

## TECHNICAL MEMORANDUM

DATE: August 29, 2012

TO: Joe Gibbens, PE – U.S. Forest Service

FROM: Tim Otis, PE – Cascade Earth Sciences  
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**SUBJECT: Monte Cristo Mining Area Water Treatment Technologies**

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### INTRODUCTION

Cascade Earth Sciences (CES) prepared this Technical Memorandum for a proposed Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Removal Action (RA) in the Monte Cristo Mining Area (MCMA; also referred to as the Site) in Snohomish County, western Washington. The MCMA is located in the Mt. Baker-Snoqualmie National Forest, approximately 28 air-miles east-southeast of Granite Falls, Washington. The Site is in the South Fork Sauk River (SFSR) watershed, which is a perennial tributary to the Sauk River, portions of which are within the Henry M. Jackson Wilderness Area. For a complete site description and project background, please refer to the Engineering Evaluation / Cost Analysis (EE/CA).

Based on recommendations from the EE/CA, completed by CES in April 2010, the USDA Forest Service has requested a report summarizing the implementation of water treatment technologies for the MCMA mines. The implementation of water treatment is only a single portion of the overall RA elements from the EE/CA. Of the ten abandoned mines evaluated in the EE/CA, the following four are to be the focus of water treatment in this report:

- Mystery Mine
- Justice Mine
- Pride of the Mountains Mine
- Pride of the Woods Mine

### ABANDONED MINE WATER DRAINAGE TREATMENT TECHNOLOGIES

Treatment of mine drainage water presents unique challenges not found in typical wastewater treatment systems. Specifically, abandoned mine sites have some or all of the following limitations.

- No available electrical power
- Steep terrain with limited low-gradient land area
- Limited or no vehicle access
- Cold winter temperatures
- Large seasonal variations in stream and surface water flows

Several studies have documented the technologies that have been used in these environments. In 1999, a consortium of Canadian mining interests known as Mine Environment Neutral Drainage (MEND), prepared a report titled “Review of Passive Systems for Treatment of Acid Mine Drainage” (MEND, 1999). In 2003, the U.S. Environmental Protection Agency (USEPA) prepared a comprehensive survey of remediation technologies being used at hard rock mining sites in the Mid-West and Western US states (Costello, 2003). These documents provide a starting point for the evaluation of treatment technologies at the MCMA.

*“Due to limited resources, especially in the case of hard rock mines, innovative technologies can offer a plausible solution to the environmental threats created by abandoned mines. Traditional water treatments are modeled after wastewater treatment plants, which are machine intensive, chemical dependent, and require continuous operations and maintenance (O&M) staff.” (Costello, 2003)*

As noted above, most remote mine sites, including the four MCMA sites targeted as the focus of this report have no electrical power and limited access, particularly during the winter months. Thus, for this review, passive treatment systems will be discussed. These systems typically have low O&M requirements, do not rely on supplied chemicals, and have no mechanical parts. Additionally, these systems have a natural appearance, are aesthetically pleasing, may support plants and wildlife, and are typically less expensive (Ford, 2003).

### **Research Methodology**

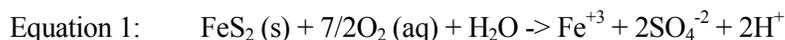
A literature review was performed of similar mine treatment documentation, USEPA guidance, modeling, and academic research. Passive treatment of mine drainage treatment systems have proven effective at many locations around the world. The MCMA presents some specific challenges for these systems. Biological systems have low activity in cold winter temperatures (MEND, 1999). Avalanches and debris flows are common in this area, particularly in drainage ways and streams. The MCMA is particularly prone to rain-on-snow events, which cause rapid melt of winter or spring snow pack, resulting in high energy runoff events. These can transport ice, rock, and woody debris within the runoff water. Thus, the focus of this research was on treatment systems that are as strong, resilient, and as maintenance free as possible.

In addition, supplemental data is presented from a CES recently designed abandoned mine treatment system.

