GEOTECHNICAL DESIGN OF A FOUR-STAGE CONSTRUCTED WETLAND FOR
THE REMEDIATION OF ACID MINE DRAINAGE

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Engineering (Geological Engineer).

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ABSTRACT

Over the last decade, constructed wetlands have been used to remediate acid mine drainage by removing metals and increasing pH. Much of the research conducted in this field has focused on understanding the chemical reactions responsible for treatment. This research focused on design parameters associated with the physical system, such as structural integrity and hydraulic capacity of the constructed wetlands.

The ultimate purpose of this research was to establish engineering design guidelines to be used for the construction of passive mine drainage treatment systems. This report includes discussions on the importance of wetland chemistry and its impact upon wetland design. The report focuses on factors related to the construction of wetland components, such as containment structures, dams and embankments, settling basins, water conveyance systems, spillways, substrate material and the design and construction of a relatively new wetland component, the anoxic limestone drain.

The various wetland components must be somehow linked together to form a treatment system. Recommendations were given on how to develop a conceptual wetland design, which includes the number and type of components which will make up the system, as well as their configuration. The conceptual design is based upon both the water quality of the mine drainage and the physical constraints present at the site.

The recommendations and guidelines given were used to re-design the passive mine drainage treatment system located at the Marshall No. 5 coal mine near Boulder, Colorado. The original system was built in 1984 and consisted of an aerobic peat bog to remove metals through organic exchange and a limestone channel for neutralization. Metal removal
rates were less than optimum because the wetland was too small and the hydraulic conductivity of the peat was too low.

The new treatment system consisted of four-stages. The first component was an anoxic limestone drain created by filling the mine tunnel with limestone and flooding it. The ALD was designed to add alkalinity and inhibit precipitation of metals on the limestone. The second component was a settling basin, designed to aerate the drainage and allow for flow control into the rest of the treatment system. The third component was a wetland, designed to function in both an aerobic and anaerobic configuration. The fourth component was a polishing cell, designed to treat the mine drainage in an aerobic environment.

The new treatment system was completed in late July 1993. Due to continual disputes with the owner of the water rights, water was not permitted to flow into the wetland cell until late September. Flow into the wetland cell has been sporadic since that time for the same reasons. As a result, water has not yet saturated and infiltrated through the polishing cell of the system; consequently, no water quality samples were obtained from that location.

Preliminary results show the pH increasing from 4.5 to 6.43 and alkalinity increasing from 8.1mg/l to 79.4mg/l from inside the adit to the downstream side of the wetland. Additional sampling and analyses are needed to fully characterize the treatment capabilities of this constructed wetland.
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<tr>
<td>PMDT</td>
<td>Passive mine drainage treatment system</td>
</tr>
<tr>
<td>TVA</td>
<td>Tennessee Valley Authority</td>
</tr>
<tr>
<td>DMG</td>
<td>Division of Minerals and Geology</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>mg/l</td>
<td>Milligrams per liter</td>
</tr>
<tr>
<td>μg/l</td>
<td>Micrograms per liter</td>
</tr>
<tr>
<td>gpm</td>
<td>Gallons per minute</td>
</tr>
<tr>
<td>cfs</td>
<td>Cubic feet per second</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts per million</td>
</tr>
<tr>
<td>L/day</td>
<td>Liter per day</td>
</tr>
<tr>
<td>ALD</td>
<td>Anoxic limestone drain</td>
</tr>
<tr>
<td>gmd</td>
<td>Grams per square meter of substrate per day</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>OMC</td>
<td>Optimum moisture content</td>
</tr>
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</table>
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Chapter 1

INTRODUCTION

In recent years, constructed wetlands have been used as passive mine drainage treatment systems (PMDTs) to reduce or eliminate the negative impact of draining mines upon stream waters. These man-made facilities are designed to remediate mine drainage without the costly maintenance encountered in active treatment systems (Holm and Lewis, 1988). Because of the extensive mining history of Colorado, many of the state’s drainage systems have been contaminated with acid mine drainage. Pollution from an estimated 50,000 abandoned mines has rendered twenty-five watersheds and 450 stream miles incapable of supporting aquatic life (Holm and Bishop, 1985).

Constructed wetlands have been used and studied rather extensively in the eastern United States. The Tennessee Valley Authority (TVA) has been responsible for much of that research. However, due to climatic and topographic variations in Colorado, the technologies developed by the TVA cannot be directly applied to sites located in Colorado (Herron et al., 1991).

The Colorado Division of Minerals and Geology (DMG) is responsible for the design and operation of constructed wetlands in Colorado. Only four systems are in existence today, the first of which was installed in 1984. Experience has indicated that the success of a system depends upon both the geotechnical design of the facility and on the optimization of the chemical processes, although the chemical effectiveness is not always of greater importance (Herron, 1992). Even though the chemical reactions may not be
working at the most efficient level, the system will function as long as the actual structures are intact. Two examples in Colorado demonstrate the importance of sound design and construction. The passive treatment system installed at the Gamble Gulch site near Cripple Creek was severely damaged, apparently by a large storm event. The Marshall No. 5 system ceased functioning within a year of start-up due to hydraulic short-circuiting of the system.

The purpose of this project is to establish design guidelines that can be used to design passive mine drainage treatment systems in high altitude regions such as the Rocky Mountains. Both theoretical and empirical design methodologies will be addressed. The design of a constructed wetland is dependent upon many factors, including site topography, accessibility, spatial constraints, and water quality (pH, alkalinity, dissolved oxygen, acidity, metals concentrations). A step-by-step outline will be given to take the designer of a PMDT from conceptual model to actual treatment system, taking the above factors into consideration. Every effort was made to include engineering equations, testing procedures, and other pertinent information so that the user need not refer to countless other sources to complete a design.

The design guidelines given were used to redesign the treatment system at the Marshall No. 5 site. Research at that site was focused on creating a passive mine drainage treatment system that did not encounter the many problems that affected the original design. The primary design goal was to create a system that possessed hydraulic stability and could withstand fluctuations in flow rate as well as storm events. A secondary goal was to design the system to have predictable flow-through characteristics. Finally, the system design will allow for experimental variations in parameters, such as hydraulic residency time and flow rate, so that the performance efficiency of the treatment system can be determined under
varying conditions. Some preliminary results were obtained after several months of system operation. However, much experimentation should be done so that a more complete understanding of the system can be gained.
Chapter 2

BACKGROUND INFORMATION ON THE MARSHALL NO. 5 SITE

2.1 SITE DESCRIPTION

The Marshall No. 5 tunnel is located approximately 4 miles south of Boulder, Colorado at S1/2, NE1/4, Sec. 21, T1S, R70W (figure 1). The area had been mined extensively for coal from the mid 1800s until 1963 (Holm and Jones, 1985). The abandoned mines discharge a significant amount of acidic waters which are laden with a variety of metals.

The project area is underlain by the Laramie Formation, a sedimentary sequence consisting of interbedded shales, claystones, and some thin layers of sandstone. Numerous coal seams are distributed throughout the formation. The rock layers are essentially horizontal, dipping only 4 degrees to the east-southeast. Surficial deposits consist primarily of stream and terrace deposits.

Surface water from the site is drained by Marshall Creek, which flows into South Boulder Creek. Both drainages are considered to be perennial. The drainage from the Marshall No. 5 tunnel is also perennial. The flow from the adit has been determined to vary from 17 to 70 gallons per minute (Guertin et al., 1985). A hydrologic study of the site defined the watershed area to be approximately 0.024 square miles (figure 2). The hydrologic study also determined that the peak runoff from a 100-year, 24-hour storm event would be 3.89 cubic feet per second (Kaman Tempo, 1983). The upper watershed
Figure 1. Location map of the Marshall No. 5 project. Scale 1:24,000.
Figure 2. Delineation of the watershed surrounding the Marshall site.
boundary was assumed to be the Community Ditch, which flows along a hill above the site.

The water quality of the mine drainage is not particularly bad, although the pH is low and levels of iron and manganese exceed drinking water standards established by the EPA. A water sampling program was conducted by the DMG prior to installation of the first treatment system in 1984. The values of various water quality parameters for the drainage and the EPA standards are listed in Table 1. These values were used in the design of the new treatment system, as they are considered to be representative of the mine drainage.

Since the mine effluent draining from the Marshall site is not highly contaminated, the design process can focus on the physical, rather than the chemical, system. The chemical components of the treatment system are likely to be over-designed, based upon the contaminant levels. However, the purpose of this study is to establish guidelines pertaining to the physical design and construction of passive mine drainage treatment systems. The results of this research will be applicable to the design of treatment systems for other, more contaminated, drainages.

2.2 ORIGINAL DESIGN CONFIGURATION

2.2.1 Original Design Components

The original system was installed in 1984. Water quality sampling was done for approximately one year. The treatment system was designed to consist of three primary components (figure 3): an artificial peat bog, a limestone bed, and a series of drop structures. Water flowed out of the adit and entered the peat bog, where remediation would
Table 1. Average water quality data from the Marshall No. 5 mine drainage and EPA drinking water standards. Bold-face type indicates constituents which do not meet EPA standards.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>EPA Standard</th>
<th>Marshall Data</th>
</tr>
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<tbody>
<tr>
<td>Fe</td>
<td>3000 mg/l</td>
<td><strong>3500-7200 mg/l</strong></td>
</tr>
<tr>
<td>Mn</td>
<td>50 mg/l</td>
<td><strong>1400 mg/l</strong></td>
</tr>
<tr>
<td>Zn</td>
<td>5000 mg/l</td>
<td>98 mg/l</td>
</tr>
<tr>
<td>Pb</td>
<td>50 mg/l</td>
<td>17 mg/l</td>
</tr>
<tr>
<td>pH</td>
<td>6.5-8.5</td>
<td><strong>4.2-4.5</strong></td>
</tr>
<tr>
<td>Sulfate</td>
<td>-----</td>
<td>250 mg/l</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>-----</td>
<td>8 mg/l</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>-----</td>
<td>0.78 mg/l</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>-----</td>
<td>17-70 gpm</td>
</tr>
<tr>
<td>Sulfate</td>
<td>-----</td>
<td>250 mg/l</td>
</tr>
</tbody>
</table>
Figure 3. Design schematic of the original treatment system. Water sampling locations are indicated (W1-W4). Drawing is not to scale.
occur. The organic substrate in the bog was intended to provide a site for chemical processes to remove contaminants (see Chapter 3 for a discussion of the reactions). The bog was located several feet downstream of the mine adit (figure 4). The bog was 55 feet long, 15 feet wide and approximately 4 feet deep and was filled with a mixture of commercial peat. The peat was held in place by a rock check dam on the downstream end of the bog, which consisted of durable alluvial gravels (figure 5). Filter fabric was placed on the upstream side to prevent clogging of the dam by the peat substrate. The peat substrate was selected due to its high cation exchange capacity (Guertin et al., 1985). Laboratory experiments determined flow rates through peat to range from 0.5 to 3 gallons

Figure 4. Photo of the Marshall No. 5 mine adit.
per minute (Guertin et al., 1985). The hypnum peat was included in the substrate selection because it is found only in alkaline environments. The basic nature of the hypnum was expected to minimize leaching problems. One drawback of the material is that it is rather fine-grained in texture, which caused the hydraulic conductivity of the substrate to be lower than expected.

The second component of the treatment system was a channel lined with limestone cobbles located downstream of the peat bog (figure 6). The purpose of the limestone was to increase the alkalinity of the drainage. The one to three inch diameter cobbles were placed to a depth of six inches in a channel approximately 18 inches wide and 300 feet long. The limestone cobbles become armored with metal hydroxides, ferric hydroxide in particular (figure 7). The armoring can occur rapidly and completely, rendering the limestone almost

Figure 5. Photo of the peat bog and rock dam.
useless. To combat the armoring problem, the limestone channel was placed downstream of the bog so that the metal-ion concentrations of the drainage could be reduced before coming into contact with the cobbles.

The third component of the treatment system was a series of drop structures (figure 8). Steel weirs were placed at various locations along the limestone channel. The drop structures are designed to aerate the drainage, thus facilitating the precipitation of metals by creating oxidizing conditions.

2.2.2 System Performance

Water quality samples were collected at four stations (W1-W4) along the treatment system. The average values (plus or minus one standard deviation) were plotted against

![Figure 6. Photo of the limestone channel shortly after installation.](image)
Figure 7. Photo of limestone cobbles armored by ferric hydroxide precipitates.

Figure 8. Steel V-notch weirs used as drop structures in the original system.
sampling location to determine metals removal along the system. Total and dissolved iron concentrations were reduced by an average of 62% and 95% respectively after passage through the peat bog (figures 9 and 10). The mechanisms thought to be responsible for the removal of iron were filtration and adsorption. Total and dissolved zinc concentrations were reduced by an average of 53% and 44% respectively (figures 11 and 12), while the concentrations of total and dissolved manganese decreased by 16% and 17% respectively (figures 13 and 14). The pH of the drainage was increased from 5.1 to 5.9 between the adit and the sampling location located at the end of the system (figure 15). These results were obtained after the system had been in operation for only a few months.

2.2.3 System Evaluation

A preliminary site investigation was conducted at the Marshall No. 5 tunnel in July 1992. The peat bog was completely overgrown with cattails and other swamp vegetation, which were established naturally. Peat at the surface was covered with orange precipitates. The hydraulic conductivity of the peat was low, as evidenced by an accumulation of hydrogen sulfide gases (H$_2$S) in the substrate. H$_2$S is produced during various reactions, and is normally released (Herron, 1992). However, the low permeability of the peat prohibited this from occurring. The rock check dam on the downstream side of the bog was no longer functioning, and most of the drainage from the adit was no longer flowing through the bog due to a diversion installed by the owner of the water rights. However, the system was never capable of managing all of the drainage from the adit even before the diversion was made. The limestone channels were completely overgrown with vegetation and difficult to identify. The limestone had been intensely armored with ferric hydroxides. When the precipitates were removed from the limestone, the rock had a pitted appearance.
TOTAL IRON CONCENTRATIONS ALONG THE TREATMENT SYSTEM FOR THE PERIOD 7/5/84 TO 10/3/84

DISSOLVED IRON CONCENTRATIONS ALONG THE TREATMENT SYSTEM FOR THE PERIOD 7/5/84 TO 10/3/84

Figure 9. Concentrations of total iron along the treatment system.

Figure 10. Concentrations of dissolved iron along the treatment system.
TOTAL MANGANESE CONCENTRATIONS ALONG THE TREATMENT SYSTEM FOR THE PERIOD 7/5/84 TO 10/3/84

Figure 11. Concentrations of total manganese along the treatment system.

DISSOLVED MANGANESE CONCENTRATIONS ALONG THE TREATMENT SYSTEM FOR THE PERIOD 7/5/84 TO 10/3/84

Figure 12. Concentrations of dissolved manganese along the system.
TOTAL ZINC CONCENTRATIONS ALONG THE TREATMENT SYSTEM FOR THE PERIOD 7/5/84 TO 10/3/84

Figure 13. Concentrations of total zinc along the treatment system.

DISSOLVED ZINC CONCENTRATIONS ALONG THE TREATMENT SYSTEM FOR THE PERIOD 7/5/84 TO 10/3/84

Figure 14. Concentrations of dissolved zinc along the treatment system.
A flow rate of 50 gallons per minute was obtained from the adit using a bucket and stopwatch. Water quality samples were taken from the adit, along with pH measurements. The pH ranged from 5.6 at the adit to 7.1 below the first drop structure. Although the treatment system was not functioning at optimum levels, it was clearly still neutralizing the drainage.

The following concentrations of metals in parts per million were determined in the laboratory: 0.1 ppm Cu, 2 ppm Fe and 0.35 ppm Mn. The concentration of Zn was not determined due to technical difficulties in the laboratory. These concentrations were of the same magnitude of those obtained by the DMG and included in Table 1.

As noted above, the major problems with the original design were the peat substrate and the size of the system. First, the peat substrate was too low in permeability to
effectively treat the mine drainage. Most of the drainage was unable to flow through the substrate and merely flowed across the surface of the bog, entering into the limestone channels essentially untreated. As a result, the limestone cobbles became armored with ferric hydroxides within months of start-up. When flow rates through the peat exceeded 10 gpm, the peat became separated into two distinct layers (Guertin et al., 1985). The fine materials would accumulate at the bottom, forming a low permeability mat of material while the less dense materials would float to the top of the bog. Such separation of the substrate does not allow for the most effective or efficient treatment of the mine drainage.

