DRAFT
PRELIMINARY WASTEWATER TREATMENT TECHNOLOGY EVALUATION
TAR CREEK SUPERFUND SITE
OKLAHOMA PICHER MINING DISTRICT

Prepared for

U.S. ARMY CORPS OF ENGINEERS
Tulsa District
1645 South 101st East Avenue
Tulsa, Oklahoma

Prepared by

WESTON SOLUTIONS, INC.
5599 San Felipe, Suite 700
Houston, TX 77056

August 2004

W.O. No. 03886.518.048.0005

TABLE OF CONTENTS

Section **Page**

TABLE OF CONTENTS (Continued)

Section **Page**

LIST OF FIGURES

Title **Page**

LIST OF TABLES

Title **Page**

1. INTRODUCTION

1.1 PURPOSE AND SCOPE

Weston Solutions, Inc. (WESTON®) was retained by the Tulsa Corps of Engineers to perform a treatment technology evaluation for wastewater[1] at the Tar Creek Superfund site located in the Oklahoma Picher Mining District. The purpose of this review was to identify and evaluate various methods of wastewater (mine water) treatment. This evaluation is preliminary and site specific evaluations will need to be conducted.

1.2 OBJECTIVES

The objectives of this wastewater treatment evaluation include:

- Summarize wastewater quality using historical analytical data.
- Estimate the quantity and flow rate of wastewater to be treated.
- Identify and screen various methods of wastewater treatment.
- Further evaluate the most likely technology to include a preliminary conceptual design and estimated costs.

All results and conclusions presented in this report are based on previously collected water quality and quantity data, and historical information.

[1] "Wastewater" as used herein includes acid mine drainage, contaminated runoff, mine water pumped during remediation, or any other water contaminated by mining operations.

2. WASTEWATER SUMMARY

2.1 WASTEWATER QUALITY

The average mine water quality for the Picher Mining District was determined using analytical laboratory data from samples collected in 2002 from various mineshafts. The water quality parameters identified for this discussion include conductance, alkalinity, dissolved oxygen, pH, sulfate, manganese, lead, zinc, copper, and iron. Average water quality values for these parameters are shown in Table 2-1. It should be noted that the waters at Tar Creek are contaminated with elevated concentrations of iron, lead, zinc, cadmium, and sulfate (Keating 2000). Recently analyzed mine drainage discharges have shown to be near neutral (5.5-7), which is not common at most acid mine drainage (AMD) sites. Also, mine water quality may vary within the district, but for this preliminary evaluation the values on Table 2-1 are used.

Based on this information the constituents of most concern are sulfate and zinc. The pH is only slightly acidic; therefore, this parameter does not appear to be a major concern.

Table 2-1, Representative Water Quality Parameters

Water Quality Parameter	Range	Median
Specific Conductance	1,500-2,500 µS/cm	1,180 µS/cm
Alkalinity as $CaCO_3$	60-160 mg/L	88.0 mg/L
Dissolved Oxygen	5-6 mg/L	0.9 mg/L
pH	5.5-7 SU	6.3 SU
Sulfate	200-600 mg/L	414 mg/L
Manganese	0.1-1.2 mg/L	0.375 mg/L
Lead	0.00008-0.032 mg/L	0.001 mg/L
Zinc	1.8-2.2 mg/L	2.14 mg/L
Copper	0.008 mg/L	.0086 mg/L
Iron	0.05-0.2 mg/L	0.022 mg/L

Note: Water quality parameters adapted from Water-Resources Investigation Report 03-4248 prepared by the US Geological Survey (2003).

2.2 WASTEWATER QUANTITY

Sources of wastewater include: (1) surface runoff from mine spoil (chat piles) and abandoned mill sites, (2) shallow ground waters seeping from the base of mine spoil, and (3) deep ground waters seeping from flooded mine workings to the surface through abandoned, unsealed wells, drill holes, mineshafts or natural fractures. The total quantity of deep ground water within the abandoned underground mine workings at Tar Creek is approximately 26 billion gallons (Keating 2000). Wastewater may be produced by any of these sources with the poorest quality and largest quantity of waters coming from acid mine drainage seeping to the ground surface from the flooded, abandoned mines. The water within the mineshafts is seeping to the ground surface at an estimated 1,000,000 gallons per day (1 MGD), or 2,628 L/min (U.S. Environmental Protection Agency 1983) in the vicinity of the Tar-Lytle Creek's confluence near the 800-ft contour elevation. Other areas show various rates of seepage at or below this elevation, primarily to the southwest and southeast. This flow rate, 1 MGD, will be used as an estimated value for calculating the preliminary design requirements of the various treatment technologies identified in this evaluation.

Site specific conditions will dictate the design requirements of the various treatment technologies. For example, a proposed chat injection pilot project may produce a temporary point source if water is extracted as part of the process. The total volume of water that may be displaced by a potential chat injection pilot test is estimated at 20,000,000 gallons (at a rate of 200,000 gallons per day or 525 L/min).