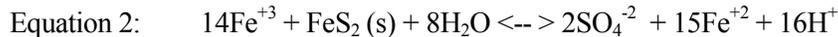
### **Acid Mine Drainage Chemistry**

The chemistry of acid mine generation is well documented in the literature, and will only be summarized here. Although the chemistry is based on simple reactions, the complexity of the problem of treatment is complicated by biological activity throughout the generation and re-mineralization process, as well as variations in rock composition and dissolved metal loadings, which can vary dramatically from site to site.

Typically in hard rock mines, pyrite decomposition begins the acid generation process. Pyrite is typically found discarded in waste piles or along mineral seams. When pyrite becomes exposed to air and water, oxidation reduces pyrite to ferric iron ( $\text{Fe}^{+3}$ ) and sulfate ( $\text{SO}_4^{-2}$ ) as shown in Equation 1. An excess of iron minerals, and build-up of hydrogen ions in the reaction decreases the pH of the water, causing the water to become acidic.



Additionally, once formed, ferric iron will directly oxidize pyrite to produce more ferrous iron and additional acidity, as shown in Equation 2.

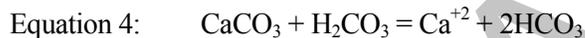
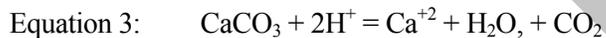


If additional dissolved oxygen is available, the cycle of Equations 1 and 2 continues. When there is sufficient acidity, acidophilic bacteria become established and accelerate these chemical reactions. Among these bacteria is Thiobacillus Ferroxidans. Additionally, Archaea organisms including Ferroplasma Acidarmanus have been shown to be involved in these reactions (Lauzon, 2000). A number of archaeal and bacterial species catalyze and control the rates of these reactions. Variation in pH, temperature, and ions present determines the mix of organisms present (Baker, 2003).

In addition to iron, other metals present in the parent rock are dissolved following this acid-generation process. These may include aluminum, arsenic, cadmium, copper, lead, manganese, nickel, and zinc.

### **Metals Removal from Mine Drainage**

Although there is much variability in current treatment methods for mine drainage water, passive systems have primarily relied on a few primary processes. These include pH adjustment, control of dissolved oxygen, and precipitation of insoluble metal hydroxides. The required pH change for metals removal varies by metal. Limestone is typically used to consume hydrogen ions, and add alkalinity, as shown in Equations 3 and 4.



In addition, many passive treatment systems utilize wetland systems, or technologies which contain sulfate reducing bacteria (SRB) to re-mineralize precipitated metals back into metal sulfides. These organisms require a carbon source. In this process, the organisms reduce the dissolved sulfate to sulfide, which combines with metal ions, as shown in Equations 5 and 6 (Costello, 2003).



Wetlands specifically can remove metal precipitates from water through a number of processes, including the following.

- Sorption and/or exchange onto organic matter
- Filtration of solids and colloids
- Formation of carbonates
- Association with iron and manganese oxides
- Metal hydrolysis (catalyzed by bacteria under acidic conditions)
- Reduction to non-mobile forms (catalyzed by bacteria)
- Formation of insoluble metal sulfides
- Biological methylation, followed by volatilization (Sobolewski, 1999)

Although there are numerous possible environmental concerns at abandoned hard rock mine sites, this discussion focuses on the treatment of water discharged from abandoned mine adits and shafts.