A second problem with the original design was its size. It could not manage the flow from the adit, leading to failure of the rock check dam. Inadequate sizing is related to both the chemical and physical systems of the wetland. The wetland must be large enough to accommodate the chemical reactions associated with remediation as well as manage the flow of mine effluent. Unfortunately, site conditions often limit the size of the treatment facility. Many of the adits draining contaminated waters are located in steep, mountainous regions that are rather inaccessible to most construction equipment. It is often impossible to construct the necessary structures that would provide the most complete treatment. Legal constraints, such as land ownership, can also limit the size of a treatment facility.

Because of the overflow problems encountered with the original design, the decision to renovate the system was made. Due to the close proximity of the Marshall site to various universities and scientific organizations, it provides an excellent opportunity for experimental design projects. The site will be used to test innovative technologies which could be utilized at other, more contaminated, sites.
Chapter 3

WETLAND CHEMISTRY

3.1 ACID MINE DRAINAGE

Contaminated mine waters occur as either coal mine drainage or metal mine drainage. It is reasonable to consider the drainage chemistries to be similar for either case (Wildeman, 1992). Acid mine drainage requires three components to exist: water, oxygen and sulfides (Herron et al, 1991). If one of the components is removed, acid mine drainage will not form. Water and oxygen are supplied by groundwater and the atmosphere, while sulfides are provided by rocks. In many regions, all three components exist in the natural environment and cause elevated levels of acidity in surrounding streams and rivers. The numerous shafts and stopes associated with underground mining provide a conduit for groundwater, acting to expose more rock to more water and oxygen. As a result, areas in which sulfide-rich rocks were mined are frequently contaminated with acidic, metal-rich mine drainage in concentrations far exceeding the natural levels.

The primary mineral which supplies sulfides to the acid mine drainage equation is pyrite (FeS$_2$). Pyrite is a common gangue mineral in metal mining situations as well as in areas where coal is mined, such as the Marshall No. 5 site. The chemistry of pyrite weathering has been discussed by Stumm and Morgan (1981) and is summarized below.
The weathering process occurs in four steps:

\[
\begin{align*}
\text{FeS}_2(s) + 7/2\text{O}_2 + \text{H}_2\text{O} & \rightarrow \text{Fe}^{2+} + 2\text{SO}_4^{-2} + 2\text{H}^+ \\
\text{Fe}^{2+} + 1/4\text{O}_2 + \text{H}^+ & \rightarrow \text{Fe}^{3+} + 1/2\text{H}_2\text{O} \\
\text{Fe}^{3+} + 3\text{H}_2\text{O} & \rightarrow \text{Fe}^{3+}\text{(OH)}_3 + 3\text{H}^+ \\
\text{FeS}_2 + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} & \rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{-2} + 16\text{H}^+
\end{align*}
\]

Pyrite is created in a reducing environment, but weathers by oxidation. Therefore, the weathering process occurs only with the addition of oxygen from outside the environment. During the oxidation process, ferric hydroxide is precipitated. The oxidation reaction also catalyzes the weathering of various metallic sulfides, leading to the liberation of Cu, Zn, Cd and Pb. The slowest reaction is the oxidation of Fe(II) to Fe(III) in solution. Once this reaction has occurred, the Fe(III) rapidly oxidizes more pyrite, as shown in the final reaction (Wildeman, 1991). The weathering of pyrite produces H⁺, causing the waters to become acidic. The presence of certain bacteria in the weathering environment acts to catalyze the oxidation of pyrite.

3.2 NATURAL WETLANDS

Ecologists have long recognized that soils in wetlands and bogs are often sinks for contaminants. The soils have a natural ability to remove contaminants from water passing through the wetlands by means of numerous chemical processes. The scientific community has only recently recognized the potential for remediation of acid mine drainage by channeling the drainage through wetlands. In addition to removing contaminants, the chemical processes at work in a wetland serve to increase the pH of the water to more
acceptable levels. Figure 16 is a diagram of a typical natural wetland, consisting of an aerobic zone and an anaerobic zone.

The utilization of a natural wetland may not be the most efficient method for removing contaminants from mine drainage for several reasons. First, there are numerous chemical processes occurring in a natural wetland, many of which are in competition with one another. For example, one reaction removes H\(^+\) while another reaction creates H\(^+\). The engineering challenge is how to design a wetland in a manner such that the most efficient removal processes are utilized to their fullest extent. The design will be rather site specific, i.e. the removal processes will depend on the chemistry of the particular mine drainage. Consider the typical reactions which occur in the aerobic zone of a wetland (Machemer et al., 1990):

\[
4\text{Fe}^{2+} + \text{O}_2 + 10\text{H}_2\text{O} \rightarrow 4\text{Fe(OH)}_3 + 8\text{H}^+ \\
2\text{O}_2 + \text{H}_2\text{S} \rightarrow \text{SO}_4^{2-} + 2\text{H}^+ \\
2\text{H}_2\text{O} + 2\text{N}_2 + 5\text{O}_2 \rightarrow 4\text{NO}_3^- + 4\text{H}^+
\]

Typical reactions that are possible in the anaerobic zone include:

\[
4\text{Fe(OH)}_3 + \text{CH}_2\text{O} (\text{organic matter}) + 8\text{H}^+ \rightarrow 4\text{Fe}^{2+} + \text{CO}_2 + 11\text{H}_2\text{O} \\
3\text{CH}_2\text{O} + 2\text{N}_2 + 3\text{H}_2\text{O} \rightarrow 4\text{NH}_3 + 3\text{CO}_2 \\
\text{SO}_4^{2-} + 2\text{CH}_2\text{O} \rightarrow \text{H}_2\text{S} + 2\text{HCO}_3^-
\]

It is apparent that the anaerobic reactions are approximately the reverse of the aerobic reactions. Depending on the chemistry of the mine drainage, one of the above processes
should be maximized. In many mine drainage situations, one of the remediation goals is to increase the pH of the drainage. The pH is raised by removing hydrogen ions from the water; anaerobic process reactions shown above affect this removal. Consequently, when increase of pH is a primary concern, anaerobic processes should be emphasized in the design.

If mine drainage were directed into a natural wetland, the most complete and efficient removal of contaminants would not occur due to the abundance of removal processes and conflicting chemical reactions. Another reason that natural wetlands are not favored in mine drainage remediation is that the constituent pollutants in mine drainages vary considerably from site to site. Thus, the effectiveness of a natural wetland in remediating a particular mine site could not be reasonably predicted. Finally, natural
wetlands are not always located within close proximity to contaminated mine adits. Using natural wetlands would seriously limit the extent to which remediation by this method could be accomplished.

3.3 CONSTRUCTED WETLANDS

Due to the many limitations inherent in natural wetlands, new technologies pertaining to the construction of man-made wetlands have developed over the past decade. The benefits of using a constructed wetland are obvious. The wetland can be engineered so that a particular removal process is maximized. Thus, a wetland can be designed to most efficiently remediate a particular site. The wetland can also be designed to have minimal impact on the surroundings.

Passive mine drainage treatment technology utilizes the "geochemical mechanisms" of neutralization, oxidation, dilution, adsorption (cation exchange), co-precipitation and precipitation in order to reduce metals concentrations in mine effluent (Holm and Bishop, 1985). Klusman and Machemer (1991) list the removal processes operating in a wetland in the following sequence of decreasing importance:

1) Exchange of metals by an organic-rich substrate (usually peat).
2) Sulfate reduction with precipitation of iron and other sulfides.
3) Precipitation of ferric and manganese hydroxides.
4) Adsorption of metals by ferric hydroxides.
5) Metal intake by living plants.

Watson and others (1989) and Wildeman and Laudon (1989) would also include the following processes on the list:

6) Filtering suspended and colloidal material from water.
7) Neutralization and precipitation through the generation of NH$_3$
and HCO$_3^-$ by bacterial decay of biologic matter.
8) Adsorption or exchange of metals onto algal materials.

The first five processes are considered to be the most important with respect to acid mine water remediation. The significance of the last three processes is not yet fully understood. There is abundant literature available for those interested in a detailed examination of wetland chemistry, including: Faulkner and Richardson 1990, Gerber and others 1985, Herlihy and Mills 1985, Kleinmann and others 1985, McIntire and Edenborn 1990, Reed and others 1988, Snoddy and others 1989, Wieder and others 1984, and Wildeman and others 1990.

The primary goals of acid mine drainage remediation are to increase the pH of the drainage and to remove metals. The benefits of increasing the pH are twofold. First, the acidity of the drainage is reduced and brought closer to neutral levels. Second, the increase in pH has an effect on the solubility of metal ions. Once the pH is raised beyond the solubility range of a metal ion, it is precipitated as a solid. Thus, increases in pH are accompanied by the precipitation of stable metal compounds. The removal processes listed above function in such a way as to achieve these remediation goals.
Chapter 4

DESIGN COMPONENTS

4.1 INTRODUCTION

The design of a passive treatment system for any contaminated mine drainage is dependent on a variety of factors related to site conditions and influent water quality. This research is focused on the geotechnical and hydraulic factors upon which a design is based. The chemistry and biota of the wetland are, of course, very important. However, the chemical factors involved in the design process will only be touched upon due to the limited scope of this research.

A constructed wetland is designed to mimic the performance of a natural wetland. Through careful design, the passive treatment system can be made to be even more effective than the natural system. A constructed wetland could consist of the following components:

- containment structure
- dams and embankments
- settling basin
- water conveyance systems
- substrate material
- underdrains
- spillway
• anoxic limestone drain

The engineering considerations associated with the first seven components will be discussed in the remainder of this chapter. In addition, pertinent information pertaining to the utilization of each component for acid mine drainage remediation will be addressed. The anoxic limestone drain is a component unique to passive mine drainage treatment systems, and will be addressed in great detail in Chapter 5.

4.2 CONTAINMENT STRUCTURE

4.2.1 General Considerations

The most fundamental component of the wetland is the substrate containment structure. The containment structure should be designed to most effectively take advantage of local conditions. On-site building materials should be utilized if suitable. Three principle construction alternatives are currently available:

• compacted soil liner,

• geosynthetic lined excavation,

• structural concrete.

The type of containment structure used is dependent upon the potential for leakage out of the wetland. Leakage could adversely impact the environment by introducing chemical contaminants into the groundwater system. Leakage will also impact the performance of the treatment system. Anaerobic wetlands remediate mine drainage as it flows through organic substrate material. If the containment structure is leaky, the mine drainage could flow around the wetland instead of through it, decreasing the treatment capability of the system. For this reason, permeabilities should be determined for both the substrate material and the surrounding soils. If the soils are relatively permeable, a
compacted soil liner or geomembrane will be required for the system to function at optimum efficiency.

The compacted soil liner is the most economical method if low permeability materials are available on-site. An excavation is made on the site, and the soil liner is then compacted to an acceptable density (related to an acceptable permeability) in the excavation. The compacted soil liner may be constructed by re-compacting soils in the excavation or by introducing other soils from nearby borrow areas.

The dry density versus moisture content curve of the soil can be obtained by conducting a proctor test in accordance with ASTM standards (ASTM D698 and D1557). In addition, permeability tests should be run on compacted samples to verify the range of dry densities and moisture contents at which acceptable permeabilities may be achieved (Figure 17). This moisture content range will not necessarily include the optimum moisture content determined by the proctor curve. For example, the lowest permeabilities of a compacted clay soil are achieved by compacting the soil wet of the optimum moisture content. Construction specifications typically state an allowable range of moisture contents and dry densities which will produce the desired permeability.

Although the soil-lined excavation is the simplest and least expensive containment structure if low permeability soils are available on site, this method has a serious drawback. As in all naturally-lined systems, leakage from the wetland will occur if the permeability of the surrounding soil is greater than that of the substrate material. Leakage into the groundwater system may not be acceptable, considering the chemical constituents in the mine drainage.
A geomembrane liner may be used as a primary liner to greatly reduce or eliminate the potential for leakage. The geomembrane may be placed onto the bottom and sides of the excavation or on top of the compacted soils, which would now function as a secondary liner. The use of geomembranes gives rise to additional maintenance and costs. If the substrate in the wetland requires periodic replacement and/or rejuvenation, damage could occur to the synthetic liners during the replacement process. Also, geomembrane liners may be sensitive to ultraviolet radiation, so they should be covered by backfill.

To completely eliminate the problems associated with lined and unlined soil containment structures, formed concrete structures can be utilized (Gusek, 1992). The use
of structural concrete in the wetland design has several pros and cons. The structure would be durable and able to withstand a multitude of weather conditions. It would also be rather easy to maintain, as damage from rodents or other fauna would be minimal. Using a concrete structure is much more capital intensive than the aforementioned liner systems and would quickly increase the costs of the project. The structure would also limit the design functions of the wetland. The wetland could not be easily or inexpensively altered to more effectively remediate drainage depending upon conditions. Finally, the concrete would need to be treated in such a manner that it would become acid-resistant and would not be damaged by mine waters. Literature review has determined that this type of containment structure is not widely used.

4.2.2 Sizing of Containment Structure

Determining the size of wetland required for a particular site depends upon a number of factors. The first consideration is the final goal of the remediation project: is the project intended to bring the mine effluent up to discharge standards, or will less than complete remediation be acceptable? The treatment goals will determine whether aerobic or anaerobic wetlands should be emphasized in the treatment process, each of which is designed and sized according to different methods. A second consideration is the treatment ability of the particular substrate material used. Each substrate removes metals at varying rates, depending upon the material chemistry and permeability. Finally, the size of a wetland system will ultimately be controlled by the topography and conditions at the site. Overall, the wetland must be designed to effectively manage all expected flow rates into the system and remediate the proposed design discharge.
Much of the research aimed at determining wetland sizes has been conducted in the Eastern United States. However, the sizing guidelines developed in that area of the country cannot necessarily be applied directly to high altitude sites in Colorado due to topographic and climatic reasons (Herron, 1992).

Many researchers have developed design guidelines for sizing aerobic wetlands based upon a combination of empirical and theoretical methods. Sizing guidelines are given in terms of loading rates, or the amount of wetland surface area required per volume of mine drainage allowed into the wetland per a specified period of time. A summary of the various sizing guidelines is illustrated in Table 2.

Brodie and others (1988) developed a formula for sizing aerobic wetlands based upon the concentration of iron in the mine drainage. The minimum sizing guidelines are as follows:

Minimum size (m$^2$) = 2*(Fe mg/l)*Flow Rate (l/min)

Table 2. Aerobic wetland sizing guidelines.

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>SURFACE AREA/ GALLON/MINUTE</th>
<th>CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kleinmann (1985)</td>
<td>200 ft$^2$</td>
<td></td>
</tr>
<tr>
<td>Brodie et al. (1988)</td>
<td>140 to 4,600 ft$^2$</td>
<td>Metal Concentrations</td>
</tr>
<tr>
<td>Hedin (1988)</td>
<td>630 ft$^2$</td>
<td>&lt;50 ppm Fe</td>
</tr>
<tr>
<td>Hedin (1988)</td>
<td>1,200 ft$^2$</td>
<td>&gt;50 ppm Fe</td>
</tr>
<tr>
<td>Girts &amp; Kleinmann (1986)</td>
<td>630 ft$^2$</td>
<td></td>
</tr>
</tbody>
</table>
All of the sizing methods listed in Table 2 were developed in areas having much longer growing seasons than those found in the high altitude Rocky Mountains. During the dormant winter period, the rate of wetland treatment and efficiency will be lower than the rest of the year. As a result, constructed wetlands built in high altitude environments will require significantly larger areas than those in lower altitude environments. Herron and others (1991) have developed an empirical sizing chart for constructed wetlands in high altitude environments. The chart is based upon both the site altitude and the overall concentration of metals found in the mine drainage. Table 3 illustrates the design guidelines.

The recommendations given in Table 3 should be followed when designing an aerobic wetland in high altitude environments. Unfortunately, it is often not possible to achieve the optimum wetland size, due to rugged mountain terrain and legal problems associated with land ownership.

Table 3. Aerobic wetland sizing guidelines for high altitude environments.