Because it is likely that groundwater will continue to fill the mines and generate discharge, there will always be a need to treat the drainage discharging from the mines. Therefore, wastewater treatment will be required long-term at varying flows and qualities, and at various locations.

This evaluation does not consider structural barriers to groundwater recharge or movement within the mines, which may be used to reduce the volume of water that will require treatment.

3. TREATMENT TECHNOLOGIES

The two general types of treatment for AMD are active and passive. Active treatment systems involve physically adding chemical components to AMD streams to change the water chemistry. Passive treatment systems utilize the chemical, biological, and physical removal processes that occur naturally in the environment to modify water quality. Passive treatment systems typically have lower operation and maintenance costs than active systems.

3.1 ACTIVE TREATMENT

Active treatment typically involves the addition of alkaline materials to raise the pH, neutralize acidity, and precipitate metals. Most active chemical treatment systems require influent channels to a storage pond, a storage tank to hold treatment chemicals, a means of mixing the chemicals in the waste stream and controlling their application, a settling pond to collect precipitated metal hydroxides, and a sludge collection system (Elizabeth Mines 2001). Active treatment can be successful; however, regular monitoring and maintenance are required. Weather, equipment failure, and budget reductions can cause lapses in treatment (Fripp et al. 2000). Because of the likelihood of fluctuations in influent quality, monitoring and system adjustments are an important component of the operation of active treatment systems.

Three types of active treatment technologies have been examined:

- Aeration/oxidation ponds
- Flocculants/Coagulants
- Neutralizers

There are several more complex active methods of wastewater treatment (e.g., reverse osmosis, electrodialysis, ion exchange resins) which are generally very expensive and probably not applicable for this site due to the large quantity of water to be treated.

3.1.1 Aeration/Oxidation Ponds

The process of aeration introduces oxygen into water to oxidize metals and promote biological activity. The process involves aeration followed by velocity reduction to allow settling. This can be accomplished with tanks or ponds, but for large volumes of wastewater, ponds are often used. Oxidized metals will generally precipitate at a lower pH. The materials required are a lined pond or treatment cell, and aeration units. Oxygen is introduced into water by use of an aerator at the base of the pond (U.S. Environmental Protection Agency 1983). The subsequent turbulence disperses air bubbles, causing the metal hydroxide floc to stay in suspension, and allowing the oxygen to react with reduced compounds in the water. The oxidized water then flows to a low velocity settling pond to allow metal precipitates to settle out. The resulting sludge must occasionally be collected and appropriately disposed.

3.1.2 Flocculants/Coagulants

Flocculants and coagulants are chemicals used to increase particle settling efficiency. These chemicals are used in conjunction with aeration and settling ponds, which otherwise may be insufficient for adequate metal precipitation. The materials required to implement a flocculant/coagulant treatment system include a holding pond, a tank for chemical storage, and a means of chemical application and mixing. Coagulants reduce electrical repulsive forces at particle surfaces allowing consolidation of small particles into larger particles (Kilborn 1999). The most common coagulants/flocculants used in water treatment are aluminum sulfate (alum) and ferric sulfate.

3.1.3 Neutralizers

The addition of neutralizers to AMD will raise the pH to a level that allows metals to precipitate as metal hydroxides. Generally, the pH required to precipitate most metals ranges from 6 to 9 (Skousen et al. 1998). There are six primary chemicals used to neutralize AMD: limestone, hydrated limestone, pebble quicklime, soda ash, caustic soda, and ammonia (Skousen et al. 1998).

Addition of neutralizing agents to AMD has been done in many different ways. For example, diversion wells are large wells filled with limestone aggregate. They contain a pipe that carries wastewater vertically down the center of the well. The water is forced up through the limestone creating a churning motion which dissolves the limestone and creates alkalinity (Skousen, 1998). Neutralizers can also be applied to moving bodies of water using a water wheel to turn a screw feeder to dispense the appropriate amount of chemical from a hopper. More conventional applications use mixing tanks or mixing areas in ponds.

3.2 PASSIVE TREATMENT

Passive treatment systems utilize the chemical, biological, and physical removal processes that occur naturally to modify water chemistry and remove metals. They are generally more cost efficient than active treatment and require less maintenance, allowing them to operate in remote locations. However, they require more area.

Four major passive technologies for the treatment of acid mine drainage have been examined:

- Anoxic limestone drains
- Microbial reactor systems
- Biosorption systems
- Constructed wetlands

These technologies may be used individually or in combination with each other. And, as with active systems, sludge management must be considered and the sludge produced may be hazardous.

There are several technologies which were not considered. These include natural wetlands, open limestone channels and others which may be applicable in concert with the evaluated technologies or in specialized applications.

3.2.1 Anoxic Limestone Drains

Successful metals precipitation requires the influent wastewater to be near neutral pH. When AMD water is acidic, the addition of alkalinity is necessary to ensure the proper chemical reactions will occur (Hedin & Nairn 1994). Anoxic limestone drains (ALDs) are limestone beds, typically constructed underground, through which an unaerated AMD stream flows by gravity (Kilborn 1999). As the stream flows through the system, limestone is dissolved to produce calcium carbonate which adds alkalinity to the system and increases the pH. Anoxic limestone drains are not a stand-alone treatment for AMD; however, they add alkalinity to the wastewater stream to improve the effectiveness of downstream treatment, such as the precipitation of metal hydroxides under aerobic conditions (Kilborn 1999).