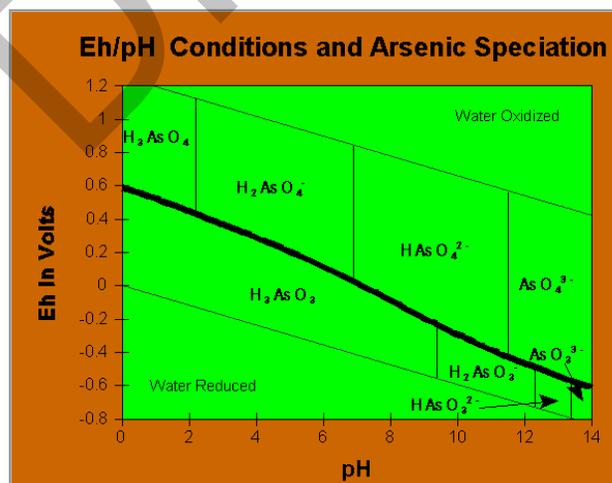
## **Segregation of Flows**

In the design of a passive treatment system, segregation of flows should be considered. If surface water directly enters the underground mine workings and then flows through highly mineralized areas, there may be advantages in diverting these surface inflows to reduce the corresponding downstream flow rate for water to be treated from the adit drainages. As a part of the RA, a study was completed that characterized the geology of the MCMA and produced a map of the underground workings. The results of this study will be instructive in the analysis of segregation of flows and sources of adit drainage water as part of future RA activities. One of the prominent features of the MCMA is jointing found in all types of rock. These joints dip from 65° to near vertical. “In so far as the ore deposits are concerned, this jointing seems to play a major role, for many of the major veins follow along planes conformable with that of the jointing” (Griffin, 1948). It is probable that groundwater flows preferentially along the permeable bedrock-overburden contact and lesser flow probably occurs in the bedrock fracture system. From the perspective of flow segregation, this structure provides multiple opportunities for surface water to enter the underground workings, and minimized the likelihood of effective segregation of flows within the mines.

## **Arsenic Geochemistry and Treatment**

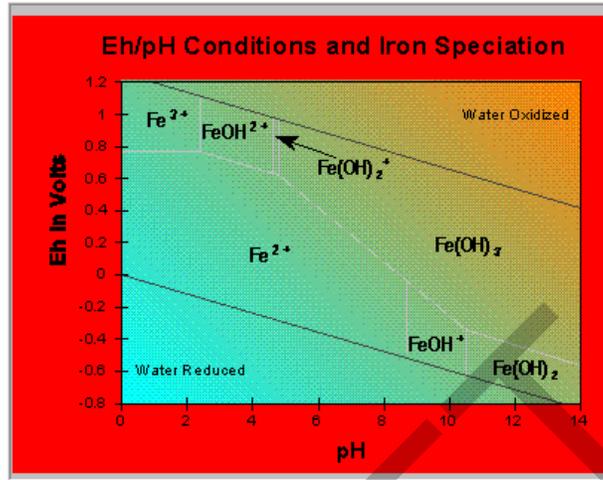
In mine drainage water from the MCMA, arsenic is the contaminant of potential ecological concern (COPEC) identified in the EE/CA Risk Assessment as having a human health cleanup goal. The cleanup goal for arsenic in surface water is 150 micrograms per liter ( $\mu\text{g/L}$ ), which is equal to the lowest enforceable ecological criteria (CES, 2010).

Arsenic in parent rock dissolves in the acid producing steps described above. Downstream, when acidity (pH) and reduction potential (Eh) conditions favor formation of precipitates, arsenic co-precipitates with ferric oxyhydroxides. Arsenic occurs principally in two oxidation states in mine drainage, arsenic V ( $\text{H}_2\text{AsO}_4^{2-}$ ) and arsenic III ( $\text{H}_3\text{AsO}_3$ ). Arsenic V adsorbs more readily onto oxidized iron species, and over a wider range of pH, than arsenic III (Bowell, 2003). The following equilibrium Eh-pH diagram (Vance, 1995) shows these relationships for arsenic species.