<table>
<thead>
<tr>
<th>ELEVATION (FT)</th>
<th>&lt; 20 PPM METALS</th>
<th>20 - 100 PPM METALS</th>
<th>&gt; 100 PPM METALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 - 7000</td>
<td>1,000 ft²/gpm</td>
<td>1,250 ft²/gpm</td>
<td>1,500 ft²/gpm</td>
</tr>
<tr>
<td>7 - 9000</td>
<td>1,250 ft²/gpm</td>
<td>1,500 ft²/gpm</td>
<td>1,750 ft²/gpm</td>
</tr>
<tr>
<td>9 - 11,500</td>
<td>1,500 ft²/gpm</td>
<td>1,750 ft²/gpm</td>
<td>2,000 ft²/gpm</td>
</tr>
<tr>
<td>&gt; 11,500</td>
<td>1,750 ft²/gpm</td>
<td>2,000 ft²/gpm</td>
<td>3,000 ft²/gpm</td>
</tr>
</tbody>
</table>
All of the sizing methods included in Tables 2 and 3 are applicable only to aerobic wetlands, where the amount of surface area directly controls the treatment processes at work. Anaerobic treatment reactions occur as the mine drainage flows through the wetland substrate, therefore the treatment ability and performance efficiency of anaerobic wetlands are based upon volumetric considerations.

The primary treatment process which occurs in the anaerobic zone is sulfate reduction (Wildeman, 1992). Sulfate-reducing bacteria in the anaerobic zone generate sulfide under reducing conditions as the mine drainage passes through the system. The sulfide reacts with metals in the mine drainage to form precipitates. A typical reaction would be as follows:

$$\text{Fe}^{2+} + \text{S}^{2-} \rightarrow \text{FeS}$$

Proper wetland sizing would cause the metals concentrations to be the limiting reagent, not the sulfide, since the sulfate-reducing bacteria could be easily overwhelmed with excess metals (Wildeman et al., 1991).

Recent studies have determined that sulfate-reducing bacteria can be expected to generate 300 nanomoles of sulfide per cubic centimeter of substrate each day (Reynolds et al., 1991, McIntire and Edenborn, 1990). Using this number, along with the flow rate of the drainage and the metals concentrations, the volume of wetland substrate required for complete removal can be determined using the following equation:

$$m^3 = \frac{(\text{flow rate L/day})(\text{metals concentration mg/L})}{300(\text{atomic weight of the metal})(\text{mols of metal req'd to react with 1 mol sulfide})}$$

Conversely, the expected quantity of metals removal for a given wetland size could be determined.
4.3 DAMS AND EMBANKMENTS

4.3.1 General Considerations

Dams and embankments will likely be part of any passive mine drainage treatment system. The stability of these structures is of vital importance to the stability of the entire treatment system. The structures must be designed to effectively impound water and substrate material and withstand any expected storm event. They should be designed with adequate slope stability and be designed to deter, or at least withstand, damage from outside sources such as rodents or vandals.

4.3.2 Engineering Guidelines

Dams used in constructed wetlands systems can be designed to be permeable or impermeable. The type of dam utilized will depend upon the type of flow path desired in the wetland which the dam is impounding. A permeable loose rock dam would be beneficial to use in a situation where the mine drainage is intended to flow over the wetland material, such as in an aerobic wetland (figure 18). Alternatively, an impermeable dam would be required for a system where the mine drainage needs to flow through the wetland substrate, such as in an anaerobic wetland (figure 19).

Regardless of the permeability of the particular dam, all dams utilized in PMDTs should adhere to several design guidelines (Herron et al., 1991). Erosion control fabric should be used on all dams and embankments. The maximum height of the dam should not exceed ten feet, as measured from the toe of the embankment to the crest of the spillway. The minimum top width of the dam should be five feet. In addition, all dams must be keyed into the foundation. Keyway dimensions of three feet in width and three feet in depth
should be adequate for most dams. The following slope dimensions should be followed for varying dam materials (Herron et al., 1991):

- angular rock 2h: 1v
- smooth rock 2.5h: 1v
- compacted soils 2h: 1v

4.4 SETTLING BASIN

4.4.1 General Considerations

The settling basin is a component which is being utilized more frequently in passive mine drainage treatment technology. The settling basin allows for flow control and acts to

Figure 18. Diagram of a typical wetland where the drainage is intended to flow over the surface of the wetland (Herron et al., 1991).
Figure 19. Diagram of a typical wetland where the drainage is intended to flow through the substrate in the wetland (Herron, et al., 1991).

increase the longevity of substrate material located downstream by reducing the metals concentrations of the mine drainage. Many sites contaminated with acid mine drainage experience variable flow rates. When using constructed wetlands, it is desirable to maintain a constant or predictable flow rate through the system. A settling basin can be constructed to serve as a retention pond which will regulate the flow into the rest of the treatment system. Flow can be managed in the settling basin by means of weirs and spillways.

A second, and perhaps more important, function served by the settling basin is associated with the chemical removal processes at work in a constructed wetlands. At sufficient pH levels, metals will readily precipitate out of solution in an oxygenated environment such as a settling basin. By coupling a settling basin with a pH-increasing
component (such as limestone), precipitation of metals can be induced. A settling basin should be installed upstream of the main organic wetlands, so that metals in the drainage will have the chance to precipitate before entering the substrate. As a result, the effective treatment life of the organic substrate could be significantly increased, since fewer metals will precipitate in the wetlands and clog the substrate.

4.4.2 Engineering Guidelines

The primary consideration associated with the design of a settling basin is sizing. The basin dimensions must be designed so that all of the expected precipitates will have the opportunity to settle out of solution within the basin. The depth of the basin must be designed with two factors in mind. First, the depth must be sufficient enough to ensure adequate storage space for the accumulation of precipitates. In addition, the depth of the basin must be great enough so that precipitates are not re-suspended by flow through the settling basin.

A simplified settling basin can be represented by a rectangle having a width W, a depth D and a length L (figure 20). The surface area of the basin is represented by WL. The flow through the settling basin can be represented by (Goldman et al., 1986):

\[ Q = A V_s \]

\( Q \) = discharge thorough the basin,

\( A \) = surface area of the basin,

\( V_s \) = settling velocity of the particles.
Upon introducing a coefficient to account for turbulence, the required surface area for a settling basin designed to manage a known discharge of water is as follows:

\[ A = \frac{1.2Q}{V_s} \]

The smallest particle size used in design is approximately 0.02 mm, which corresponds to a medium silt. The settling velocity associated with a medium silt is 0.0029 m/sec (0.00096 ft/sec). This particle size was selected as a reasonable design parameter because finer particles would require too much time to settle out of solution, resulting in enormous surface area requirements.

The minimum suggested settling basin depth is two feet. A conservative design approach would be to limit the L/D ratio to 200 (Goldman et al., 1986).

Figure 20. Diagram of a typical settling basin (Goldman, et al., 1986).
4.5 WATER CONVEYANCE SYSTEM

4.5.1 General Considerations

The rate of flow through a constructed wetland is vital to the effectiveness of the wetland as a treatment system. Generally, fully enclosed conveyances such as pipes are utilized in order to minimize contact with oxygen. The pipes must be non-reactive with the contaminated waters or the substrate. In addition, they must be resistant to ultraviolet light if they will be exposed to the surface. Standard PVC tubing has been successfully utilized in many passive mine drainage treatment systems.

Since many of the mine sites being studied in the western United States are in mountainous regions, the pipes must be able to endure freezing temperatures. Thus, the pipes should be insulated and buried beneath the frost line. Although such burial will increase costs initially, it will minimize costs resulting from the repair of frozen pipes.

The most critical operational factor involved in the pipe system is the accumulation of metal hydroxide deposits. As discussed earlier, pyrite oxidation causes the precipitation of ferric hydroxides. These deposits can render a wetland useless if they are permitted to clog the pipe systems. Fortunately, several steps can be taken in the design of the wetland to reduce the amount of accumulation.

One of the most effective methods in reducing the accumulation of hydroxides in the pipe network is to allow for the precipitation of them elsewhere in the system. Specifically, a holding pond can be installed at the beginning of the treatment system. By allowing for the precipitation to occur before the water enters the conveyances, the amount of accumulation in the pipes will be greatly reduced.

Although a retention pond would remove a significant amount of hydroxides, precipitation in the pipes will still occur. One way to accommodate for metals accumulation
is to overdesign the pipe diameter. If proper design calls for a 2-inch diameter pipe, perhaps a 4-inch diameter pipe could be utilized instead. To combat blockage problems, the pipe channels should be as continuous as possible, eliminating sharp bend or turns. Flow control mechanisms such as valves should also be avoided if possible, as precipitates tend to accumulate in such structures. Finally, the plumbing system should be designed to facilitate periodic cleaning. Utilization of wye or tee junctions allows for easy cleaning of the pipes.

4.5.2 Engineering Considerations

The water conveyance system must be designed so that all expected flow rates into the treatment system can be sufficiently managed. The pipe diameters required depend upon two design parameters: the maximum expected flow rate into the system and the desired flow rate which will undergo remediation.

The design storm responsible for the maximum expected flow rate into the system is dependent upon the relative importance of the treatment system and the size of the watershed. Based upon those factors, a particular intensity storm with a given recurrence interval is selected as the design storm event. The magnitudes of the various expected hydrologic events are best determined by a complete hydrologic study of the site. The study should determine the drainage area impacting the site, as well as the expected response of the land to the precipitation event.

Because the pipe capacity must be great enough to sufficiently manage the flow resulting from the design storm, the pipe network is likely to be over-designed with respect to the desired treatment capacity of the wetlands.
One can determine the diameter of pipe required for a wetland system using a fundamental equation of fluid mechanics (Fetter, 1988):

\[ Q = AV \]

where:

- \( Q \) = design discharge,
- \( A \) = cross-sectional area of the pipe = \( \frac{\pi D^2}{4} \),
- \( V \) = velocity of the flow

The design of the pipes can be approached in two ways. If there is a known amount of discharge which the pipes are intended to effectively transmit, the required pipe diameter can be determined. Conversely, if a particular diameter of pipe is available, one can determine the amount of discharge which the pipe can manage.

In order to use the aforementioned equations, it is necessary to know the velocity of the fluid as it is transmitted through the pipe network. The velocity can be calculated using Bernoulli’s Equation, another fundamental equation of fluid mechanics (Chaudhry, 1993):

\[ \frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g} + h_m + h_i \]

where \( p \) = pressure, \( z \) = elevation, \( v \) = velocity and \( h \) = head losses through the system. Bernoulli’s Equation is based upon the conservation of energy as a fluid flows through a system. Bernoulli’s Equation can be evaluated at critical points along the treatment system so that a complete understanding of the hydraulic system can be gained.

The losses in the system result from friction in the pipe and entrance or exit losses. The magnitude of the losses depends upon the type of material involved and the distance...
traveled by the fluid; a smooth PVC pipe will experience smaller head losses than a rough corrugated metal pipe with many bends.

4.6 SUBSTRATE MATERIAL

The substrate in a constructed wetland is the material through which the contaminated water flows. It may consist of mixtures of organic and inorganic soils, and usually contains animal manure. The composition and permeability of the substrate material are critical factors controlling the effectiveness of the wetland in removing contaminants from the mine drainage. The drainage must be permitted to flow freely through the substrate, maximizing its contact with the organic material. The following materials have been used successfully as substrate (Gusek, 1992):

- mushroom compost (manure and barley mash waste),
- peat moss,
- aged manure,
- decomposed wood products,
- limestone,
- straw.

The effectiveness of a particular substrate at remediation is dependent on a variety of factors. The chemistry of the contaminated drainage dictates the type of substrate used; however, the permeability of the material seems to have the greatest physical effect on the performance of the wetland. Studies have shown that, over time, the organic substrate tends to become more compact and less permeable (Lemke, 1989).

One factor leading to the decrease in permeability is the biochemical decay and disintegration of the organic matter. The permeability also decreases due to mechanical
sorting caused by the drainage flowing through the substrate. This sorting effect is particularly important in peat (Guertin et al., 1985). Studies have shown that continual flow over and through a bed of peat causes the less dense, woody components to separate and float to the top of the wetland. What remains is an extremely dense, low permeability mat of organic material. As a result, the mine drainage effectively flows between the two layers, passing through the wetland virtually untreated.

Several researchers have studied the permeability of organic substrates under various flow conditions (Bolis et al., 1992, Lemke 1989, Cooper and Hobson 1989, Watson et al., 1989, Staubitz et al., 1989). The values of hydraulic conductivity obtained by the researchers are presented in Table 4. These values can be used to obtain a preliminary design discharge, although testing should be conducted to determine the actual k value. The testing method used should correspond to the expected flow conditions in the field, e.g. use a downflow permeameter if the wetland will be designed to function in a downflow capacity.

Potential substrate candidates should be tested to determine the percent organic material and pH. If the organic content is too low, not enough biological matter will be available to fuel the chemical reactions occurring in the wetland. Conversely, too much organic material could overwhelm the system. Wildeman recommends using material with an organic content ranging from 30% to 50% (Wildeman, 1992). A second concern is the pH of the material. Since the substrate is being used to remediate acidic waters, its pH should be neutral or basic. Ultimately, the type of substrate used in a system will depend upon material availability and chemical suitability.

Anecdotal information provided by Herron (1993) gives rise to some practical recommendations with respect to the use of organic substrates in constructed wetlands.
Table 4. Hydraulic conductivity of substrates used in constructed wetlands for the remediation of acid mine drainage.

<table>
<thead>
<tr>
<th>Material</th>
<th>K (cm/sec)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC lab downflow</td>
<td>3.50 x 10^{-3}</td>
<td>Lemke 1989</td>
</tr>
<tr>
<td>MC bench downflow</td>
<td>3.14 x 10^{-3}</td>
<td>Lemke 1989</td>
</tr>
<tr>
<td>MC pilot downflow</td>
<td>2.96 x 10^{-4}</td>
<td>Lemke 1989</td>
</tr>
<tr>
<td>MC lab upflow</td>
<td>6.65 x 10^{-2}</td>
<td>Lemke 1989</td>
</tr>
<tr>
<td>MC bench upflow</td>
<td>1.44 x 10^{-2}</td>
<td>Lemke 1989</td>
</tr>
<tr>
<td>MC pilot upflow</td>
<td>1.38 x 10^{-2}</td>
<td>Lemke 1989</td>
</tr>
<tr>
<td>Dry M lab (CH)</td>
<td>4.0 x 10^{-6} to 2.0 x 10^{-3}</td>
<td>Bolis 1992</td>
</tr>
<tr>
<td>Sat M lab (CH)</td>
<td>4.4 x 10^{-6} to 2.9 x 10^{-3}</td>
<td>Bolis 1992</td>
</tr>
<tr>
<td>Innoc M lab (CH)</td>
<td>5.6 x 10^{-6} to 4.9 x 10^{-3}</td>
<td>Bolis 1992</td>
</tr>
<tr>
<td>Dry M field (CH)</td>
<td>3.7 x 10^{-3} to 1.1 x 10^{-2}</td>
<td>Bolis 1992</td>
</tr>
<tr>
<td>Sat M field (CH)</td>
<td>3.5 x 10^{-5} to 7.2 x 10^{-3}</td>
<td>Bolis 1992</td>
</tr>
<tr>
<td>Innoc M field (CH)</td>
<td>5.6 x 10^{-5} to 3.6 x 10^{-3}</td>
<td>Bolis 1992</td>
</tr>
<tr>
<td>Dry M lab (CH)</td>
<td>4.0 x 10^{-2}</td>
<td>Bolis 1992</td>
</tr>
<tr>
<td>Dry M lab (FH)</td>
<td>2.1 x 10^{-2}</td>
<td>Bolis 1992</td>
</tr>
<tr>
<td>Sat M lab (FH)</td>
<td>3.0 x 10^{-3}</td>
<td>Bolis 1992</td>
</tr>
<tr>
<td>Dry innoc M field (CH)</td>
<td>9.9 x 10^{-5} to 7.1 x 10^{-3}</td>
<td>Bolis 1992</td>
</tr>
<tr>
<td>Sat innoc M field (CH)</td>
<td>3.4 x 10^{-4} to 6.9 x 10^{-3}</td>
<td>Bolis 1992</td>
</tr>
</tbody>
</table>

MC = mushroom compost, M = manure, CH = constant head, FH = falling head, Innoc = inoculated with bacteria, Sat = saturated prior to test, Dry = dry until commencement of test
Mushroom compost appears to be very effective at removing contaminants. Low density materials, such as wood chips and straw, are not recommended for use due to containment problems. The light materials often become suspended in the mine drainage and are washed out of the system. The use of peat has resulted in operational difficulties associated with maintaining acceptable flow rates through the system. Regardless of the type of substrate used, care should be taken to avoid compaction of the material upon emplacement in the wetland. If wetland vegetation is planted in the substrate, the wetland should be saturated within one or two days to facilitate plant growth.