If the pH indicated on Table 2-1 is characteristic of all mine water to be treated, this type of aggressive alkalinity adjustment may not be warranted. However, it is likely that deep mine water will require neutralization.

3.2.2 Microbial Systems

Microbial reactor systems, also known as bioreactors, are treatment systems that utilize natural microbial processes to promote sulfate reduction and metals precipitation (Kilborn 1999). These systems require a biodegradable substrate to support the growth of organisms which metabolize the substrate and produce short chain organic acids. These organic acids promote the growth of sulfate reducing bacteria (Kilborn 1999) which reduce sulfate to hydrogen sulfide, which raises the pH. This will cause precipitation of metals as low solubility metal sulfides. The concept behind this substrate configuration is that AMD will flow vertically over the substrate using a series of weirs and open-bottom dams to passively control the water flow. Bioreactors are not completely passive systems since maintenance and monitoring is required to prevent precipitate from plugging the pipes or weirs. Also, the substrate is expected to require replacement once a year (Kilborn 1999). However, loading rates could cause substrate replacement to be more frequent, or less frequent.

3.2.3 Biosorption Systems

Biosorption systems are another biological treatment technology that relies on the removal of metal ions from solution by adsorption/absorption to biological material. Bacteria, algae, fungi, and yeast are examples of microorganisms that can accumulate heavy metals. Metal ions form complexes with living or dead biomass. Living cells can be used to treat water containing metals concentrations that are not toxic to bacteria. Dead biomass can be used to treat toxic wastewater. The use of dead biomass binds metals to the cell walls, can be effective in adverse weather conditions, and does not require a nutrient supply. However, dead biomass must be replaced approximately once a year depending on loading rates (Kilborn 1999).

3.2.4 Constructed Wetlands

Most of the technologies discussed so far are either anaerobic for sulfate reduction or aerobic for metals oxidation. Wetlands are natural ecological systems where both aerobic and anaerobic conditions may occur allowing physical, chemical, and microbial processes to change water chemistry. These naturally-occurring processes include oxidation, reduction, precipitation, adsorption, active plant uptake (phytoremediation), and microbial mechanisms (Kilborn 1999). Wetlands are heterogeneous in nutrient distribution, organic substrate, reduction/oxidation and microbial activity (Perry & Kleinmann 1991). It is possible to control this level of heterogeneity by designing features into the wetland which can mitigate differences in influent concentrations and loadings.

There are two general types of constructed wetlands: aerobic, and anaerobic. Aerobic wetlands are designed to carry out oxidation reactions, while anaerobic wetlands rely on an anoxic environment to promote microbial reducing reactions (Kilborn 1999). An effective passive treatment system will usually incorporate both types of environments to allow for removal of metals under oxidizing conditions, and sulfide removal along with pH neutralization under reducing conditions.

A general design for a constructed wetland for ADM treatment consists of a series of aerobic ponds, settling ponds, anoxic limestone drains where applicable, and vertical or surface flow anaerobic cells. Since AMD water quality and quantity varies between sites, the site-specific water chemistry (metals loading rate, dissolved oxygen [DO], pH, etc.) and wastewater flow will affect the overall design of the wetland. When designed properly, a constructed wetland can effectively and continuously treat large quantities of AMD with minimal maintenance.

4. TECHNOLOGY SCREENING

The following is a discussion of the treatment technologies as they apply to the Tar Creek site in general. Each location will need to be evaluated to determine the most effective method of treatment considering the water chemistry and flow rate. The main factors to consider when selecting a method of treatment for AMD sites include (Skousen et al. 1998):

- Raw water flow rate
- pH
- Acidity/alkalinity in mg/L as CaCO3
- Contaminants present and loading rates

It is necessary to implement a treatment system at the Tar Creek site that will allow for precipitation of zinc and other metals including iron, lead, and cadmium, as well as sulfate reduction. This system must also be able to treat relatively high flow rates. If the pH of wastewater is essentially neutral, as indicated by previous investigations, a method of introducing additional alkalinity may not be necessary; however, this may change when deep mine water is to be treated.

4.1 ACTIVE TREATMENT

Active treatment requires continuous addition of chemical agents to affected waters; therefore, these technologies generally have higher operation and maintenance costs than passive systems. The initial capital cost of construction of an active treatment system, along with the continued cost of chemical agents and more active sludge management, makes active treatment more expensive for large flow rates. The three general methods of active treatment (aeration ponds, flocculants and neutralizers) are reviewed below:

4.1.1 Aeration/Oxidation Ponds

Oxidation ponds are simple physical and biological systems for metals oxidation and precipitation. They are limited in their capacity to remove toxic metals from contaminated water (Kilborn 1999) and may not be a stand alone method of treating AMD. They do, however, aid in raising the dissolved oxygen content of water causing precipitation of metals, primarily iron, to occur more easily in later stages of treatment. However, at Tar Creek iron may not be the primary precipitate and an aeration/oxidation pond system would have to be coupled with other forms of treatment.