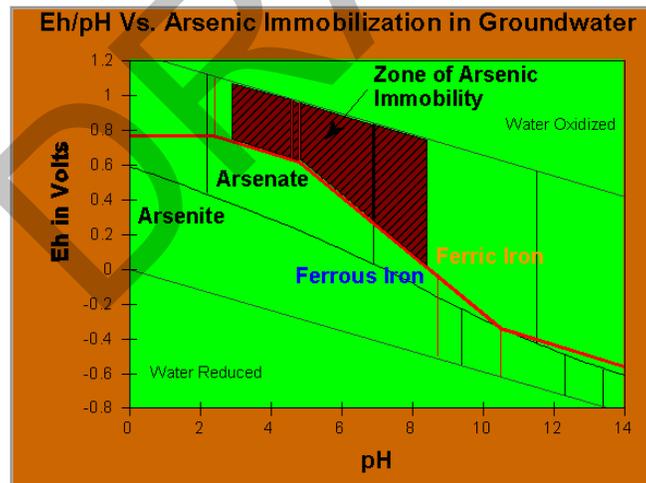


In order to immobilize arsenic in a passive treatment system, the oxygen level and pH need to be moved to a state where arsenic V predominates. This typically involves oxidation of any arsenic III to arsenic V and increasing the pH to near neutral or above. As with arsenic, iron dissolved in above reactions 1 and 2, forms

precipitates then thru aeration, the oxygen content is increased, and dilution moves pH toward neutral. Iron equilibrium Eh-pH relationships are shown in the following diagram (Vance, 1995).



Ferric oxides in groundwater sediments have been shown to adsorb 0.5 to 5 pounds of arsenic per cubic yard of aquifer matrix. To optimize co-precipitation of arsenic with iron within a treatment system, as in groundwater systems, the Eh-pH conditions should be kept where both iron and arsenic remain immobilized in their precipitated states. This can be shown by superimposing the arsenic and iron relationships as shown in the following diagram (Vance, 1995).



Industrial wastewater treatment studies have shown that iron hydroxide concentrations should be a minimum of 4 to 8 times higher than that of soluble arsenic to effectively co-precipitate arsenic (Krause, 1985). However, the precise mechanisms of this adsorption are complex and not completely understood. Models to predict the adsorption of arsenic onto soils are still being developed (Goldberg, 2008). Studies in the Animas River Watershed of Colorado have shown that the deposits of crystalline iron oxyhydroxides in bogs downstream of mine adits is primarily in the form of goethite ( $\alpha$ -FeOOH) and schwertmannite ( $Fe_8O_8(OH)_6SO_4$ ). Further, the trace elements contained in the deposited iron is dependent on the parent rock

mineralogy. Maximum concentrations of arsenic in these iron bog solids averaged 5,000 parts per million (0.5%; Stanton, et. al., 2003).

## **Other Treatment Issues**

### **Copper, Lead, and Zinc Treatment**

Besides iron and arsenic, the EE/CA identified copper, lead, and zinc as having proposed surface water cleanup goals of 2.38, 0.36, and 12.77 µg/L, respectively.

### **Aluminum and Sulfate**

The presence of high concentrations of aluminum and sulfate in the seep water can result in the formation of aluminum hydroxide and gypsum which can cause premature system failure due to limestone armoring. This is particularly important in subsurface flow conditions where repair or replacement would be particularly costly. In extreme circumstances, these products can plug or reduce flow in the passive treatment system. Additionally, these products will co-precipitate with other metals causing depositions in settling ponds. The design of any treatment system should consider the aluminum and sulfate chemistry in designing and sizing treatment components.

### **Passive Treatment Technologies**

The choice of treatment technology depends on the types and amounts of metals to be removed, as well as other factors such as flow rate, available land area, topography, and weather. In addition, since there are significant unknowns with any passive treatment system, a pilot scale system is recommended to determine anticipated removal efficiencies. Typical passive methods to treat mine drainage include the following:

1. Aerobic Wetlands
2. Limestone channels
3. Anoxic Limestone Drain
4. Anaerobic Wetlands
5. Successive Alkalinity Producing Systems
6. Sulfate Reducing Bacteria systems
7. Permeable Reactive Barriers
8. Lime dispensing (Aquafix)

Diagrams of some of these systems are illustrated in Attachment 1. A brief summary of passive treatment technologies is presented in the 2006 University of Indiana study, and presented in Table 1. Each of these eight passive treatment systems is described in the following sections.