4.7 UNDERDRAINS

4.7.1 General Considerations

The purpose of an underdrain is to drive the mine drainage through the organic substrate in a wetland so that treatment can occur in the anaerobic zone. An underdrain is created by embedding pipes in a highly conductive gravel bed. Underdrains can be used in the bottom of the wetland cell to collect mine drainage which has infiltrated through the substrate. The use of such underdrains has several benefits. The drains will not be likely to short-circuit due to clogging by precipitates. Also, limestone cobbles could be used in the underdrain to introduce alkalinity as the mine effluent passes through the drain.

4.7.2 Engineering Considerations

The most important consideration associated with underdrains is the appropriate selection of filter material, such as coarse gravel, limestone cobbles or filter fabric. The hydraulic conductivity of the filter material must be greater than that of the overlying substrate so that fluid will easily flow through the drain. However, the difference in
permeability cannot be so great that the substrate material will erode away and wash into the underdrain.

Terzaghi and Peck (1948) have suggested the following criteria for selection of filter material which will transmit fluids without eroding the substrate:

\[
\frac{D_{15(F)}}{D_{85(B)}} < 4 \quad \frac{D_{15(F)}}{D_{15(B)}} > 4
\]

B refers to the base material which requires protection; for wetland design B would correspond to the organic substrate. F refers to the filter material; for wetland design F would correspond to the gravel material in the underdrain. The D terms refer to the particle diameters through which a given percent (by weight) of the material will pass. \(D_{15(F)}\) corresponds to the diameters through which 15% of the filter material will pass. The filter selection criteria can be represented graphically as grain size distribution charts (Figure 21, Das, 1990).

4.8 SPILLWAY

4.8.1 General Considerations

Spillways should be installed throughout the treatment system for several reasons. Spillways function by channeling excess mine drainage out of the system so that dams and embankments are not overtopped and eroded. Spillways also protect the system from unexpected inflows of water from powerful hydrologic events. A second function served by spillways is associated with system monitoring. Weirs or flumes can be installed in spillways and can be used to monitor flow rates throughout the system (figure 22).
Figure 21. Graphical representation of filter selection criteria (Das, 1990). The shaded zone represents acceptable filter material for the base material represented by Curve $a$.

Figure 22. Photo of a concrete spillway and V-notch weir.
4.8.2 Engineering Considerations

The following equation is used for spillway design (Shames, 1992):

\[
Q = AV; V = \left( \frac{1.486}{n} \right) R^{2/3} S^{1/2}
\]

- \( n \) = Manning’s roughness coefficient,
- \( S \) = slope or stream gradient
- \( R \) = hydraulic radius (area of channel/wetted perimeter)
- \( Q \) = design discharge in cfs

Values of Manning’s roughness coefficient are given in Table 5.

The second important function served by a spillway is the determination of flow rate via weirs. Weirs are used to calculate flow rate based upon the height of water flowing above the crest. Weirs can be sharp- or broad-crested, and are shaped in a variety of forms. The most common forms are the rectangular weir and the V-notch weir (figures 23 and 24). The rectangular weir calculation is as follows:

\[
Q = \frac{2}{3} C'_d L'_w \sqrt[3]{2g(h')^3}
\]

The discharge capacity of a rectangular weir is based upon the area through which water can pass and the head above the crest. The weir coefficient (\( C'_d \)), length of the weir (\( L'_w \)) and head above the weir (\( h' \)) are modified based upon the degree of contraction experienced by the water as it flows over the weir. Design charts are used to determine the necessary adjustments (Figure 25).
Table 5. Manning's roughness coefficients (Chaudhry, 1993).

<table>
<thead>
<tr>
<th>Material</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>0.012</td>
</tr>
<tr>
<td>Cast Iron</td>
<td>0.013</td>
</tr>
<tr>
<td>Corrugated Metal</td>
<td>0.025</td>
</tr>
<tr>
<td>Cement</td>
<td>0.011</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.013</td>
</tr>
<tr>
<td>Clay</td>
<td>0.013</td>
</tr>
<tr>
<td>Clean, straight streams</td>
<td>0.030</td>
</tr>
<tr>
<td>Stream with gravel, cobbles and boulders</td>
<td>0.040</td>
</tr>
<tr>
<td>Stream with cobbles and large boulders</td>
<td>0.050</td>
</tr>
</tbody>
</table>
Figure 23. Diagram of a rectangular weir.

Figure 24. Diagram of a V-notch triangular weir.
Figure 25. Coefficient adjustments for rectangular weir calculations.
The performance of a V-notch weir is based upon the same principals. The area of the weir is related to the angle of the notch, as well as the height of the notch. The formula for a V-notch weir is as follows:

\[ Q = C_w \frac{8}{15} \tan\alpha \sqrt{2gh^2} \]
Chapter 5

ANOXIC LIMESTONE DRAIN

5.1 FUNCTION AND PURPOSE

A relatively new component of passive mine drainage treatment technology is the anoxic limestone drain (ALD). Dominant treatment processes in constructed wetlands include oxidation and hydrolysis of iron and other metals in solution. Hydrolysis reactions produce acidity, which must be buffered by an influx of alkalinity to avoid substantial decreases in pH. The use of limestone as a buffer is highly desirable, due to its non-toxic impact upon wetlands biota, low sludge production, and low risk of overloading (Brodie et al., 1988). However, hydrolysis of iron in an oxygenated environment leads to rapid precipitation of ferric hydroxides onto the limestone cobbles (Nairn et al., 1990, Hedin and Nairn, 1990). As a result, the buffering capacity of the limestone is greatly reduced or eliminated, due to the impenetrable armor coating. During the early stages of passive mine drainage treatment development, this armoring process was viewed as an unavoidable and unfortunate problem which would seriously affect the performance of a system.

ALD technology developed in response to the operational problems encountered by the use of limestone as a buffer. An ALD serves two basic functions. First, the limestone acts to increase the alkalinity of the drainage, thus increasing its pH. The second function of the ALD is to create and sustain anoxic conditions within the wetland (Brodie, 1991). Anoxic conditions prohibit oxygen from coming into contact with the drainage. The precipitation of metals is inhibited, thus preventing the limestone from becoming armored.
with ferric hydroxides and other precipitates. As a result, the life and effectiveness of the limestone is greatly increased.

5.2 METHODS OF CONSTRUCTION

In order for an ALD to be effective, contact with atmospheric oxygen should be eliminated or minimized. The Tennessee Valley Authority (TVA) has experimented with a basic trench system. A typical trench ALD is shown in Figure 26. This system was created quite by accident at Impoundment 1, a constructed wetland which treats acid mine drainage from the Fabious Coal Preparation Plant in northeastern Alabama. An earthen dam was constructed over an existing haul road which was built using a high calcium limestone. The limestone roadbed was not intended to function in a treatment capacity, although it served to pre-treat the mine drainage before it entered into the constructed wetland system (Brodie et al., 1991).

The trench system is built by digging an excavation into the mine backfill or elsewhere on the site. The trench is then filled with crushed limestone having a high calcium content (>90% CaCO₃). Limestone having a low calcium content (< 90% CaCO₃) or dolomitic limestones (high Mg content) are not recommended for use due to slower dissolution rates.

The limestone in the trench is sealed from the environment by a compacted clay cover and geofabric. It is recommended to use at least two feet of cover material to ensure complete removal of atmospheric oxygen (Nairn et al., 1990). The cover over the ALD should be crowned to discourage infiltration of rainwater from above, and to accommodate any subsidence experienced due to limestone dissolution. Finally, the
Figure 26. Diagram of a typical trench ALD.
crown should be treated to prevent revegetation by plants whose roots could extend down into the ALD. Such root action could allow for oxygen to enter the ALD.

Another method for constructing an ALD was addressed in this research. Herron observed that pyrite oxidation often ceases in flooded mines, indicating that anoxic conditions exist (Herron, 1992). An ALD could be created within abandoned mine workings by filling the tunnels with limestone and then flooding the mine. Such a system was created at the Marshall No. 5 site by building a dam at the mine adit (figure 27).

5.3 DESIGN CONSIDERATIONS

5.3.1 Design Life

An important design consideration associated with the use of ALD’s is the determination of adequate size. The size of the ALD will be dependent upon the desired

Figure 27. Diagram of ALD created by flooding the mine adit.
design life of the system as well as the ability of the limestone to dissolve and introduce alkalinity. The determination of design life is poorly understood and not well-supported by empirical data. Nonetheless, some theoretical guidelines are available which may help determine an approximate design life.

In order to determine an expected design life of an ALD, the dissolution rate of the limestone to be used must be ascertained. Field experiments should be conducted to determine feasible dissolution rates of the limestone involved in a particular ALD. Once an accurate dissolution rate is determined, the volume of limestone required to achieve a particular design life can be calculated. Gusek recommends passing a known quantity of mine drainage at known flow rate through a bench scale ALD (Gusek, 1992). The dissolution rate of the limestone can be calculated by determining the amount of limestone which has dissolved over the time period allotted for the test. The field test would more accurately reflect the ability of the limestone to dissolve in the mine drainage than would a laboratory experiment.

It should be noted that the dissolution rate is likely to change over time, if any oxygen is introduced into the system. The introduction of oxygen would eliminate the anoxic environment of the drain, which would lead to precipitation of ferric hydroxides onto the limestone. Due to the immeasurable, but likely, variability in dissolution rate, a safety factor should be introduced when determining the design life of an ALD. Herron recommends that the actual design life should be assumed to be no greater than half the calculated life, due to the many uncertainties associated with the ALD (1993). The determination of design life is at best an approximation, since no long term ALD results are available.
5.3.2 Hydraulic Considerations

In addition to dissolution rate, the size of an ALD depends upon the hydraulic properties of the limestone. In order to maintain a functioning ALD, the maximum expected flow through the system should be determined. The flow could be calculated by direct measurements, but a hydrologic study would best determine the maximum probable flow. The cost of constructing an ALD is rather low in comparison to conventional treatment methods, so it is best to overdesign the system (Brodie et al., 1991).

Once the hydraulic capacity of the ALD is determined, the overall dimensions can be calculated. Darcy's Law can be applied to determine the required cross-sectional area of the trench, given the maximum expected flow rate (Fetter, 1988):

\[ Q = KA_i \]

where \( Q \) = expected discharge into the trench,
\( K \) = hydraulic conductivity of the limestone,
\( A \) = cross-sectional area,
\( i \) = slope gradient through the trench.

The hydraulic conductivity of the limestone can be calculated using a constant head permeability test (figure 28). In a laboratory, the limestone cobbles are placed into a permeameter of known dimensions. A constant hydraulic head is introduced over the apparatus. Fluid is passed through the permeameter, and the time to collect a certain volume is recorded. Difficulties arise due to the coarse nature of the cobbles. The boundary conditions between the cobbles and the sides of the permeameter will not be very tight. As
Figure 28. Diagram of a constant head permeameter.

As a result, fluid will tend to flow along the sides of the permeameter instead of through the cobbles; the test may function to calculate the hydraulic conductivity of the permeameter instead of the cobbles. The use of large, bench-scale permeameters could alleviate this problem. The following equation is used to determine the value of $K$ (Fetter, 1988):

$$K = \frac{VL}{Ath}$$

where $V =$ volume of water discharged in time $t$,

$L =$ length of the sample,

$A =$ cross-sectional area of the sample,

$h =$ hydraulic head over the sample.
5.4 DESIGN GUIDELINES

Earlier portions of this chapter have focused on the design and construction of ALD systems. Although the use of such a component for acid mine drainage remediation appears to ensure successful treatment, the success of an ALD is not so easily achieved. The water quality of the mine drainage in question directly affects the performance of an ALD. Specifically, the influent pH, acidity, alkalinity, iron and aluminum concentrations and levels of dissolved oxygen control the effectiveness of an ALD (Brodie et al., 1991). The previously mentioned water quality characteristics should be determined before consideration is given to the use of an ALD.

It is not yet understood exactly how the mine drainage characteristics affect the performance of an ALD, although general guidelines can be given based upon experience. Empirical evidence gathered by the TVA has led to the development of the following design guidelines with respect to ALDs (Brodie et al., 1990):

Case 1: \( \text{Alkalinity} > 100 \text{ mg/l, Fe} > 50 \text{ mg/l} \)

ALD may be beneficial, but not necessary. The mine drainage may contain sufficient alkalinity to effectively buffer the pH without additional inputs of limestone.

Case 2: \( \text{Alkalinity} > 100 \text{ mg/l, Fe} < 50 \text{ mg/l} \)

ALD not necessary, only wetlands, due to sufficient levels of alkalinity and low levels of iron in the mine drainage.
Case 3:  
**Alkalinity < 100 mg/l, Fe > 50 mg/l**

ALD recommended and necessary. The mine drainage does not possess enough alkalinity to buffer the decrease in pH expected to result from the hydrolysis of abundant iron.

Case 4:  
**Alkalinity < 100 mg/l, Fe < 50 mg/l**

ALD recommended, but not necessary. The mine drainage does not have excessive iron, so the pH is not expected to drop much due to iron hydrolysis. The amount of alkalinity is expected to sufficiently buffer the pH.

Case 5:  
**Alkalinity < 0 mg/l, Fe < 50 mg/l**

ALD will likely become necessary as Fe approaches 50 mg/l. Although excessive H⁺ is not expected to be generated through iron hydrolysis due to low iron levels, an influx of alkalinity may be required as the iron level increases.

Case 6:  
**Dissolved oxygen > 2.0 mg/l OR pH > 6.0 and Eh > +300 mv**

ALD not recommended due to high potential for Fe oxidation and subsequent armoring of the limestone cobbles.
6.1 INTRODUCTION

Previous chapters have discussed in some detail the engineering characteristics of the various components that make up a passive mine drainage treatment system. This chapter will focus on the development of a conceptual wetland design. A conceptual design is a preliminary design plan based upon the mine drainage characteristics. Included in the conceptual design are considerations such as:

• spatial constraints at the site
• treatment requirements of the mine drainage
• type of wetland to be utilized (aerobic or anaerobic)
• number and type of treatment cells
• layout of treatment cells

Once a conceptual design has been developed, the final wetland design can be completed.

6.2 GEOLOGICAL INVESTIGATION

The first step in any project is to conduct a thorough site investigation. The purpose of this investigation is to identify any adverse geologic conditions which could affect the PMDT. Information pertaining to bedrock material, surficial deposits, surface and subsurface water, drainage area and other basic geological factors should be gathered.
Much of this information can be obtained by interpreting published maps and air photos before going into the field.

The field investigation should focus on identifying the geomorphic processes at work in the area, and determining the potential effect on the PMDT. Activities which could affect the system design include landslide activity, seeps, and subsidence.

The geologic investigation will provide useful information such as: the type and quantity of materials available for construction; the amount of land suitable for construction; the maximum cell depth (based upon depth to water table and depth to bedrock); potential geologic problems or hazards associated with the construction process.

The site investigation is important because the final design will be based ultimately upon the conditions and characteristics identified during the preliminary investigation. The mine drainage characteristics may suggest a particular wetland size or configuration, but the recommended design can only be adhered to if the site will accommodate it.

### 6.3 MINE DRAINAGE CHARACTERIZATION

It is necessary to obtain information pertaining to the mine effluent. Water quality samples should be gathered at various times during the year, at various flow rates, so that an accurate characterization can be made. The mine effluent should be analyzed to determine the following information:

- dissolved oxygen
- alkalinity
- oxidation potential (Eh)
- acidity (pH)
- levels of total metals (Al, Fe, Mn, Zn, Pb, etc.)
• levels of dissolved metals (Al, Fe, Mn, Zn, Pb, etc.)
• conductivity
• flow rate
• level of sulfates

Appendix D lists the equipment needed to conduct a water sampling program.

6.4 TYPE OF WETLAND

There are two types of wetlands that could be utilized in a PMDT: aerobic or anaerobic. The wetland types could be used individually, or a combination of both could be implemented. The type of wetland required for a site will depend upon the remediation requirements of the mine drainage. In general, an aerobic wetland is best suited to waters having net alkalinity, while an anaerobic wetland is more appropriate for waters having net acidity (Hedin and Nairn, 1990). Regardless of wetland type used, the wetland cells should be constructed with irregular boundaries, to encourage plant growth and diversity. A discussion of each wetland type follows.