The DO content of the affected surface water at the site is approximately 5-6 mg/L (typically saturation is about 8 mg/L). This is a moderate DO content and is not low enough to require an active oxidation/aeration pond. However, mine water will probably be encountered which has a much lower DO and, if an aeration/oxidation system was used, it would likely require some form of supplemental aeration. There are many proven active aeration technologies including surface aerators and diffusers. The selected technology will depend on water depth but, for ponds, is usually some type of surface aerator. However, a passive aeration system using gravity to cascade water over rocks or stair steps could be installed at the influent to raise the DO content.

4.1.2 Flocculants/Coagulants

Flocculants and coagulants are generally used at sites that contain unique or unusual metal compositions. They are used as a means of promoting further precipitation of metals where settling ponds alone are insufficient (Skousen et al. 1998). Again, this is not a stand alone method and would need to be coupled with mixing and settling.

4.1.3 Neutralizers

Neutralizers are used to add alkalinity to AMD to allow for precipitation of metals. Based on the data collected to date, the pH of the affected water at the site is near neutral; therefore, the addition of alkalinity may not be necessary.

4.1.4 Active Treatment Summary

Most active methods are used to change water chemistry to allow oxidation and precipitation of metals. The Tar Creek AMD also contains high concentrations of sulfate that is most likely treated by microbial activity under reducing conditions. Therefore, both aerobic and anaerobic active treatment technologies may be required. For large flow rates, it is more cost effective to implement passive treatment systems, so active treatment systems are not carried forward in this evaluation.

However, location specific circumstances, such as the chat injection pilot study project, will produce temporary point sources that will not require long-term treatment and active treatment, such as with package treatment plants, may be applicable and should be evaluated.

4.2 PASSIVE TREATMENT

Passive treatment utilizes processes that occur in nature to change water chemistry; therefore, they typically require less maintenance. Passive methods can treat water containing high levels of metals, as well as sulfur compounds because they can be designed to create both oxidizing and reducing environments.

4.2.1 Anoxic Limestone Drains

Anoxic limestone drains (ALDs) are used to add alkalinity to AMD affected water with DO below 1 mg/L. An ALD is usually constructed as the initial stage in AMD treatment to allow for neutralization of water and they are not stand alone methods of treatment. They must be supplemented with aerobic and anaerobic ponds to allow for metals and sulfate removal.

As mentioned before, the pH of the water at Tar Creek is near neutral and probably does not require the addition of alkalinity, so ALDs may not be required. This should be re-evaluated if deep mine water has a lower pH.

4.2.2 Microbial Reactor Systems[2]

To date, there have only been short term pilot studies on various types of bioreactors conducted at low flow rates (Kilborn 1999). The pilot plant data indicates that bioreactors are a feasible technology for the treatment of small AMD streams. Microbial reactors can be designed into passive systems, such as ponds where wastewater can be stored and gradually routed through the microbial reactor system. Bioreactors could be a supplementary treatment system, but they are not suitable for high volume effluents such as encountered at the Tar Creek site (Kilborn 1999).

4.2.3 Constructed Wetlands

The water quality characteristics at the Tar Creek site require oxidation of metals with sulfate reduction; both can be accomplished with a constructed wetland system. Wetlands provide residence time and aeration so metals in the water can precipitate. These systems also encourage the interaction of affected water with organic-rich substrates which reduce sulfate and contribute significantly to the treatment process.

Constructed wetlands can treat large volumes of water and require relatively little maintenance. The need for AMD treatment at this site is probably perpetual, so ease of maintenance is very important.

Prior to implementing this approach, the following concerns for use of constructed wetlands need to be addressed:

- Toxicity to wildlife, such as ducks (sometimes called “passive nuisance”),
- Eventual metals accumulation to toxic levels to the microorganisms accomplishing the treatment, and
- Substrate replacement and sludge removal requirements.

[2] Microbial reactors can be classified as active or passive technologies, usually depending if they are in tanks or ponds.

4.2.4 Passive Treatment Summary

To treat the AMD, which will continue in perpetuity, and the water which will be produced during remediation, constructed wetlands are the most likely technology. Other technologies may be useful for relatively low flow, short duration wastewater streams generated during particular remedial activities.

5. CONSTRUCTED WETLANDS

To assess the preliminary design concept and cost requirements of treating the wastewater at the Tar Creek site by using constructed wetlands, the following summary has been prepared.