### **Aerobic Wetland**

Oxidizing or aerobic wetlands consist of shallow water (<12 inches) over organic soils, planted with emergent wetland vegetation, typically cattails, reeds, sedges, and rushes. They are designed to remove metals by oxidation and precipitation of iron, aluminum, and manganese hydroxides. In addition, other metals such as arsenic co-precipitate with iron in these systems. Although the near-surface layer of water in these wetlands is aerobic, deeper areas of water, and the substrate are typically anaerobic (USDA, 1995). Since the oxygen levels within a wetland vary depending on the ability of surface water to provide oxygen, all wetland systems typically have both aerobic and anaerobic zones.

Typical hydraulic loading rates for aerobic wetlands are 0.3 to 2.0 inches per day (Kadlec and Knight, 1996), which calculates to 12 to 79 acres per cubic feet per second (cfs) of flow. For the Justice and Mystery Mine adit drainages, which each average about 0.25 cfs, this calculates to a range of 3 to 20 acres.

### **Open Limestone Channel**

Limestone channels introduce alkalinity into mine drainage water by limestone dissolution. Although the limestone can become coated with iron or aluminum hydroxides, studies show that coated limestone continues to dissolve at a minimum of 20% of the unarmored rate. The length and gradient of the lined channel can be designed to optimize the required limestone dissolution rate (Skousen, 2001). These lined channels are typically used in conjunction with other treatment steps.

### **Anoxic Limestone Drain**

If the dissolved oxygen is low in mine drainage, and iron and aluminum concentrations are low enough to control clogging, an anoxic limestone drain system can be used. This passive system is essentially a buried bed or trench of crushed limestone through which acid mine drainage flows. The goal is to add alkalinity and raise pH, by gradually dissolving the limestone. Exclusion of oxygen within the bed limits armoring or coating of the limestone. When treated mine drainage leaves this system and is exposed to oxygen in the atmosphere, metal hydroxide precipitates form, and must be captured in a settling pond. The crushed limestone should be sized to allow free flow through the bed, while providing adequate surface area for dissolution to occur. Typical successful systems crush limestone between 2 and 4 centimeters (MEND, 1999).

### **Anaerobic Wetland**

Anaerobic wetland systems rely on the lack of oxygen and microbial processes to generate alkalinity. These systems are typically used to raise the pH of acidic drainage prior to further passive treatment. The substrate for anaerobic wetlands typically consists of material with high organic content such as sawdust, manure, or compost, which serves as a nutrient source for reducing bacteria (MEND, 1999). They are designed to direct flow primarily through subsurface, oxygen depleted media.

It should be noted that all wetland systems are by nature heterogeneous, having both aerobic and anaerobic zones, areas of both oxidation and reduction, and areas of both dissolution and precipitation. In addition, biological communities will vary by location and ambient conditions. Therefore, if treatment depends on a low-oxygen environment, wetland design should create constraints to encourage the anaerobic conditions needed for the specific mine drainage chemistry.

### **Successive Alkalinity Producing System**

This system is the addition of an organic layer to the simpler anoxic limestone drain system. The successive alkalinity producing system design is typically a ponded cell which has a vertical flow downward through an organic mulch layer overlying a limestone layer. The ponded water limits oxygen in the lower layers. The organic layer further removes dissolved oxygen and promotes the establishment of sulfate reducing bacteria communities (discussed below). The anaerobic environment reduces  $Fe^{+3}$  to  $Fe^{+2}$ , minimizing iron hydroxide precipitation. Finally, the water enters the limestone area to reduce the pH and add alkalinity. Hydraulic head drives the water thorough the system. After discharge from the successive alkalinity producing system, water typically flows to an aerobic settling pond or wetland to precipitate metals oxides. Many of these systems also contain flushing systems, in order to remove precipitates that may form in the cells. This

system functions under the same principal as anaerobic wetlands, with an underdrain design that may allow larger flow rates on a smaller system footprint.