6.4.1 Aerobic Wetlands

Water flows over the surface in an aerobic wetland. By remaining at the surface, atmospheric oxygen is available to react with the mine drainage. Since the primary treatment reactions occur at the surface, it is not necessary to construct a deep wetland cell. However, the cell should not be too shallow, or it could freeze over during the winter months. An appropriate cell depth would range between 4 and 12 inches.
An aerobic wetland should be used to treat net alkaline waters. Mine drainage having net alkalinity will have sufficiently high levels of alkalinity to buffer the acidity produced by hydrolysis reaction. The aerobic conditions in the wetland aerate the drainage, thus facilitating oxidation of metals. To increase dissolved oxygen levels in the wetland, features such as waterfalls and cascades should be included in the design. Sizing guidelines for aerobic wetlands were listed in Table 2 and Table 3 in Chapter 4.

6.4.2 Anaerobic Wetlands

In situations where the mine effluent is acidic, an anaerobic wetland is recommended. The mine drainage flows through the wetlands in this case, interacting with the organic substrate. Since the performance of anaerobic wetlands is based upon substrate volume, the cell depth should be large enough to accommodate adequate volumes. Deeper cells will lower the level of dissolved oxygen and result in reducing conditions. Wetland cells could be several feet deep, although most aquatic vegetation can only withstand depths of 18 inches. The cell depth should be variable throughout the wetland, to facilitate plant diversity.

The principle treatment method at work in an anaerobic wetland is sulfate reduction. Sulfate reducing bacteria, such as *Desulfovibrio*, are necessary for this process to function properly (Postgate, 1979). The bacteria help reduce sulfates into sulfides, which precipitate in the wetland. The sulfate reduction reaction is represented below (Wildeman *et al.*, 1992):

\[
\text{SO}_4^{2-} + 2\text{CH}_2\text{O} \text{ (organic material)} + 2\text{H}^+ \rightarrow \text{H}_2\text{S} + 2\text{H}_2\text{O} + 2\text{CO}_2 \text{ (pH < 7)}
\]

\[
\text{SO}_4^{2-} + 2\text{CH}_2\text{O} \rightarrow \text{HS}^- + 2\text{HCO}_3^- + \text{H}^+ \text{ (pH > 7)}
\]
Under reducing conditions, H\textsubscript{2}S and CO\textsubscript{2} are created while acidity is reduced. If the pH of the drainage becomes too low, the gases will exsolve, thus limiting the pH decrease. The loss of H\textsubscript{2}S increases the pH of the drainage, and creates the characteristic rotten egg smell associated with wetlands and swamps. If the conditions are less acidic, the second reaction produces HS\textsuperscript{-}, which forms extremely insoluble sulfides with many of the metals found in mine drainage.

6.5 NUMBER AND TYPE OF TREATMENT CELLS

The possible combinations of treatment cells is countless. Factors such as water chemistry, site constraints and available funding all impact the final treatment design at a site.

It is best to design a system to include several cells, or stages. By incorporating several different cells into the PMDT, each one can be designed to function in a particular fashion. For example, one cell can be used to introduce alkalinity, another to facilitate metals precipitation through aeration, and another to manage flow. By using several different stages, problems associated with conflicting reactions within individual cells can be minimized. In addition, the multi-stage design allows for flexibility in the operation of the system. If one particular cell appears to be removing contaminants much more efficiently than another, the less efficient cell could be modified.

The number of cells required will depend upon the treatment efficiency of the wetlands involved. If a particular wetland cell is capable of removing 10 grams of metals per every square meter of substrate every day (gmd), but the mine drainage requires the removal of 50 gmd, then the wetland cell must be substantially increased in size, or additional cells must be constructed. Constructing additional cells is recommended, since
managing the flow through wetlands becomes more difficult as the size of the wetland increases due to hydraulic factors (Herron, 1992).

The particular remediation requirements of the mine drainage will determine the type of treatment cell utilized. Acidic waters having high concentrations of iron will not require the same treatment cells as a circumneutral drainage with abundant manganese. The following suggestions for treatment are given, based upon mine drainage characteristics:

<table>
<thead>
<tr>
<th>CHARACTERISTIC(S)</th>
<th>TREATMENT CELL</th>
</tr>
</thead>
<tbody>
<tr>
<td>alkaline</td>
<td>aerobic wetland</td>
</tr>
<tr>
<td>acidic, high DO</td>
<td>anaerobic wetland</td>
</tr>
<tr>
<td>acidic, low DO, low Fe</td>
<td>ALD</td>
</tr>
<tr>
<td>high metals</td>
<td>settling pond</td>
</tr>
<tr>
<td>high Mn</td>
<td>algae pond</td>
</tr>
</tbody>
</table>

6.6 LAYOUT OF TREATMENT CELLS

The previous section discussed some of the alternative treatment cells available for mine drainage remediation. Each cell does not fully remediate the mine drainage itself; the cells are used in conjunction with one another to achieve the best treatment possible. It is impossible to discuss the design configuration required to treat every mine drainage situation; there are simply too many possible combinations. However, several example configurations can be given, based upon various mine drainage characteristics. Some recommended configurations are as follows:
1) High Fe, moderate Mn, low alkalinity

COMPONENTS: ALD, settling pond, deep wetland, shallow wetland.

The high level of iron suggests that excessive H⁺ will be generated due to iron hydrolysis. Since the mine drainage has low alkalinity, additional alkalinity is required to buffer the expected drop in pH. For these reasons, an ALD would be beneficial. A settling pond should be located downstream of the ALD to allow for precipitation of metals to occur in an aerated environment. The next stage of treatment should be a deep wetland, where anaerobic conditions will allow for sulfate reduction to occur. Finally, the drainage should flow into a shallow wetland. Here, aerobic conditions will act to remove any metals remaining in the drainage.

2) Moderate Fe, high Mn, net alkalinity

COMPONENTS: deep wetland, algae pond, shallow wetland.

Since the mine drainage has net alkalinity, an ALD is not required to offset the increase in pH expected to occur from iron hydrolysis. Instead, the first component of the treatment system should be a deep wetland. Sulfate reduction will act to remove much of the iron from the mine drainage. The next component should be an algae pond, where Mn removal will occur. Finally, the drainage should flow into a shallow wetland, to allow for aerobic processes to remove any remaining metals.

3) Low Fe and Mn, low alkalinity

COMPONENTS: deep wetland, shallow wetland, deep wetland.

The contaminant levels in the mine drainage are not very high, so complete metals removal should be possible. The drainage should first flow through a deep wetland so that
sulfate reduction can occur, removing metals and introducing alkalinity. The drainage should then flow into a shallow wetland, where aerobic removal processes will dominate. The final stage would be to channel the drainage through another deep wetland, to ensure acceptable pH levels are attained.
Chapter 7

CASE STUDY OF THE MARSHALL NO. 5
PASSIVE MINE DRAINAGE TREATMENT SYSTEM

7.1 INTRODUCTION

As discussed in Chapter 2, the original treatment system located at the Marshall No. 5 site consisted of three components: an artificial peat bog, a limestone bed, and a series of drop structures. The peat bog was intended to be the primary location for mine water remediation. The purpose of the limestone was to increase the alkalinity of the drainage. The drop structures were designed to aerate the drainage, thus facilitating the precipitation of metals by creating oxidizing conditions.

The major problems with the original design were the peat substrate and the size of the system. The peat substrate was too low in permeability to effectively treat the mine drainage. Untreated mine drainage flowed over the surface of the wetland into the limestone channel, armoring the cobbles with ferric hydroxides within months of start-up. A second problem with the original design was its size. It could not manage the flow from the adit, leading to failure of the rock check dam.

The DMG made the decision to renovate the treatment system. Before a new design could be created, several design goals were agreed upon:

- allow for complete metals removal
- increase the pH from 4.5 to 7
With those goals in mind, the design process began with the development of a conceptual model. The final designs were derived based upon the recommendations given in this thesis. The actual specifications and calculations for the new treatment system are included in Appendix A and Appendix B.

7.2 CONCEPTUAL DESIGN

The first step was to conduct a site investigation to identify the extent of mining activity in the area. Numerous subsidence holes were found in the project area and helped to identify the areas in which mining had taken place. Since mining began in the 1800s, no mine maps are known to exist. The coal seams present in this area are relatively isolated, so the associated mine workings are isolated from each other as well. The areas of subsidence were located in the hills surrounding the wetland site, and were therefore considered to present no danger to the project.

The site investigation did not identify any geologic hazards which could adversely impact the project. However, the maximum expected run-off from the surrounding watershed area was used for all design calculations to prevent any damage from occurring due to an unusually large storm event. As part of the preliminary investigation, a hydrologic report of the site was obtained (Kaman Tempo, 1983). The report determined that the expected run-off from the surrounding drainage area would equal 4 cfs for the 24-hour, 100-year
storm event. The report recommended that this event be chosen as the design storm for any structures built on the Marshall site.

Spatial constraints at the site were dictated by man, not by topography. The project site is located on Open Space land which is managed by the City of Boulder. Although a great deal of land was available, the City permitted construction to occur only in the same general vicinity of the original treatment system.

The water quality characteristics listed in Table 1 were considered to be average values. Given those values, the mine drainage could be described as having low metal concentrations and low alkalinity. Design guidelines given in Chapter 6 would recommend the following configuration: deep wetland, shallow wetland, deep wetland. However, a specific design goal was to include a new ALD configuration which had never been utilized in Colorado constructed wetlands. For this reason, the final design configuration was as follows: ALD, settling pond, deep wetland, shallow wetland (Figure 29 and Figure 30).

7.3 NEW DESIGN COMPONENTS

7.3.1 Anoxic Limestone Drain

The anoxic limestone drain at the Marshall site was constructed by placing an earth-fill dam outside the mine opening (figure 31). The adit is approximately 5 feet high and 10 feet wide. The mine tunnel slopes gently downward as it extends back into the rock. The slope allows for anoxic conditions to exist at some point into the tunnel where the water level intersects the ceiling of the tunnel. Thus, anoxic conditions can exist even during periods of low flow.

The tunnel was back-filled with approximately 73 tons of 1/2” to 2” crushed limestone. The limestone drain began approximately 15 feet behind the adit and extended to
Figure 29. Schematic of the new treatment system. Diagram is not to scale.
Figure 30. Photo of the new treatment system, looking downstream. The mine drainage flows out of the adit into the settling pond, visible in the foreground. The drainage then flows through the wetland and the polishing cell before exiting the treatment system and returning to natural channels.

50 feet beyond the adit. A PVC pipe was emplaced along the full length of the ALD and exited outside the adit (figure 32). This pipe allowed for the collection of water samples in the mine tunnel before coming into contact with the ALD. A concrete spillway fitted with a steel weir was installed at the adit (figure 33 and Figure 34).

This type of ALD has never been constructed in Colorado and will be used as a reference for designing similar ALDs in the state. An expected design life was not calculated for this project due to time constraints resulting from the late construction start-up.
Figure 31. Photo of the dam placed outside the mine adit, flooding the mine tunnel.

Figure 32. Photo of PVC pipe embedded in the ALD.
Figure 33. Diagram of concrete spillway and steel V-notch weir placed in the dam outside the mine opening, including dimensions.
Figure 34. Photo of concrete spillway and steel V-notch weir placed in the dam outside the mine opening.

7.3.2 Settling Pond

The second stage in the treatment process was a settling pond with the following dimensions: 5 feet deep, 20 feet wide, 30 feet long (figure 35). The settling pond serves as a retention basin for precipitates and allows control of flow into the rest of the treatment system. A six-inch diameter irrigation gate located at the downstream end of the pond allows the flow rate into the rest of the system to be monitored and adjusted (figure 36). The downstream end of the irrigation gate connects to a pipe which transmits mine drainage into the next component of the system (figure 37). The settling pond also has a spillway which channels drainage out of the pond and into an adjacent diversion ditch.
Figure 35. Photo of the settling pond, featuring a spillway and irrigation gate valve to manage flow into the system.

Figure 36. Close-up photo of the irrigation gate, used to control flow into the rest of the treatment system.
Based upon Goldman's equation from Chapter 4, the surface area of the settling pond would have to equal 5000 ft$^2$ to allow for complete settlement of particles from the design storm of 4 cfs. That size pond was not feasible at the Marshall site due to spatial restrictions imposed by Open Space. The actual surface area of the pond is sufficient for discharge amounts of 215 gpm. Typical flow rates out of the adit do not exceed 70 gpm, therefore the pond size is more than adequate to treat typical discharge amounts. Although the design storm does not impact sizing from the remediation perspective, it will control sizing based upon hydraulic stability; the settling pond must be large enough to pass the design storm without overtopping.
Water can exit the settling pond through one of two components: a gate valve or a spillway. The gate valve empties into the wetland cell while the spillway channels drainage down a ditch. Using Bernoulli's Equation and the equation of continuity, it was determined that the gate valve could pass 2.57 cfs. Any flows in excess of that amount would be routed through an emergency spillway. The spillway used is a combination V-notch and rectangular weir. The weir was determined to have a discharge capacity of 2.47 cfs; therefore, all of the design storm can be successfully passed through the settling pond without causing any structural damage from overtopping and subsequent erosion. However, it should be noted that the spillway alone could not pass all of the design storm. For this reason, the gate valve should remain open during the wetter months of the year. If space and budget permit, it would be best to design the system so that human effort is not required to maintain the integrity of the facility.

7.3.3 Deep Wetland

The third stage of the treatment system is a wetland with the following dimensions: 4.5 feet deep, 20 feet wide, 40 feet long (figure 38). The cell is filled with cow manure obtained from a local dairy. The organic cell functions in both an aerobic and anaerobic capacity. The anaerobic portion of the treatment occurs as mine drainage infiltrates downward through the substrate and enters an underdrain. The underdrain consists of a series of 3-inch diameter perforated PVC pipes embedded in pea gravel (figure 39). The 3-inch diameter pipes connect to a 6-inch diameter pipe near the downstream end of the wetland (Figure 40). The 6-inch pipe exits the wetland through the dam at the downstream end and is connected to a stand pipe (figure 41). The stand pipe allows for the hydraulic head over the wetland to be controlled.
Figure 38. Photo of the wetland cell, filled with manure and mine drainage.

Figure 39. Three-inch perforated PVC pipe embedded into a bed of pea gravel.
Figure 40. Cross-sectional schematic of the wetland cell.

Figure 41. Photo of standpipe and rock spillway, located on the downstream end of the wetland cell.
The anaerobic sizing equation from Chapter 4 was used to determine the size of wetland required to treat the design discharge of 30 gpm. Based upon the research of Reynolds and others (1991), the volume of wetland substrate (approximately 2800 ft³) could generate enough sulfides to treat 1329 grams of iron each day. Using the same equation again, it can be determined that only 1145 grams of iron are expected to enter the wetland at a flow rate of 30 gpm. Therefore, the wetland size will adequately manage the chemical reactions required for remediation to occur.

The volume of substrate material in the wetland is sufficient to theoretically remove all of the iron from the mine effluent. However, one must consider that all of the water flowing into the wetland may not undergo anaerobic removal processes because the hydraulic conductivity of the substrate material may not permit all of the drainage to permeate the substrate. One can determine the amount of water which will pass through the substrate by constructing a flow net of the wetland or by applying Darcy's Law directly. A flow net consists of mutually perpendicular flow lines and equipotential lines. The flow lines trace the path traveled by the fluid, while the equipotential lines represent lines of equal hydraulic head. Once the flow net is constructed, the expected discharge through the wetland can be calculated using the following equation:

\[ Q = kH\left(\frac{N_f}{N_d}\right) \]

where \( k \) = hydraulic conductivity of the substrate, \( H \) = the total head on the system, \( N_f \) = the number of flow channels in the flow net, and \( N_d \) = the number of equipotential drops in the flow net.
Darcy’s Law may be applied to wetlands constructed of only one material type. The flow rate of fluid through the substrate can be calculated using the following equation:

\[ Q = k_i A \]

where \( k \) = hydraulic conductivity of the substrate,
\( i \) = slope
\( A \) = cross-sectional area through which the water is flowing.

It was determined that under a hydraulic head of 1 foot, the wetland could be expected to transmit 101 gpm. Any water in excess of this amount will flow over the surface of the wetland and pass over the spillway into the polishing cell. The spillways are over-designed and can pass 465 cfs.

7.3.4 Shallow Wetland

The final stage of treatment is a shallow wetland or polishing cell with the following dimensions: 2 feet deep, 20 feet wide, 35 feet long. The polishing cell was filled with pea gravel and some of the peat from the original wetland. The conditions are primarily aerobic. The purpose of the polishing cell is to increase the oxygen content of the drainage to facilitate the precipitation of any metals remaining in solution. The depth of the shallow wetland was designed to be irregular, having many deep pools (2 ft) surrounded by more shallow areas (figure 42). The irregularities promote diverse plant growth.
Figure 42. Close-up photo of the polishing cell, showing algal blooms thriving in deep pools of gravel and peat.