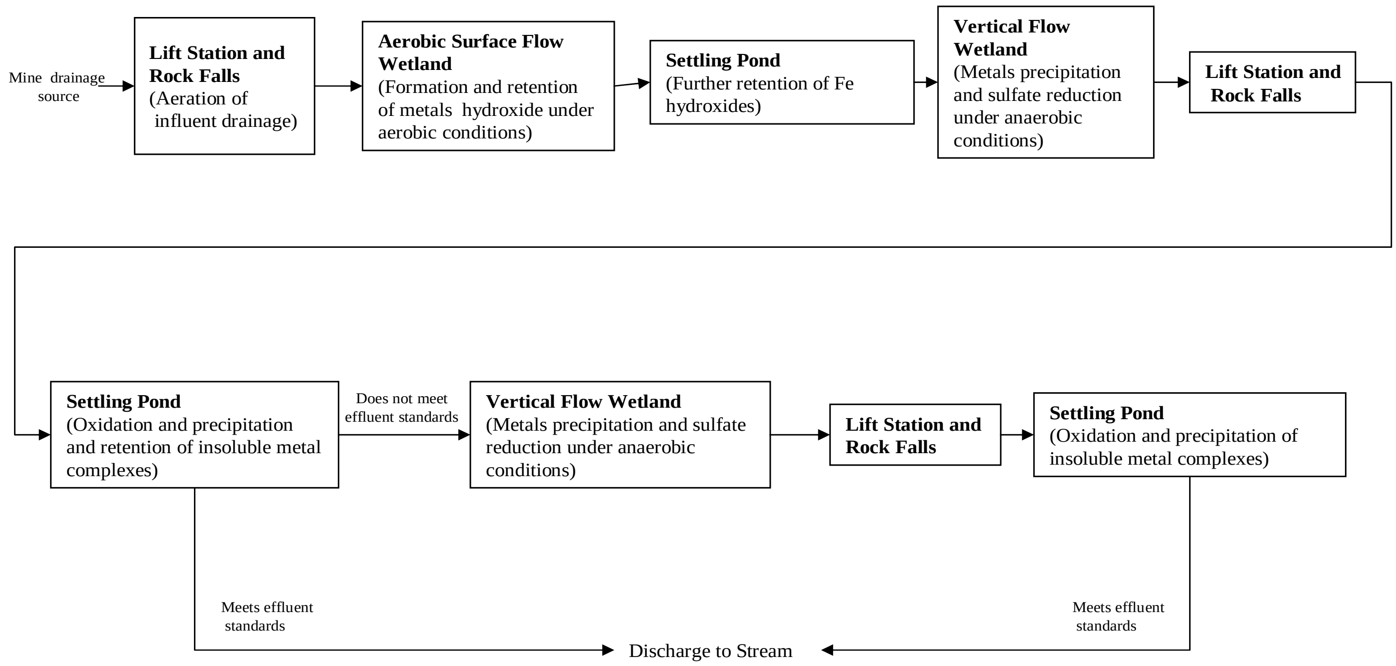
5.1 CONCEPTUAL DESIGN

Because the site requirements to treat the anticipated volume of wastewater (potentially 26 billion gallons) are large and the sources are widespread, it is assumed that multiple wetlands will be distributed throughout the site. For the purposes of this assessment, it has been estimated that seven constructed wetlands will be used. Each wetland is assumed to treat an influent flow rate of 1 MGD (2,628 L/min).

As discussed, a constructed wetland may consist of a series of limestone drains, settling ponds, aerobic and/or anaerobic cells, etc. The layout should be based on site-specific topography, flow rate, and water chemistry. A general conceptual design which may be customized for use at several locations on the site is displayed in Figure 5-1. As shown, the mine drainage is pumped by a lift station to a series of rock falls for aeration because, even though the wastewater quality shown in Table 2-1 has a relatively high DO (5-6 mg/L), it is likely that low DO water will be encountered in deeper mine water. The aerated water is then transported through an aerobic surface flow wetland followed by a settling pond for metal precipitation and retention. The next stage is an anaerobic vertical flow wetland to allow for further metal precipitation and sulfate reduction. The water is then re-aerated and transported to a settling pond to allow precipitates to settle. If the treated water meets the effluent standards, then it is discharged to a stream. If effluent standards are not met, another vertical flow wetland can be incorporated. Each stage of the system is discussed below.

Figure 5-1

Preliminary Conceptual Design of Constructed Wetlands



5.1.1 Aerobic Surface Flow Wetland

An aerobic surface flow wetland consists of a large area pond with horizontal surface flow to oxidize metals and provide residence time to allow the resulting metal oxides and hydroxides to precipitate (Skousen, J. 2004). Aeration prior to treatment, e.g., rock falls, increases the efficiency of the oxidation process, which increases the precipitation process (Penn DEP 2004). Generally, an aerobic wetland will have a water depth of 6-18 inches (Heden & Nairn 1993). A schematic cross-section of an aerobic wetland is presented in Figure 5-2. The most common vegetation in aerobic wetlands is cattails. They are shown to have appreciable cation exchange capacity to remove metal ions (Kilborn 1998). This process is more efficient if the influent water has a pH greater than 5.5 (Hedin & Nairn 1993). Since the pH at Tar Creek varies from 5.5 to 7, there may not be a need for the addition of alkalinity. A settling pond generally follows a surface flow wetland to allow for further settling of metal hydroxide precipitates.