### **Sulfate Reducing Bacteria systems (also known as Biochemical Reactors)**

In 2006, the USEPA developed guidance for the use of sulfate reducing bacteria for the treatment of acid mine drainage (USEPA, 2006). This guidance gives a detailed description of the technology, including the biological characteristics of sulfate reducing bacteria, lessons learned from coal mining systems, and a review of ten case studies where sulfate reducing bacteria systems are being used. In this memorandum, these are discussed by topic, reviewing four (4) bioreactors, five (5) permeable reactive barriers, two (2) pit lake treatment systems, and two (2) ‘in development’ technologies. Sulfate reducing bioreactors, in particular, for the treatment of mine drainage have been reviewed in detail by several authors (Gusek, 2003 and Doshi, 2006). These systems are designed to optimize the environment of sulfate reducing bacteria communities.

### **Permeable Reactive Barrier**

Permeable reactive barriers are essentially sulfate reducing bacteria systems designed to intercept the flow of groundwater, directing it through a constructed trench, where introduced organic matter promotes sulfate reducing bacteria activity. Design guidance for permeable reactive barriers are based on both a review of existing systems, as well as column experiments and modeling (Waybrant, 2002).

### **Lime Dispensing Technology (Aquafix)**

In addition to passive systems, a number of semi-passive technologies have been developed. Lime dispensing systems have been tested at sites to add alkalinity. Not strictly passive systems, nevertheless, they do not require power or daily monitoring. A pilot of the Aquafix system was tested by USEPA in 2002 at the Alameda Mine, near Grants Pass, Oregon and at the Dinero Tunnel, near Leadville, Colorado (USEPA, 2003). This unit dispenses calcium oxide from a bin via a water wheel. A number of operational problems were noted, including accumulation of granular lime below the dispenser, and clogging of the inlet hose with iron hydroxides. Due to the remote location on harsh weather conditions, this technology is not recommended for the MCMA.

### **Treatment System Selection**

The key to effective passive treatment system design is site characterization. The pH ranges of mine drainage can vary from near neutral to 2.5 or lower. In addition, both alkalinity and acidity need to be measured in mg/L calcium carbonate equivalence to determine net alkalinity (Ford, 2003). Dissolved metal loadings are also highly variable between sites. Thus, each site requires a customized treatment system.

Attachment 2 shows a typical flowchart for selecting a passive acid mine drainage treatment system, based on water chemistry and flow.

This decision tree method of selection begins with pH. Net alkaline drainage water is suitable for a treatment system of primary settling of precipitates, followed by an aerobic wetland. Net acid water requires analysis of oxygen content and iron ratio to determine the optimum passive treatment system. The following decision branches depend on pH, iron content, dissolved oxygen content, and flow rate. Under this scheme, if the water does not meet effluent limits, chemical treatment and/or recirculation through the treatment system is proposed. For the MCMA sites, the treatment goals are either Applicable or Appropriate and Relevant Requirements (ARARs) or based on average background water quality (CES, 2010). Given the remote location of these sites, if the proposed cleanup goals are not reached with passive treatment, no additional

active chemical treatment or recirculation pumping is proposed. If, following bench testing described below, it is determined that it is not practical to meet one or more of the proposed cleanup goals using passive methods, the basis of decision not to meet those levels should be documented in the RA memorandum, noting that compliance would be technically impractical from an engineering perspective.

### **Design Approach**

As a part of the design of a passive treatment system, a phased approach is recommended, based on the variable success of systems of this type. A test phase is recommended, including some or all of the following. In particular, if the mine-water chemistry is unique, and if a biochemical reactor is proposed, all three steps recommended (Gusek, 2003).

### **Proof of Principal Testing**

This is typically static laboratory tests in culture bottles, using locally-available materials to determine the suitability of materials and probable metal removal rates.

### **Bench Scale Testing**

Bench tests are done in the field, and require a substantial quantity of substrate material (100 kilograms), operated for at least 3 months, to simulate the chemical and biological reactions that may occur at full scale.