7.3.5 Vegetation

A wetland system is not complete without vegetation. Plants serve a role in the treatment process by taking metals into their root systems. Studies have indicated that the amount of metals removed by plants is rather low, accounting for perhaps 5% of metal accumulation (Guertin et al., 1988). However, plants also supply the biomass necessary for other removal processes to occur (Wildeman, 1992). Furthermore, plants create a more aesthetically pleasing environment. Many species of sedges, rushes and cattails have proven to be quite tolerant of the increased levels of metals and acidity found in mine drainages. All emergent wetland vegetation was removed during demolition of the original system and replanted into the polishing cell of the new system. No additional planting was
conducted, as per City of Boulder Open Space specifications. The City wants native vegetation to establish itself at the site naturally. Appendix C lists many species of wetland vegetation which are tolerant to acidic mine waters.

7.4 SYSTEM PERFORMANCE

Construction of the new treatment system was completed in late July 1993. Due to conflicts with the owner of the water rights, water did not flow into the treatment system until late September. However, water samples were collected from the ALD and settling pond since August.

Preliminary results indicate that the system is functioning well (Appendix F). The results are presented in Table 6.

Table 6. Preliminary results of the new treatment system.

<table>
<thead>
<tr>
<th></th>
<th>Mine Drainage</th>
<th>ALD</th>
<th>Settling Pond</th>
<th>Wetland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkalinity (mg/l)</td>
<td>8.1</td>
<td>42.1</td>
<td>58.9</td>
<td>79.4</td>
</tr>
<tr>
<td>pH</td>
<td>4.5</td>
<td>5.33</td>
<td>5.84</td>
<td>6.43</td>
</tr>
</tbody>
</table>

The pH has increased 43% to near neutral values. The alkalinity of the drainage has significantly increased throughout the system, by almost 10 times. Field inspections identified abundant ferric precipitates surrounding the settling pond and covering the spillway exiting the ALD. The precipitates indicate that the ALD-settling pond system is performing as designed.
7.5 CONCLUSIONS

Passive mine drainage treatment systems appear to be low cost, viable solutions to the problem of acid mine drainage remediation. Although the technologies associated with constructed wetlands are still developing, positive results have been obtained. The success of a PMDT is dependent upon chemical and physical design parameters. The author considers the following subjects to be of great importance with respect to the physical design of a passive mine drainage treatment system:

- hydraulic conductivity of organic substrate material,
- changes in substrate permeability over time,
- accurate determination of substrate permeability,
- clogging of substrate by chemical precipitates over time,
- predictable flow rates through organic material,
- maintaining flow through closed pipe conveyances,
- control of hydraulic head in the treatment system,
- maintaining anoxic conditions where required,
- sufficient hydraulic capacity to manage a certain design storm,
- creating the desired flow configuration through the wetland,
- preventing leakage from treatment cells,
- protecting treatment cell structures from erosion.

Cooperative research focusing on the combined influence of chemical and physical design parameters is recommended to gain a more complete understanding of this innovative and promising mine drainage treatment method.
REFERENCES


REFERENCES (CONTINUED)


REFERENCES (CONTINUED)


REFERENCES (CONTINUED)


REFERENCES (CONTINUED)


REFERENCES (CONTINUED)


REFERENCES (CONTINUED)


APPENDIX A
MARSHALL NO. 5 BID DOCUMENTS
BID SCHEDULE
Marshall No. 5 Project
RN-MINES-305

PROJECT WORK DESCRIPTION

The project work will include excavation of an existing constructed wetland, stockpiling of all emergent wetland vegetation from the existing wetland, construction of an anoxic limestone drain by damming the mine adit and filling the tunnel with limestone, and construction of a settling pond, wetland and polishing cell to be used for the treatment of the contaminated mine drainage. The project work is bid out under 8 work items.

BID ITEM NUMBER 1: MOBILIZATION AND DEMOBILIZATION

See attached specifications.

BID ITEM NUMBER 2: REMOVAL OF EXISTING WETLAND

An artificial wetlands (peat bog) was constructed on the site in 1984. The approximate dimensions of the peat bog are as follows: 55 feet long, 15 feet wide, 4.5 feet deep. Prior to demolition, all emergent wetlands vegetation shall be removed from the wetlands, and stockpiled for use in the new treatment system. Once vegetation is removed, the wetlands may be excavated. The excavated peat material will be disposed of in a location specified by the PROJECT MANAGER.

Measurement and Payment

There will be no measurement for payment for removal of the existing wetland. Payment will be made on the basis of the lump sum bid price for Bid Item Number 2. Such payment will constitute full compensation for all labor, materials, equipment, and all other items necessary and incidental to completing the job as described.

BID ITEM NUMBER 3: CONSTRUCT ANOXIC LIMESTONE DRAIN

An anoxic limestone drain will be constructed by filling the Marshall Mine Tunnel with limestone. Approximately 73 tones of 1/2 to 2 inch diameter limestone shall be used to fill the tunnel. The adit is approximately 5 feet high and 10 feet wide. Excavation of a small dam, created by sloughing of the mine roof, may be necessary to facilitate placing the limestone in the mine opening. If excavation is necessary, the small dam must be removed slowly to allow controlled release of the dammed-up water.

An earthfill dam will be constructed at the mine adit to flood the mine workings. The dam will be approximately 6 feet high, and will extend across the mine opening. The interior and exterior slopes of the dam embankment must not exceed 2h: 1v. The dam will be keyed into the side slopes and its base. The key-ways must be a minimum of 1 foot (1') deep and eighteen inches (18") wide. A spillway will be constructed in the center of the dam with a bottom width of two feet (2'), 2h: 1v side slopes, and a depth of one foot (1'). A layer of
durable rock four to six inches (4" to 6") in size must line the spillway bottom sides, and
the outslope of the dam embankment. The top width of the dam will be 5 feet. Filter fabric
(Dupont Typar 3401 or equivalent) shall be placed into the dam approximately 6 inches
below the surface to protect the integrity of the dam structure. The rock for the spillway
may be placed directly over the filter fabric.

Measurement and Payment

There will be no measurement for payment for constructing the anoxic limestone drain.
Payment will be made on the basis of the lump sum bid price for Bid Item Number 3. Such
payment will constitute full compensation for all labor, materials, equipment, and all other
items necessary and incidental to completing the job as described.

BID ITEM NUMBER 4: CONSTRUCT SETTLING POND

A settling pond, 5 feet deep, 20 feet wide, and 30 feet long will be constructed immediately
below the anoxic limestone drain. The pond embankments will have exterior slopes of 2h:
1v and interior slopes of 1.5h: 1v. The pond will be located in the excavation made during
the removal of the original wetlands facility. Cut and fill will be conducted as necessary to
achieve the specified dimensions. The overall shape of the settling pond will be oval, but
the pond does not need to be symmetrical or regular in shape. Irregularities in the shape of
the pond will facilitate plant growth, and create a more natural-looking structure. Four two
foot (2') minimum diameter durable rocks shall be placed, at the direction of the PROJECT
MANAGER, near the inlet of the settling pond to create a baffle.

The dam embankments must be keyed into the unexcavated surface a minimum of one foot
(1') deep and eighteen inches (18") wide. A spillway will be constructed near the northeast
corner of the dam, with a bottom width of two feet (2'), 2h: 1v side slopes, and a depth of
one foot (1'). A layer of durable rock four to six inches (4" to 6") in size must line the
spillway bottom sides, and the outslope of the dam embankment. The spillway will be
placed so excess drainage will flow out of the settling pond directly into the natural
drainage east of the settling pond. A gated valve will allow the drainage from the settling
pond to enter the treatment system. The top width of the dam at the northern end of the
settling pond will be 5 feet. Embankments may have to be constructed on the east and west
sides of the settling pond. These embankments must have a minimum top width of three
feet (3') at the southern end, grading to a top width of five feet (5') at the north end. Filter
fabric (Dupont Typar 3401 or equivalent) shall be placed into the dam embankments
approximately 6 inches below the surface to protect the integrity of the dam structure. The
rock for the spillway may be placed directly over the filter fabric.

To control flow from the settling pond into the wetland, a heavy-duty cast iron, twelve inch
(12") diameter sliding irrigation gate must be installed. The irrigation gate must be attached
to a poured concrete block encasing a twelve inch diameter HDPE pipe. The concrete block
will have dimensions of two feet on all sides. The concrete shall be mixed to attain a
minimum compressive strength of 3,000 psi at 28 days. The irrigation gate shall be placed
with the bottom of the gate one foot below the embankment spillway level, and the top at
the level of the spillway. The HDPE pipe shall extend through the dam embankment with a
bend which will allow the water to flow directly onto the top of the wetland substrate without any fall.

Measurement and Payment

There will be no measurement for payment for construction of the settling pond. Payment will be made on the basis of the lump sum bid price for Bid Item Number 4. Such payment will constitute full compensation for all labor, materials, equipment, and all other items necessary and incidental to completing the job as described.

BID ITEM NUMBER 5: CONSTRUCT WETLAND

The wetland treatment pond will be constructed with the dimensions of 4.5 feet deep, 20 feet wide, and 40 feet long, immediately below the settling pond. The pond embankments will have exterior slopes of 2h: 1v and interior slopes of 1.5h: 1v. The pond will be located in the excavation made during the removal of the original wetlands facility. Cut and fill will be conducted as necessary to achieve the specified dimensions. The overall shape of the settling pond will be oval, but the pond does not need to be symmetrical or regular in shape. Irregularities in the shape of the pond will facilitate plant growth, and create a more natural-looking structure.

The dam embankments must be keyed into the unexcavated surface a minimum of one foot (1') deep and eighteen inches (18") wide. A spillway will be constructed near the northeast corner of the dam, with a bottom width of two feet (2'), 2h: 1v side slopes, and a depth of one foot (1'). A layer of durable rock four to six inches (4" to 6") in size must line the spillway bottom sides, and the outslope of the dam embankment. The spillway will be placed so excess drainage will flow out of the wetland directly into the polishing pond. The top width of the dam at the northern end of the wetland will be 5 feet. Embankments may have to be constructed on the east and west sides of the wetland. These embankments must have a minimum top width of three feet (3') at the southern end, grading to a top width of five feet (5') at the north end. Filter fabric (Dupont Typar 3401 or equivalent) shall be placed into the dam embankments approximately 6 inches below the surface to protect the integrity of the dam structure. The rock for the spillway may be placed directly over the filter fabric.

The bottom of the excavated pond must be flat. A maximum slope of 2% is allowed. Four drainage channels of 2-inch diameter, Schedule 40, perforated PVC pipe will be placed along the bottom of the excavated pond. The pipes will help channel the drainage through the wetland into the polishing cell. Approximately 164 feet of 2-inch diameter piping will be required. The four pipes will join into a common 6-inch diameter, Schedule 40, non-perforated pipe. Two 2" x 6" 90° elbows and two 2" x 6" x 6" Tee joints will be required. The 6-inch pipe will join another 6-inch pipe which will be of the Schedule 80 type, via a 6" x 6" x 6" Tee joint. The Schedule 80 pipe will be directed through the dam at the downstream end of the wetlands, and will direct the flow into the polishing cell.

The perforated pipes in the wetland will be placed on a layered gravel pack. The bottom layer will consist of approximately 4 inches of 1.5 inch diameter crushed rock.
Approximately 6 inches of pea gravel will be placed onto the crushed rock. The PVC pipe will be buried between the layers.

Approximately 120 cubic yards of a manure/topsoil mixture will be placed into the wetlands to serve as a medium for the treatment of the mine drainage. The material will be loosely placed into the excavation, and will not be compacted under any circumstances. The material should be purchased at Timberline Gardens in Arvada. A particular mixture of substrate material will be specified at the pre-bid meeting.

**Measurement and Payment**

There will be no measurement for payment for construction of the wetland. Payment will be made on the basis of the lump sum bid price for Bid Item Number 5. Such payment will constitute full compensation for all labor, materials, equipment, and all other items necessary and incidental to completing the job as described.

**BID ITEM NUMBER 6: CONSTRUCT POLISHING POND**

The final stage of the treatment system is a polishing cell. The cell will be approximately 35 feet long, 20 feet wide and 2 feet deep. Approximately 32 cubic yards of pea gravel will be placed into the cell. The depth of the pea gravel will vary from six inches (6") to two feet (2’) throughout the cell. The purpose of the variable depth is to create pools for the establishment of different types of vegetation. Most of the cell should have a depth of 6 inches, with several deeper pools.

The pond embankments will have exterior slopes of 2h: 1v and interior slopes of 1.5h: 1v. The pond will be located in the excavation made during the removal of the original wetlands facility. Cut and fill will be conducted as necessary to achieve the specified dimensions. The overall shape of the polishing pond will be oval, but the pond does not need to be symmetrical or regular in shape.

The dam embankments must be keyed into the unexcavated surface a minimum of one foot (1’) deep and eighteen inches (18") wide. A spillway will be constructed near the middle of the north dam embankment, with a bottom width of two feet (2’), 2h: 1v side slopes, and a depth of one foot (1’). A layer of durable rock four to six inches (4" to 6") in size must line the spillway bottom sides, and the outslope of the dam embankment. The top width of the dam at the northern end of the polishing cell will be 5 feet. Embankments may have to be constructed on the east and west sides of the polishing cell. These embankments must have a minimum top width of three feet (3’) at the southern end, grading to a top width of five feet (5’) at the north end. Filter fabric (Dupont Tyvar 3401 or equivalent) shall be placed into the dam embankments approximately 6 inches below the surface to protect the integrity of the dam structure. The rock for the spillway may be placed directly over the filter fabric.

**Measurement and Payment**

There will be no measurement for payment for construction of the polishing cell. Payment will be made on the basis of the lump sum bid price for Bid Item Number 6. Such payment
will constitute full compensation for all labor, materials, equipment, and all other items necessary and incidental to completing the job as described.

BID ITEM NUMBER 7: DRAINAGE DITCHES

Drainage ditches must be constructed along the south, east and west sides of all of the cells in the treatment system. Along the east and west sides of the treatment system, no drainage ditch will be necessary if the dam embankments create a drainage larger than the specified ditch. The ditches must be 2 feet wide and 1.5 feet deep, and have a triangular cross-section. The south ditch must be located above the mine adit, and can be constructed to flow into the east or west ditches.

Measurement and Payment

There will be no measurement for payment for construction of the drainage ditches. Payment will be made on the basis of the lump sum bid price for Bid Item Number 7. Such payment will constitute full compensation for all labor, materials, equipment, and all other items necessary and incidental to completing the job as described.

BID ITEM NUMBER 8: RE-VEGETATION

All emergent wetlands vegetation removed from the original wetlands must be transplanted into the new wetland and polishing cell at the direction of the PROJECT MANAGER. The PROJECT MANAGER must be notified when transplanting is to occur. All embankments, drainage ditches, and areas impacted by construction equipment must be re-vegetated according to the seeding recommendations of the City of Boulder Open Space.

Measurement and Payment

There will be no measurement for payment for re-vegetating the site. Payment will be made on the basis of the lump sum bid price for Bid Item Number 8. Such payment will constitute full compensation for all labor, materials, equipment, and all other items necessary and incidental to completing the job as described.

BID ITEM NUMBER 9: EQUIPMENT RENTAL

See attached specifications.
PROJECT OBSERVATION

The PROJECT MANAGER will be at the project site periodically to monitor construction activities and ensure that each work item is completed and constructed to design specifications. The following items must be observed and approved by the PROJECT MANAGER before proceeding with additional work:

1. Key-ways for dam embankments.
2. Installation of filter fabric.
3. Excavated wetland and polishing pond.
4. Placement of PVC pipe must be inspected prior to covering with pea gravel.
5. Transplanted plants from the original wetland to the new wetland and polishing pond.
AMENDMENT NUMBER 1 TO RN-MINES 305

1. The CONTRACTOR is responsible for repairing all damage to the roads into the project site, including re-vegetation. All cuts shall be regraded to the pre-existing contours. The fence at the entrance from Highway 93 may be modified to allow trucks to pull off the highway. After construction is completed, the fence must be put back with a 15 foot setback, and a steel ranch gate. The gate will be supplied by the City of Boulder. The CONTRACTOR must install the gate as part of this project.