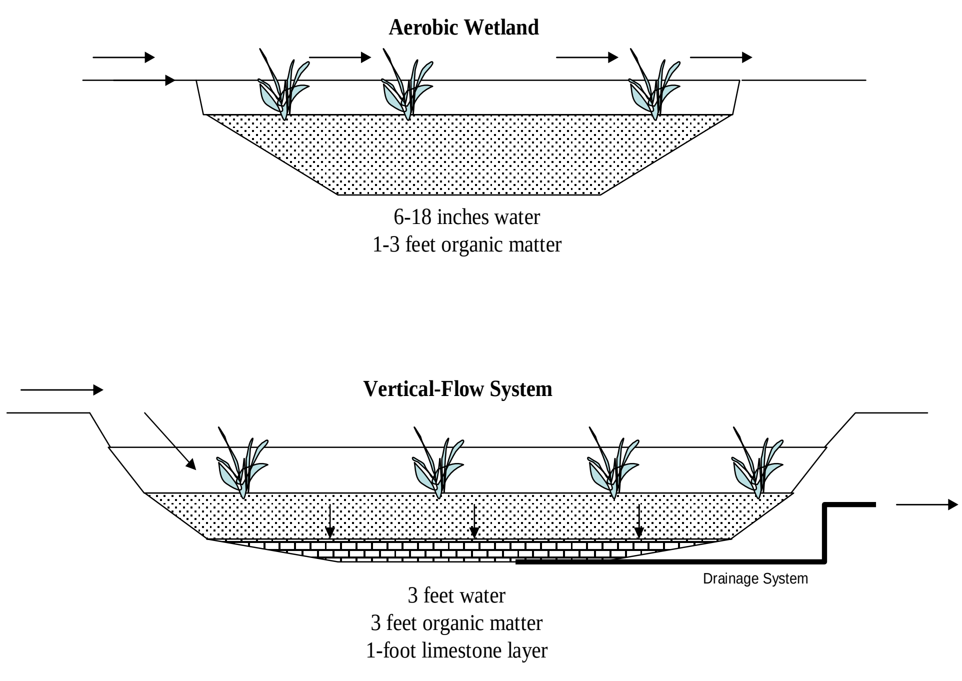
5.1.2 Vertical Anaerobic Flow Wetland

Vertical flow systems, also known as successive alkalinity producing systems (SAPS), combine the mechanisms of anaerobic wetlands and anoxic limestone drains to compensate for the limitations on both (Zipper et al. 2001). The anaerobic wetland system promotes a reducing environment by microbial activity through use of an organic substrate. The three major elements of a vertical flow system are (from the surface down) the organic substrate, the limestone layer, and the drainage system. The organic substrate harbors the sulfate-reducing bacteria (SRBs) and the limestone layer produces alkalinity and raises the pH. The system is constructed in a lined basin. A 1-foot thick limestone layer is constructed below a 3-foot thick layer of organic substrate with a 3-foot layer of standing water on top, for a total depth of approximately 7 feet (Nairn 2000). Figure 5-2 shows a cross-section of a vertical flow wetland. As the water flows downward through the organic layer (usually composed of bark or wood mulch, spent mushroom compost, manure, or hay) the SRBs reduce sulfate under anaerobic conditions, while the limestone layer adds alkalinity to the water to prevent redissolving metals and to meet effluent pH requirements. A drainage system at the bottom of the basin transports the water from the vertical flow cell into a settling pond. The settling pond may be necessary to allow for oxidation, pH adjustment, and subsequent precipitation of metal complexes before being discharged. The precipitates and sediment that accumulate within the settling pond must be periodically dredged and disposed of properly.

If the applicable effluent standards are not met at the discharge point, another vertical flow cell may be incorporated into the passive system to allow for further contaminant removal. As a conservative estimate, the conceptual design includes one aerobic and two anaerobic vertical flow cells for each of the assumed seven treatment systems.

Figure 5-2

Types of Wetland Cells Proposed at Tar Creek



5.2 SIZE DETERMINATION

The size of a constructed wetland is a function of the influent flow rate, the contaminant loading rate, and the acidity. Although size plays a major role in the efficiency of a constructed wetland, other factors to consider include plant coverage and density, substrate chemistry, and retention time. In the past, cattail density in most constructed wetlands has been limited to less than 10 plants/m^2 and plant coverage has been less than optimal (Kilborn 1999). Fertilization to increase plant growth and density may contribute to a more efficient wetland, as well as prevent larger wildlife, such as ducks, from inhabiting the wetland. An increase in the amount of organic matter within the substrate and the retention time within each cell will also increase metal adsorption (Fennessy & Mitsch 1989), thus decreasing the amount of surface area necessary to treat a large volume of water.