### **Pilot Scale Testing**

Pilot systems are typically operated for a full year before the design of the system is finalized. If successful, this pilot can be incorporated into the larger complete design. This may be best done as an adaptive management strategy of staged construction, where the primary components of a treatment system are installed and evaluated for a period of two or three years, then a second construction project is planned to incorporate changes to improve the treatment efficiency and perform maintenance on portion of the treatment components.

### **Summary**

Since the water chemistry from each adit drainage is unique, the starting point for design must be the chemistry of the water, flow rate, seasonal variations in both, and the target effluent levels. Table 2 shows a summary of sampling events between 2008 and 2011 at the Mystery, Justice, Pride of the Mountains, and Pride of the Woods Mines. Using the decision process shown in Attachment 2, treatment processes are proposed at each of the four sites.

### **Recommendations for Treatment**

Table 2 shows results from monitoring events in 2008, 2010, and 2011, related to design of passive treatment systems, along with recommended treatment options for each of the four subject mine sites. Sampling for acidity and ferrous iron were not done as a part of previous sampling events, but are being incorporated into the 2012 sampling events.

### **Justice Mine**

The field measured pH values were near neutral, but laboratory values varied from 5.7 to 8.1 standard units (s.u.). All iron is oxidized as ferric iron, and the mean dissolved oxygen concentration is 11.37 mg/L. Next, the mean flow rate of 122 gallons per minute (gpm) puts this into the high flow category. However, total iron concentrations in this water are extremely low, at a mean of 55 µg/L. Thus, even as total arsenic is available

for precipitation at a mean concentration of 279  $\mu\text{g/L}$ , there is inadequate iron present to co-precipitate out of solution (iron/arsenic ratio of 0.2). A ratio of 20 is recommended for effective co-precipitation of arsenic. Some form of iron addition is recommended as a part of the treatment design. The Attachment 2 diagram lists no limestone addition, and since this water has a mean alkalinity of over 25  $\text{mg/L}$ , none is recommended. However, bench testing should verify pH changes during co-precipitation with iron, since significant addition of acidity occurs when ferric iron oxidizes pyrite (Equation 2). Recommended treatment includes addition of iron using a passive flow-through system, settling pond, and aerobic wetland. Since the drainage area is steep and not suitable for construction of a passive treatment system, the adit drainage should be either ditched or piped to a central location downslope from the mine. The exact location will be determined during the design phase, but should be located near the Townsite for operation and maintenance activities.

### **Mystery Mine**

Field pH measured values averaged 3.74 s.u., consistent with laboratory values. Dissolved oxygen averaged 10.83  $\text{mg/L}$ , total iron averaged 4,918  $\mu\text{g/L}$ , total arsenic averaged 397  $\mu\text{g/L}$ , yielding an iron/arsenic ratio of 12.4. Mean flow rate of 114  $\text{gpm}$  puts this discharge into the high flow category. The treatment system decision from Attachment 2 consists of an open limestone channel and a settling pond. However, consideration should be given to alternatives to a settling pond.

It is notable that although the flow rate from Mystery Mine is similar to the Justice Mine, no arsenic from this source has been measured in Glacier Creek, whereas a clear increase in arsenic is measured below the Justice Mine discharge point, in both surface water and sediment. This indicates that the arsenic from the Mystery Mine adit drainage is being precipitated between the adit and Glacier Creek. In addition, much of the slope below the Mystery Mine consists of large talus boulders, and the adit seep disappears below this talus slope at a point below the waste rock piles. It then flows downslope below the talus and enters Glacier Creek as subsurface flow within the riparian zone. An alternative to a settling pond would be to follow the limestone channel portion with a direct discharge away from the waste rock pile near the mine adit. In that way, the precipitated iron, arsenic, and other metals would be away from human contact, and continue to have the entire distance to Glacier Creek to precipitate. Semi-annual aquatic monitoring of the system and Glacier Creek would provide a means for detecting changes in the system, etc.