2. The CONTRACTOR is responsible for completing the project according to the specifications. If there is a failure due to design errors, weather, or other circumstances beyond the CONTRACTOR'S control, the Division of Minerals and Geology will be responsible for maintenance. The OWNER (Division of Minerals and Geology) is responsible for any re-vegetation maintenance after the project is completed.

3. Three V-notch weirs must be installed to measure the flow through the system. The first weir must be installed in the spillway of the dam below the anoxic limestone drain. The second weir must be installed in the overflow spillway on the east side of the settling pond. The third weir must be installed below the treatment system in a location designated by the PROJECT MANAGER. The weirs must be constructed from 1/4" stainless steel plate. A 90 degree V-notch with a vertical depth of 6 inches must be cut into the center of the plate. The inside edge of the plate must be sharpened at an angle of 60 degrees. The weir must be installed in a concrete retaining structure. The concrete must be four inches (4") thick on the bottom and sides. The inlet side must have wing-walls and an apron constructed to avoid piping along the sides and bottom. The bottom of the V-notch must be a minimum of four inches (4") above the bottom of the spillway. The minimum depth of the finished spillway will be sixteen inches (16"), and the minimum width will be twenty inches (20").

4. The City of Boulder has special requirements for projects on Open Space land. A copy of the Three-Way Agreement that the successful bidder will be required to sign is attached. This agreement contains the special requirements for construction on Open Space land.

5. The substrate to be used in the wetland must consist of horse or cow manure with a minimum organic content of thirty percent (30%) and a maximum organic content of fifty percent (50%) of the dry weight.

6. The limestone to be used in the anoxic limestone drain must have a minimum calcium carbonate content of ninety percent (90%).

7. The irrigation slide gate to be installed at the outlet between the settling pond and the wetland must be a Waterman C 10-4 or equivalent. The size of the slide gate is hereby changed to six inches (6") in diameter. The PVC pipe to be attached is
hereby also changed to six inches (6") in diameter. The slide gate must be installed according to the manufacturer’s specifications.

8. The filter fabric to be installed in the dam embankments is hereby changed to an erosion control fabric. This item is now included as an additional item, if required on the attached bid schedule. This item is not guaranteed. The material must consist of Miramat 1000 or equivalent. The erosion control fabric must be placed on the inside of each pond a minimum of one foot (1') below the water line or the substrate line. The erosion control fabric will then be draped over the pond embankment and the edges buried a minimum of six inches (6") below the natural ground surface.

9. No soil borrow areas are available on site. The CONTRACTOR must balance all cuts and fills in constructing the treatment system, or import material.

10. The perforated pipes in the wetland must be covered with Miramat 1000 erosion control fabric or equivalent prior to placing pea gravel. The pea gravel must be 3/8 inch diameter rounded rock.

11. Prior to construction, a silt fence must be installed across the drainage below the construction area. The specifications for installing the silt fence are attached. All drainage from the construction site and the staging area should pass through the silt fence. If the CONTRACTOR uses any area for purposes other than access, the surface drainage from this area must be passed through a silt fence. The silt fence must be removed upon completion of re-vegetation.

12. A new drawing of the spillway riser from the wetland pond is attached. The angle of the riser has been changed. Also, a cleanout is included. The cleanout will be constructed by installing a tee where the vertical riser extends through the embankment. A short section of pipe will be installed horizontally, followed by threaded fitting and cap. The cleanout must be covered with a minimum of one foot of soil.

13. The re-vegetation specifications are included in the attached Three-Way Agreement. Seed will be supplied by the OWNER. No forbs will be seeded the first year. The OWNER will be responsible for seeding shrubs in 1994. Also, the OWNER will be responsible for weed control after the project is completed.

14. A fence is required to be constructed around the area disturbed during construction of the treatment system. A new bid item is included on the attached bid schedule. The fence must be constructed according to City of Boulder Open Space specifications. Copies of the specifications may be obtained from the City of Boulder.

15. The spillway aprons (outfalls) on all ponds must be constructed of grouted rock. The grouted rock must be a minimum of eight inches (8") thick. The outside of the aprons must be primarily rock. The concrete must be formulated to have a minimum compressive strength of 3,000 psi at 28 days. The rock in the existing wetland dam
may be used for the spillway aprons. The aprons must be constructed of sufficient width that no water flows over the earthen portion of the dam embankments.
APPENDIX B
CALCULATIONS SUPPORTING THE DESIGN OF THE NEW TREATMENT SYSTEM
SETTLING POND CALCULATIONS

Settling Pond Dimensions:
- Length = 35 feet
- Width = 20 feet
- Depth = 5 feet
- Distance between top of gate valve and surface of wetland = 44 inches

Required Surface Area (Settlement of Particles):

The surface area required for $Q_{\text{max}} = 4$ cfs was calculated as follows:

$$A_s = \frac{1.2Q}{V_s} = \frac{(1.2)(4)}{(0.00096)} = 5000 \text{ ft}^2$$

This area was not available at the Marshall No. 5 site. The same equation was used to determine the allowable discharge based upon the surface area available:

$$600 \text{ ft}^2 = \frac{1.2Q}{(0.00096)}$$

$Q = 0.48$ cfs

$= 215$ gpm

The discharge from the adit has been determined to range from 17-70 gpm. Therefore, the size of the settling pond is more than adequate to allow for particle settlement under normal operating conditions.
For proper sizing, Goldman recommends that:

\[
\frac{L}{D} < 200 \\
\frac{30}{5} = 6
\]

The dimensions of the settling pond fall well within those recommendations, as indicated above.

**Structural Integrity of the Settling Pond:**

The settling pond was designed to withstand \(Q_{\text{max}} = 4\) cfs. Two outlets are available for water which exits the settling pond: a gate valve and a spillway. The gate valve channels water into the shallow wetland component of the treatment system, while the spillway channels the water out of the treatment system into a diversion channel.

**Gate Valve:**

To determine the discharge capacity of the 6 inch diameter gate valve, the expected velocity into the gate valve must first be determined. Bernoulli’s Equation is written from the surface of the settling pond to the surface of the wetland:

\[
\frac{P_1}{\gamma} + Z_1 + \frac{V_1^2}{2g} = \frac{P_2}{\gamma} + Z_2 + \frac{V_2^2}{2g} + h_t + h_m
\]
Since both ends of the system are exposed to the atmosphere, the pressure terms equal zero. The elevation term on the settling pond side of the system \( (z_1) = 44 \) inches, while the elevation on the wetland side of the system is taken as datum. The velocity of the water in the settling pond is assumed to be zero. As the water flows from the settling basin into the gate valve and through a pipe into the wetland, it will experience head losses due to frictional resistance and minor losses resulting from entering or exiting the valve and pipe. Taking all of the aforementioned information into account, Bernoulli’s Equation reduces to:

\[
Z_1 = \frac{V_2^2}{2g} + f \frac{L}{D} \frac{V_2^2}{2g} + K \frac{V_2^2}{2g}
\]

Rearranging the equation to isolate the velocity term results in the following expression:

\[
Z_1 = \frac{V_2^2}{2g} \left( 1 + f \frac{L}{D} + K \right)
\]

For an open gate valve, \( K = 0.12 \). In the above expression, there are two unknowns: \( V_2 \) and \( f \). The friction factor \( f \), is based upon the relative roughness of the pipe and the Reynolds number \( (Re) \). The friction factor may be determined through the following iterative process:

- Guess an initial value of \( f \)
- Calculate \( V \) from Bernoulli’s Equation
- Calculate \( VD'' \) (Velocity * Diameter in inches) for the valve of \( V \) obtained above
- Using a Moody Diagram (Figure B1) determine f from the calculated VD” and relative roughness ratio
- If the calculated f does not equal the initial guess, repeat the iterative process, using the calculated f as the initial guess
- Repeat the iterative process until the initial guess and the calculated f become equal.

For the Marshall No. 5 system, the roughness (e) of the commercial steel pipe is 0.00015, and the pipe diameter (D) is 6 inches, resulting in a relative roughness ratio (e/D) of 0.003.

The iterative process resulted in the following:

<table>
<thead>
<tr>
<th>Initial Guess</th>
<th>Calculated f</th>
<th>VD”</th>
<th>Resultant f</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>155.5</td>
<td>933</td>
<td>0.015</td>
</tr>
<tr>
<td>0.015</td>
<td>13.18</td>
<td>79.1</td>
<td>0.016</td>
</tr>
<tr>
<td>0.016</td>
<td>13.1</td>
<td>78.6</td>
<td>0.0165</td>
</tr>
</tbody>
</table>

The iterative process resulted in a friction factor of 0.0165. Knowing this factor, it is now possible to solve for V directly, using Bernoulli’s Equation:

$$3.67 = \frac{V_2^2}{(2)(32.2)} \left[1 + 0.0165 \left(\frac{16}{0.5}\right) + 0.12\right]$$

$$V_2 = 11.98 \text{ ft/sec}$$
Figure B1. Moody diagram.

This velocity can be used to calculate the Reynolds number as follows:

\[ R_e = \frac{VDp}{\mu} \]

\[ = \frac{(11.98)(0.5)(1.94)}{3.229 \times 10^{-5}} \]

\[ = 3.6 \times 10^5 \]

The value of \( R_e \) indicates that the flow through the pipe is turbulent, not laminar.

Knowing the expected maximum velocity, it is possible to calculate the maximum discharge which the gate valve could be expected to manage:
\[
Q = VA
= (11.98)\left(\frac{\pi}{4}\right)(0.5)^2
= 2.35 \text{ cfs}
\]

For discharge values in excess of 2.35 cfs, the emergency spillway will be required to function to prevent overtopping of the settling pond embankments.

**Emergency Spillway:**

The spillway is designed to pass water through the settling pond so that the dams and embankments do not overtop and erode. The base of the spillway is flush with the top of the gate valve. The spillway is fitted with a combination V-notch and rectangular weir (figure B2).
Figure B2. Cross-section of combination V-notch weir and rectangular weir.

The discharge which can be managed by a V-notch weir depends upon the height of water above the bottom of the notch, the height of water above the top of the notch, the angle of the notch (α) and a weir coefficient (Cw). A typical value of the weir coefficient is 0.6. The following equation is used to calculate the allowable discharge through a V-notch weir:

\[
Q = C_w \frac{8}{15} \tan \alpha \sqrt{2gH}\frac{a}{2}
\]

\[
= (0.6) \left( \frac{8}{15} \right) (\tan 45^\circ) \left( \sqrt{2(32.2)} \right) (0.5)^2 (1)^\frac{1}{2}
\]

\[
= 0.642 \text{ cfs}
\]
The discharge permitted by the rectangular weir depends upon the area through which water is allowed to flow. The dimensions of the weir are modified to account for variations in flow due to constrictions as the fluid passes over the weir (Figure 25 in Chapter 7). The allowable discharge through the rectangular weir was calculated as follows:

\[ Q = \frac{2}{3} C_d' L_w' \sqrt{2gh'}^3 \]
\[ = \frac{2}{3} (0.64)(1.66)\sqrt{2}(32.2)(0.503)^3 \]
\[ = 2.02 \text{ cfs} \]

The combination weir is capable of passing 2.66 cfs, but cannot manage \( Q_{\text{max}} \) of 4 cfs. Therefore, it is necessary to keep the gate valve completely open during the wetter seasons of the year. The open gate valve and the emergency spillway can together manage 5.01 cfs, more than the expected value of \( Q_{\text{max}} \).

**WETLAND CALCULATIONS**

**Wetland Dimensions:**
- Length = 40 feet
- Width = 20 feet
- Depth = 4.5 feet

**Expected Flow Through The Wetland:**

The hydraulic conductivity of the manure substrate was determined to be 0.000984 ft/sec in the laboratory. The head over the wetland can be varied by using a standpipe located at the downstream end of the wetland. The standpipe consists of a 6-inch diameter pipe which
has 1-inch diameter holes drilled into it. The maximum head which can be imposed over the wetland is 1 foot; the head can be reduced by increments of 1 inch. Using Darcy’s Law, it is possible to determine the maximum expected flow through the wetland under the greatest head differential (1 foot, water flowing out of bottom hole):

\[
Q = K_i A = (0.000984) \left( \frac{1}{3.5} \right) (40)(20) = 0.225 \text{ cfs} = 101 \text{ gpm}
\]

This allowable discharge was confirmed during a field test. Water from the adit was pumped into the wetland at a rate of 100 gpm; the substrate easily managed the flow.

The design flow rate is 30 gpm. The flow rate through the wetland can be controlled by the level of the standpipe. To allow for the required Q to pass out of the standpipe hole, a certain head of water will be required to exist above the hole. It is desirable to maintain a relatively small head over the hole, so that the overall head across the wetland will essentially equal the level of the hole. It was decided that an acceptable head over the standpipe holes would be 2 inches. Knowing this value and the design flow rate, it is possible to determine the required area of the hole:
The original standpipe design featured a 1-inch diameter hole. It will be necessary to drill another 1-inch hole at each head increment along the standpipe to accommodate the small head above the holes. Since it is necessary to have 2 inches of standing water in the standpipe (above the open hole), it will be necessary to plug up two of the holes above the open hole.

**Treatment Capacity of the Wetland:**

Reynolds and others (1991) and McIntire and Edenborn (1990) have determined that the treatment capability of an organic substrate is dependent upon the amount of sulfides produced in the anaerobic zone of the wetland. They determined that 300 nanomoles of sulfide can be generated per cubic foot of substrate material per day. Using this relationship, the following equation was developed to calculate the required volume of substrate:
The maximum expected flow rate into the wetland is 163503 L/day, and the maximum iron concentration was measured at about 7 mg/L. Iron and sulfide react in a one to one proportion to produce FeS. Knowing that information, the required volume of substrate can be calculated as follows:

\[
m^3 = \frac{(\text{flow rate L/day})(\text{metals concentration mg/L})}{300(\text{atomic weight of the metal})(\text{mols of metal req'd to react with 1 mol sulfide})}
\]

\[
m^3 = \frac{(163503)(7)}{(300)(55.85)(1)}
= 68.3 \text{ m}^3
\]

The volume of substrate in the wetland is 79.3 m³, therefore the wetland size is sufficient to treat all of the expected flow into the system.

DIVERSION CHANNELS AND SPILLWAYS

There is a diversion channel located along the perimeter of the treatment system. The channel is designed to pass all expected flows safely around the system. The emergency spillway in the settling pond empties water into this diversion channel. There are additional spillways located along the dam embankments, which protect the structures as water flows from one system component to another. All of the spillways have the following cross-section (not to scale):
The diversion channels along the treatment system have a slope of 0.088 (Kaman Tempo, 1983). The channel bottom consists of smooth river rock embedded in concrete (n = 0.013). Knowing this information, Manning’s Equation can be used to calculate the expected velocity through the channel:

\[ V = \frac{1.486}{n} R^{\frac{1}{2}} S^{\frac{1}{2}} \]

\[ V = \left( \frac{1.486}{0.013} \right)^{\frac{1}{2}} (0.928)^{\frac{1}{2}} (0.088)^{\frac{1}{2}} \]

\[ = 32.26 \text{ ft/sec} \]

Knowing the velocity, the discharge capacity of the spillway can be determined as follows:
\[ Q = VA \\
= (32.26)(6) \\
= 193.6 \text{ cfs} \]

The spillway size is more than sufficient to pass all expected flows.

The spillways located in the dam embankments have a slope of 0.5. Manning's Equation is again used to calculate the expected velocity of the flow:

\[ V = \left( \frac{1.486}{0.013} \right)(0.928)\frac{S}{n}(0.5)^{\frac{1}{2}} \]

\[ = 76.9 \text{ ft/sec} \]

Knowing the velocity, the discharge capacity of the spillway can be determined as follows:

\[ Q = VA \\
= (76.9)(6) \\
= 461.4 \text{ cfs} \]

The spillway size is more than sufficient to pass all expected flows.
APPENDIX C
COMMERCIALY AVAILABLE WETLAND PLANT SPECIES
Table C-1. List of wetland grasses.

