	34600	0	Aerobic Wetland, Limestone leach bed, Steel slag treatment	yes	2005	2006
Lamberts Run mine drainage		West Fork	$569,000	2004	0	400	19200	0	4 ALD, Aerobic wetland	yes	2005	2008
Valley Point #12 AMD		Upper Mononhahela	$253,549	2004	0	9400	45400	0	Land Reconstruction	yes	2005	2008
Slabcamp #2		Upper Mononhahela	$186,500	2003	610740	36300	45000	0	OLC (2700ft)	yes	2004	2004
Morris Creek/ WVU tech		Upper Mononhahela	$987,425	2003	0	33240	285860	32360	4 Land Reconstructions	yes	2004	2006
Long Branch Passive		Upper Kanawha	$294,004	2003	0	8580	8600	10200	Lined Waterways/ outles (8000ft)	yes	2006	2006
Blaser Refuse and portals		Cheat	$744,193	2000	73520	4500	24300	0	3 Land Reconstructions	yes	2003	2004
Lower Mudlick refuse		Tygart Valley	$150,000	2000	3595	70	440	0	OLC (1230ft), Land Reclaimation, wetland enhancement	yes	2003	2005
Cheat River Passive		Cheat	$360,000	1998	0	4800	15800	0	Passive		2003	2003
	NF Greens Run (Task Drain)	Cheat			0	2156	10164	0				
	Sovern Run (Task Drain)	Cheat			0	4800	15800	0				
	Sovern Run (Task Drain)	Cheat			0	4800	15800	0				

Appendix B

Letter from Institutional Research Board



MARSHALL UNIVERSITY
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Office of Research Integrity

March 14, 2014

Daniel Kirby
112 Spring Street
Frostburg, MD 21532

Dear Mr. Kirby:

This letter is in response to the submitted thesis abstract entitled *"Effective Treatment of Acid Mine Drainage in the West Virginal Coal Region."* After assessing the abstract it has been deemed not to be human subject research and therefore exempt from oversight of the Marshall University Institutional Review Board (IRB). The Code of Federal Regulations (45CFR46) has set forth the criteria utilized in making this determination. Since the information in this study does not involve human subjects as defined in the above referenced instruction it is not considered human subject research. If there are any changes to the abstract you provided then you would need to resubmit that information to the Office of Research Integrity for review and a determination.

I appreciate your willingness to submit the abstract for determination. Please feel free to contact the Office of Research Integrity if you have any questions regarding future protocols that may require IRB review.

Sincerely,

Bruce F. Day

Bruce F. Day, ThD, CIP
Director

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