5.2.1 Aerobic Surface Flow Wetland

Aerobic wetlands can be sized based on the criteria developed by the U.S. Bureau of Mines for abandoned mined lands (AML) (Penn DEP 2004). AML criteria for aerobic wetland sizing are based on water treatment at coal mines and are dependent on iron, manganese, and acidity. Criteria specific to Tar Creek water quality will have to be developed to accurately determine the size of treatment units, but some conservative assumptions are made to use the AML criteria, as follows:

Minimum wetland size (ac) = [Fe loading (lb/day)/180 (lb/ac/day]+

[Mn loading (lb/day)/9 (lb/ac/day]+

[Acidity (lb/day)/60 (lb/ac/day]

The flow rate at each of the seven sites has been estimated as 1 MGD per site, and the manganese and iron concentrations in Table 2-1 are used to determine metals loadings. According to Keating's Task Force Report (2000) the median acidity is 320 mg/L as $CaCO_3$. The recommended aerobic surface flow wetland size for each of the seven wetlands in the Tar Creek site under these criteria is approximately 44.8 acres (181,300 m^2).

5.2.2 Vertical-Flow Wetland Cells

Vertical flow wetland cells are designed to require less area than aerobic or conventional anaerobic wetlands. The vertical flow allows for higher efficiency and less surface area. The sizing of vertical flow cells is a function of the metals loading. The wetland size can be calculated by dividing the metal loading rate (mmole/day) with a sulfate reduction rate of 150 mmole/cubic meter/day (Wildeman et al. 1993). The metal loading is the total concentrations of iron, manganese, and zinc that form metal sulfides. (It should be noted that copper is not a major chemical of concern and the copper loading rate was not included in this calculation.) Therefore, as previously mentioned, the estimated flow rate used for calculation of metal loading rates is one MGD (2,628 L/min/site). Each vertical flow wetland cell will require an approximate volume of 550 cubic meters. To be conservative, assume cells that are 20 m X 20m X 2 m deep. It is assumed that two 20m X 20m vertical flow cells will be necessary for treatment at each site. However, the small surface area will produce high hydraulic loading and maintenance (substrate replacement) will take cells out of service, so four 20m X 20m cells per site will be assumed. The area required is 1600 sq m, or 4 acres.

There have also been two settling ponds proposed in the preliminary conceptual design. These settling ponds have been estimated to have an area of 0.02 acres (100 m^2) each based on average settling pond sizes within numerous case studies (Kilborn 1999). Again, this small size will produce high hydraulic loading and maintenance will be required, so four settling ponds per site are assumed.

The estimated total land area required including the aerobic wetland (44.8 acres), four vertical flow cells (4 acres) and four settling ponds (0.1 acres) is approximately 50 acres. To estimate the land area required by rock falls and lift stations, an additional 10% of the required land area can be added for a total of approximately 55 acres (222,600 m^2). This will allow for the treatment of approximately 1 MGD by a single wetland system. The total land area required to implement the seven proposed wetland systems is approximately 350 acres (1,400,000 m^2).

5.3 PRELIMINARY COST ESTIMATION

The cost to implement a constructed wetland treatment system is directly related to the size. The estimated cost for construction of an aerobic wetland with plants is approximately $20/m^2 (Kilborn 1999). The estimated cost for construction of a vertical flow wetland with plants is approximately $75/m^2 (Kilborn 1999). To account for the potential need for pumps, piping, rock water falls, and the four settling ponds, an additional 30% of the total cost is estimated to cover these expenses.

Cost Estimated for One Wetland System

<u>Project Capital Cost Estimate</u>		
Aerobic wetland	181,300 m^2 @ $20/m^2	$3,626,000
Vertical flow wetland	1600 m^2 @ $75/m^2	120,000
Estimated Cost		3,746,000
Additional 30% (Cost for lift stations, rock falls, settling ponds, etc.)		1,123,800
Estimated Total Cost for One Wetland System		**$4,869,800**
Total Cost for Seven Wetland Systems (round numbers)		**$34 million**
<u>Annual Operation and Maintenance</u>		
Estimated as 20% of Capital Cost for One Wetland (round numbers)		**$1 million/yr**
Total O&M Cost for Seven Wetlands (round numbers)		**$7 million/yr**

This estimate does not include cost for any investigation activities, monitoring, pilot scale projects, permitting, preliminary and final design, etc.

5.4 RECOMMENDATIONS

5.4.1 Regulatory Issues

Target effluent values must be established prior to design of mine drainage remediation systems. Possible criteria include the State of Oklahoma Water Quality Standards, U.S. EPA National Recommended Water Quality Criteria, or Safe Drinking Water Act Standards (Keating 2000). The water quality at Tar Creek does not currently meet applicable standards (Keating 2000). Discharge criteria must be evaluated based on the state designation of the water quality and changes in the state designation, such as may occur as the site is remediated. Designations and standards may change substantially as the area water quality is improved.

The metal hydroxide sludge and spent substrate will need to be classified as hazardous or non-hazardous and properly disposed. The costs associated with sludge treatment or disposal have not been considered for this evaluation.