<table>
<thead>
<tr>
<th>Species</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agropyron elongatum</td>
<td>Tall Wheatgrass</td>
</tr>
<tr>
<td>Agropyron smithii</td>
<td>Western Wheatgrass</td>
</tr>
<tr>
<td>Agrostis alba</td>
<td>Red Top</td>
</tr>
<tr>
<td>Alopecurus arundinaceous</td>
<td>Creeping Foxtail</td>
</tr>
<tr>
<td>Alopecurus pratensis</td>
<td>Meadow Foxtail</td>
</tr>
<tr>
<td>Bouteloua curtipendula</td>
<td>Sideoats Grama</td>
</tr>
<tr>
<td>Bouteloua gracilis</td>
<td>Blue Grama</td>
</tr>
<tr>
<td>Bromus inermis</td>
<td>Smooth Brome</td>
</tr>
<tr>
<td>Bromus marginatus</td>
<td>Mountain Brome</td>
</tr>
<tr>
<td>Buchloe dactyloides</td>
<td>Buffalo Grass</td>
</tr>
<tr>
<td>Cynodon dactylon</td>
<td>Bermuda Grass</td>
</tr>
<tr>
<td>Deschampsia caespitosa</td>
<td>Tufted Hairgrass</td>
</tr>
<tr>
<td>Distichlis stricta</td>
<td>Inland Saltgrass</td>
</tr>
<tr>
<td>Festuca ovina</td>
<td>Sheep Fescue</td>
</tr>
<tr>
<td>Festuca rubra</td>
<td>Red Fescue</td>
</tr>
<tr>
<td>Hordeum jubatum</td>
<td>Foxtail</td>
</tr>
<tr>
<td>Oryzopsis</td>
<td>Indian Ricegrass</td>
</tr>
<tr>
<td>Panicum virgatum</td>
<td>Switchgrass</td>
</tr>
<tr>
<td>Phalaris arundinacea</td>
<td>Reed Canarygrass</td>
</tr>
<tr>
<td>Phleum pratense</td>
<td>Timothy</td>
</tr>
<tr>
<td>Poa compressa</td>
<td>Canada Bluegrass</td>
</tr>
<tr>
<td>Poa pratense</td>
<td>Kentucky Bluegrass</td>
</tr>
<tr>
<td>Schizachyrium scoparium</td>
<td>Little Bluestem</td>
</tr>
<tr>
<td>Stipa comata</td>
<td>Needle and Thread</td>
</tr>
</tbody>
</table>
Table C-2. List of wetland forbs.

<table>
<thead>
<tr>
<th>Species</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Achillea millefolium</em></td>
<td>Common Yarrow</td>
</tr>
<tr>
<td><em>Aquilegia caerulea</em></td>
<td>Colorado Blue Columbine</td>
</tr>
<tr>
<td><em>Iris missouriensis</em></td>
<td>Rocky Mountain Iris</td>
</tr>
<tr>
<td><em>Lupinus sericeus</em></td>
<td>Silky Lupine</td>
</tr>
<tr>
<td><em>Mimulus guttatus</em></td>
<td>Monkey Flower</td>
</tr>
<tr>
<td><em>Campanula rotundifolia</em></td>
<td>Harebell</td>
</tr>
<tr>
<td><em>Castilleja</em></td>
<td>Paintbrush</td>
</tr>
<tr>
<td><em>Artemisia ludoviciana</em></td>
<td>Louisiana Sage</td>
</tr>
<tr>
<td><em>Liatris punctata</em></td>
<td>Blazing Star</td>
</tr>
<tr>
<td><em>Linum lewisii</em></td>
<td>Flax</td>
</tr>
<tr>
<td><em>Dalea purpurea</em></td>
<td>Purple Prairie Clover</td>
</tr>
<tr>
<td><em>Ratibida columnifera</em></td>
<td>Prairie Coneflower</td>
</tr>
<tr>
<td><em>Sphaeraclicea coccinea</em></td>
<td>Scarlet Globemallow</td>
</tr>
</tbody>
</table>
APPENDIX D
WATER SAMPLING EQUIPMENT
Table D-1. List of equipment used to obtain water quality samples at the Big 5 pilot wetland (Wildeman, 1992).

- Beckman pH/Eh meters (2)
- YSI conductivity meters (2)
- City water 5 gallon carboy
- DI water carboy with spigot, 5 gallon
- dilute HNO3 carboy with spigot, 5 gallon
- buckets for field measurements and water samples (7)
- Barrel filters (2)
- N2 tanks (2)
- Tool kit
- 1/2 gallon flow measurer and stop watch
- Rubbermaid Roughneck containers, 16 gallon (2)
- Rubbermaid Roughneck container, 8 gallon
- Coleman cooler, 55 gallon
- Paper towels
- Filter forceps
- Rubber gloves
- Filters (cellulose acetate) (16)
- Filters (glass fiber) (10)
- Sample bottles (1 L) (35)
- Sample bottles (1/2 L) (3)
- Vials concentrated HNO3 (24)
- Spike solution
- Lights solution
- Buffer solutions (pH 4 and 7)
- KCl solution
- Kim wipes
- Spare electrodes (Eh and pH)
- Log book
- Calibration sheet
- Sample bottle labels
APPENDIX E

RAW DATA OBTAINED FROM THE OLD TREATMENT SYSTEM
Table E-1. Raw data obtained through water quality testing of the old treatment system at W1. Sampling locations are given in Figure 3. Values are given in μg/l (----- indicates no value obtained). T = total metals and D = dissolved metals.

<table>
<thead>
<tr>
<th>Date</th>
<th>Fe (T)</th>
<th>Fe (D)</th>
<th>Mn (T)</th>
<th>Mn (D)</th>
<th>Zn (T)</th>
<th>Zn (D)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-5-84</td>
<td>3600</td>
<td>3340</td>
<td>990</td>
<td>980</td>
<td>150</td>
<td>40</td>
<td>4.75</td>
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<tr>
<td>7-9-84</td>
<td>3100</td>
<td>2700</td>
<td>940</td>
<td>970</td>
<td>280</td>
<td>44</td>
<td>4.8</td>
</tr>
<tr>
<td>7-25-84</td>
<td>3600</td>
<td>4600</td>
<td>880</td>
<td>890</td>
<td>84</td>
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<td>8-2-84</td>
<td>3800</td>
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<td>890</td>
<td>920</td>
<td>61</td>
<td>25</td>
<td>5.22</td>
</tr>
<tr>
<td>8-28-84</td>
<td>-----</td>
<td>4200</td>
<td>930</td>
<td>920</td>
<td>52</td>
<td>32</td>
<td>5.23</td>
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<tr>
<td>8-31-84</td>
<td>4600</td>
<td>4300</td>
<td>972</td>
<td>1000</td>
<td>29</td>
<td>28</td>
<td>5.1</td>
</tr>
<tr>
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<td>980</td>
<td>1000</td>
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<td>4700</td>
<td>1000</td>
<td>1000</td>
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<td>5.24</td>
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<td>9-20-84</td>
<td>4400</td>
<td>4600</td>
<td>1030</td>
<td>1090</td>
<td>93</td>
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<td>10-3-84</td>
<td>5700</td>
<td>5100</td>
<td>1100</td>
<td>1200</td>
<td>190</td>
<td>36</td>
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<tr>
<td>Average</td>
<td>4300</td>
<td>3864</td>
<td>971</td>
<td>997</td>
<td>105</td>
<td>34</td>
<td>5.12</td>
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</table>
Table E-2. Raw data obtained through water quality testing of the old treatment system at W2. Values are given in μg/l.

<table>
<thead>
<tr>
<th>Date</th>
<th>Fe (T)</th>
<th>Fe (D)</th>
<th>Mn (T)</th>
<th>Mn (D)</th>
<th>Zn (T)</th>
<th>Zn (D)</th>
<th>pH</th>
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</thead>
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<tr>
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<td>1020</td>
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<td>980</td>
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<tr>
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<td>930</td>
<td>970</td>
<td>330</td>
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<td>990</td>
<td>960</td>
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<td>5.55</td>
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<td>8-31-84</td>
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<td>100</td>
<td>960</td>
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<td>9-3-84</td>
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<td>820</td>
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<td>12</td>
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<td>1200</td>
<td>100</td>
<td>970</td>
<td>950</td>
<td>53</td>
<td>31</td>
<td>5.54</td>
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<tr>
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<td>100</td>
<td>------</td>
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<td>------</td>
<td>------</td>
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<td>------</td>
</tr>
<tr>
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<td>947</td>
<td>957</td>
<td>54</td>
<td>22</td>
<td>5.47</td>
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</table>
Table E-3. Raw data obtained through water quality testing of the old treatment system at W3. Values are given in μg/l.

<table>
<thead>
<tr>
<th>Date</th>
<th>Fe (T)</th>
<th>Fe (D)</th>
<th>Mn (T)</th>
<th>Mn (D)</th>
<th>Zn (T)</th>
<th>Zn (D)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-5-84</td>
<td>5970</td>
<td>100</td>
<td>990</td>
<td>990</td>
<td>93</td>
<td>27</td>
<td>5.6</td>
</tr>
<tr>
<td>7-9-84</td>
<td>3000</td>
<td>1100</td>
<td>1060</td>
<td>1000</td>
<td>140</td>
<td>44</td>
<td>5.28</td>
</tr>
<tr>
<td>7-25-84</td>
<td>630</td>
<td>100</td>
<td>920</td>
<td>910</td>
<td>50</td>
<td>41</td>
<td>5.93</td>
</tr>
<tr>
<td>8-2-84</td>
<td>100</td>
<td>100</td>
<td>840</td>
<td>910</td>
<td>67</td>
<td>17</td>
<td>6.19</td>
</tr>
<tr>
<td>8-28-84</td>
<td>110</td>
<td>100</td>
<td>1000</td>
<td>880</td>
<td>26</td>
<td>10</td>
<td>5.86</td>
</tr>
<tr>
<td>8-31-84</td>
<td>220</td>
<td>100</td>
<td>820</td>
<td>860</td>
<td>32</td>
<td>28</td>
<td>5.82</td>
</tr>
<tr>
<td>9-3-84</td>
<td>100</td>
<td>100</td>
<td>750</td>
<td>720</td>
<td>26</td>
<td>10</td>
<td>5.87</td>
</tr>
<tr>
<td>9-10-84</td>
<td>110</td>
<td>100</td>
<td>950</td>
<td>960</td>
<td>39</td>
<td>12</td>
<td>5.74</td>
</tr>
<tr>
<td>9-20-84</td>
<td>370</td>
<td>100</td>
<td>820</td>
<td>850</td>
<td>20</td>
<td>12</td>
<td>5.86</td>
</tr>
<tr>
<td>Average</td>
<td>1179</td>
<td>211</td>
<td>906</td>
<td>898</td>
<td>55</td>
<td>22</td>
<td>5.79</td>
</tr>
</tbody>
</table>
Table E-4. Raw data obtained through water quality testing of the old treatment system at W4. Values are given in μg/l.

<table>
<thead>
<tr>
<th>Date</th>
<th>Fe (T)</th>
<th>Fe (D)</th>
<th>Mn (T)</th>
<th>Mn (D)</th>
<th>Zn (T)</th>
<th>Zn (D)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-5-84</td>
<td>5200</td>
<td>100</td>
<td>1030</td>
<td>980</td>
<td>78</td>
<td>20</td>
<td>5.43</td>
</tr>
<tr>
<td>7-9-84</td>
<td>6140</td>
<td>970</td>
<td>1060</td>
<td>1020</td>
<td>120</td>
<td>40</td>
<td>5.37</td>
</tr>
<tr>
<td>7-25-84</td>
<td>1700</td>
<td>100</td>
<td>920</td>
<td>910</td>
<td>50</td>
<td>41</td>
<td>5.98</td>
</tr>
<tr>
<td>8-2-84</td>
<td>460</td>
<td>100</td>
<td>860</td>
<td>890</td>
<td>28</td>
<td>13</td>
<td>6.18</td>
</tr>
<tr>
<td>8-28-84</td>
<td>1400</td>
<td>100</td>
<td>680</td>
<td>720</td>
<td>23</td>
<td>10</td>
<td>6.23</td>
</tr>
<tr>
<td>8-31-84</td>
<td>130</td>
<td>100</td>
<td>610</td>
<td>610</td>
<td>23</td>
<td>13</td>
<td>5.97</td>
</tr>
<tr>
<td>9-3-84</td>
<td>110</td>
<td>100</td>
<td>750</td>
<td>560</td>
<td>31</td>
<td>10</td>
<td>6.03</td>
</tr>
<tr>
<td>9-10-84</td>
<td>810</td>
<td>100</td>
<td>850</td>
<td>870</td>
<td>44</td>
<td>17</td>
<td>6.04</td>
</tr>
<tr>
<td>9-20-84</td>
<td>240</td>
<td>100</td>
<td>400</td>
<td>730</td>
<td>69</td>
<td>11</td>
<td>5.84</td>
</tr>
<tr>
<td>10-3-84</td>
<td>100</td>
<td>100</td>
<td>950</td>
<td>980</td>
<td>28</td>
<td>19</td>
<td>5.90</td>
</tr>
<tr>
<td>Average</td>
<td>1629</td>
<td>187</td>
<td>811</td>
<td>827</td>
<td>49</td>
<td>19</td>
<td>5.89</td>
</tr>
</tbody>
</table>
APPENDIX F

RAW DATA OBTAINED FROM THE NEW TREATMENT SYSTEM
Table F-1. Raw data obtained through water quality testing of the new treatment system.  
Note: MD = mine drainage, ALD = anoxic limestone drain, SP = settling pond, W = wetland and PC = polishing cell, = no sample obtained from that location.

Sampling Date: August 29, 1993.

<table>
<thead>
<tr>
<th></th>
<th>MD</th>
<th>ALD</th>
<th>SP</th>
<th>W</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>---</td>
<td>5.36</td>
<td>5.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eh (mv)</td>
<td>---</td>
<td>99.2</td>
<td>88.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkalinity (mg/L)</td>
<td>---</td>
<td>45.6</td>
<td>52.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sampling Date: September 5, 1993.

<table>
<thead>
<tr>
<th></th>
<th>MD</th>
<th>ALD</th>
<th>SP</th>
<th>W</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>---</td>
<td>5.39</td>
<td>5.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eh (mv)</td>
<td>---</td>
<td>89.2</td>
<td>82.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkalinity (mg/L)</td>
<td>---</td>
<td>37.2</td>
<td>61.2</td>
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</tr>
</tbody>
</table>

Sampling Date: September 9, 1993.

<table>
<thead>
<tr>
<th></th>
<th>MD</th>
<th>ALD</th>
<th>SP</th>
<th>W</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>---</td>
<td>5.16</td>
<td>5.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eh (mv)</td>
<td>---</td>
<td>93.5</td>
<td>84.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkalinity (mg/L)</td>
<td>---</td>
<td>42.5</td>
<td>53.5</td>
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</table>

Table F-1 (continued)
Sampling Date: September 24, 1993.

<table>
<thead>
<tr>
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<th>ALD</th>
<th>SP</th>
<th>W</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5.79</td>
<td>5.32</td>
<td>5.87</td>
<td>6.59</td>
<td>-----</td>
</tr>
<tr>
<td>Eh (mv)</td>
<td>59.7</td>
<td>95.8</td>
<td>86.4</td>
<td>24.7</td>
<td>-----</td>
</tr>
<tr>
<td>Alkalinity (mg/L)</td>
<td>24.4</td>
<td>40.8</td>
<td>54</td>
<td>84.4*</td>
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</tr>
</tbody>
</table>

Sampling Date: October 10, 1993.

<table>
<thead>
<tr>
<th></th>
<th>MD</th>
<th>ALD</th>
<th>SP</th>
<th>W</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5.58</td>
<td>5.56</td>
<td>6.29</td>
<td>6.59</td>
<td>-----</td>
</tr>
<tr>
<td>Eh (mv)</td>
<td>82.6</td>
<td>85.4</td>
<td>37</td>
<td>21.7</td>
<td>-----</td>
</tr>
<tr>
<td>Alkalinity (mg/L)</td>
<td>34</td>
<td>53.2</td>
<td>83.2</td>
<td>125.2</td>
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</tr>
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</table>

Sampling Date: October 23, 1993.

<table>
<thead>
<tr>
<th></th>
<th>MD</th>
<th>ALD</th>
<th>SP</th>
<th>W</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5.16</td>
<td>5.46</td>
<td>5.69</td>
<td>6.11</td>
<td>-----</td>
</tr>
<tr>
<td>Eh (mv)</td>
<td>96.3</td>
<td>97.8</td>
<td>60</td>
<td>37.9</td>
<td>-----</td>
</tr>
<tr>
<td>Alkalinity (mg/L)</td>
<td>37.2</td>
<td>33.6</td>
<td>49.2</td>
<td>74.4</td>
<td>-----</td>
</tr>
</tbody>
</table>