5.4.2 Pilot Scale Project

It is important that constructed wetlands are understood in terms of their individual components and their mutual physical, chemical, and biotic interactions since they are composite systems (Kilborn 1999). A conceptual design that works in principle may not have the capability of functioning continuously for many years. The evaluation of performance of a pilot demonstration will provide valuable information on design, sizing, cost, and construction of future full-scale treatment systems (Keating 2000). The equations used here to estimate treatment unit sizes are primarily developed for coal mines and are very sensitive to metals loading and acidity. They should be specifically developed for this site. Pilot studies should be designed to:

- provide reliable data on variation in water chemistry and flow rate from location to location,
- determine design parameters such as metals, suspended solids, sulfate, acidity, and hydraulic loading rates,
- determine the life of the organic and limestone substrates,
- determine the best plants to use and the density,
- the potential for passive nuisance (e.g., ducks living in ponds that may present an ecological health risk),
- determine the potential for odor production, particularly from the anaerobic cells, and
- determine the quantity and classification of the sludge and spent substrate so the handling requirements can be determined.

The overall effectiveness of the sequencing of coupled oxidation and sulfate-reducing systems should be evaluated and adjusted prior to full-scale implementation.

Information requirements which pilot tests may not provide, but need to be predicted by other means (e.g., more sampling, groundwater models), include:

- the potential to reduce the flow needing treatment by use of structural barriers to reduce recharge and control groundwater flow,
- the potential to enhance in situ treatment, and
- the impact on wastewater quality with the introduction of deep mine water.

6. REFERENCES

DeHay, K. 2003. Assessment and Comparison of 1976-77 and 2002 Water Quality in Mineshafts in the Picher Mining District, Northeastern Oklahoma and Southeastern Kansas. US Geological Survey. Oklahoma City, OK.

Elizabeth Mine Alternatives Analysis Report. 2001. Section 5. Alternative 1-Collect and Treat Surface Water Runoff with Active Treatment System.

Fripp, J., Ziemkiewicz, P. F. and Charkavorki, H. 2000. Acid Mine Drainage Treatment. EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-14) U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Fennessy, S. and Mitsch, W. J. 1989. Design and use of wetlands for renovation of drainage from coal mines. IN Ecological Engineering: an introduction to technology. W. J. Mitsch and S.E. Jorgensen, pp.232-252. John Wiley & Sons. New York, NY.

Governor Frank Keating's Tar Creek Superfund Task Force. 2000. Water Quality Improvement Alternatives. Water Quality Subcommittee Task 2 Report.

Hedin, R. S.; Watzlaf, G. R.; Nairn, R. W. 1994. Passive treatment of acid mine drainage with limestone. J. Environ. Qual., Vol. 23, No. 6, pp. 1338-1345

Hedin, R. S. and Nairn, R. W. 1993. Contaminant removal capabilities of wetlands constructed to treat coal mine drainage. CROC Press. Boca Raton, FL.

Kilborn Inc.. 1999. Review of Passive Systems for Treatment of Acid Mine Drainage. MEND Report 3.14.1. Toronto, Ontario.

Nairn, R. W. ; Mercer, M. N.; Lope, S. A. 2000. Alkalinity Generation and Metals Retention in Vertical-Flow Treatment Wetlands. CONFERENCE: American Society for Surface Mining and Reclamation; Annual meeting; A new era of land reclamation-17th. P: 412-420

Pennsylvania Department of Environmental Protection. 2004. The Science of Acid Mine Drainage and Passive Treatment
http://www.dep.state.pa.us/dep/deputate/minres

Perry, A. and R. L. P Kleinmann. 1991. The use of constructed wetlands in the treatment of acid mine drainage. Natural Resources Forum 15: 178-184.

Skousen, J., K. Politan, T. Hilton, and A. Meek. 1990. Acid mine drainage treatment systems: chemicals and costs. Green Lands 20(4): 31-37.

Skousen, J., A. Rose, G. Geidel, J. Foreman, R. Evans, W. Hellier, and Members of the Avoidance and Remediation Working Group of the ADTL. 1998. A Handbook of Technologies for Avoidance and Remediation of Acid Mine Drainage. Acid Drainage Technology Initiative (ADTI). National Mine Land Reclamation Center, West Virginia University. Morgantown, W. V. 131 p.

Skousen, J. 2004. Overview of Passive Systems for Treating Acid Mine Drainage http://www.wvu.edu/~agexten/landrec

U.S. Environmental Protection Agency. 1983. Neutralization of acid mine drainage, design manual. USEPA 600/2-83-001. Cincinnati, OH.

Wildeman, T. R., Duggan, L., Phillips, P., Rodriguez-Easton, S., Simms, R., Bender, J., Taylor, N., Britt, C., Mehs, D., Forse, J., Drebacher, P., and Herron, J., 1993. Passive Treatment Methods for Manganese: Preliminary results from two pilot sites. Proceedings, 1993 National Meeting of the American Society for Surface Mining Reclamation . Spokane, WA.

Zipper, C. and Jage, C. 2001. Passive Treatment of Acid-Mine Drainage with Vertical-Flow Systems. VCE 460-100
http://www.ext.vt.edu/pubs/mines