### **Pride of the Mountains Mine**

This mine is the most remote of the four sites, and is located approximately 800 ft horizontally (east) and 500 ft vertically from Glacier Creek. The pH is near neutral, ranging from 5.9 to 7.0 s.u., with a mean of 6.8 s.u.; dissolved oxygen averages 8.88  $\text{mg/L}$ . Total iron averages 744  $\mu\text{g/L}$ , total arsenic averages 365  $\mu\text{g/L}$ , for an iron/arsenic ratio of 2.0. Mean flow rate of 3.48  $\text{gpm}$  categorizes this as low flow. Total alkalinity averages 12.6  $\text{mg/L}$ . No arsenic increase has been measured in Glacier Creek below this adit drainage. The drainage chemistry is most similar to the Justice Mine, with the notable difference of having 13 times the iron concentration, and approximately 3% of the flow rate. Given the difficulty of access, distance from Glacier Creek, and small flow rate, it is recommended that the adit seep be directed to an infiltration into subsurface flow as near the adit as practical, with a structural barrier to control human contact. A pilot project could field test this approach using a portion of the adit flow directed into an infiltration area.

### **Pride of the Woods Mine**

This adit seep has a mean pH of 4.37 s.u., mean dissolved oxygen of 10.72  $\text{mg/L}$ , mean total arsenic of 1,009  $\mu\text{g/L}$ , mean total iron of 6,801  $\mu\text{g/L}$ , and an iron/arsenic ratio of 6.7. Flow rate is small at 0.47  $\text{gpm}$ . No ferric iron is present. This seep has the highest aluminum concentration of the four seeps, with an average of 3,100  $\mu\text{g/L}$  (3.1  $\text{mg/L}$ ). The treatment system recommended using Attachment 2 shows a settling pond for

pH under 4.5 s.u., and an anaerobic wetland or successive alkalinity producing system for pH over 4.5 s.u. Since the aluminum concentration is below 25 mg/L, the flow rate is small, and the pH is over 4.5 s.u., a subsurface treatment system, followed by infiltration is recommended. A pilot test of local organic and rock materials, including a sulfate reducing bacteria reactor, is recommended to optimize the metals removal. However, because the waste rock pile is planned to be removed as part of the RA, pilot testing and design work should not be started until the water quality and quantity is redefined after removal of the waste rock pile. A similar situation occurred at the Azurite Mine, with significant changes in water quality and quantity measured from pre to post-RA.

### **Cost Estimating**

As a part of this analysis, cost estimates were prepared only for the proposed Justice and Mystery Mine treatment systems. The Engineer's Opinion of Probable Cost documents for these projects are included as Tables 3 and 4.

### **Case Study – Champion Mine Wetland Treatment System**

In 2008, CES installed a passive treatment system to remove iron and arsenic from the adit drainage of the Champion Mine, near Cottage Grove, Oregon. The characteristic of the untreated adit water was as follows:

- near neutral pH (dilution of deeper acidic flows by alkaline seeps near the mine portal)
- dissolved iron concentration near 6,500 µg/L
- dissolved arsenic concentrations of approximately 30 µg/L
- adit flow rate was approximately 0.25 cfs

The treatment system consists of concrete contact chambers containing polyacrylamide logs, custom formulated to facilitate precipitation; a settling pond; and a series of five tiered aerobic treatment wetlands, totaling approximately 1 acre in size. The system was completed in late summer 2008. Charts 1 and 2 show the removal of arsenic and iron from the adit drainage water. Station CC-SW-01 is at the adit, station CC-PD-02 is located immediately after the settling pond, and station CC-PD-03 is immediately following the treatment wetland. Based on annual October sampling, removal efficiencies for dissolved arsenic through the treatment system were 92%, 93%, and 90%, respectively, for the first three years, iron removal efficiencies were 95%, 96%, and 94% for the same sample periods.

### **REFERENCES**

- Ball, B.R. and Brix, K.V. Passive treatment of metalloids associated with acid rock drainage.
- Bowell, R. 2003. The influence of speciation in the removal of arsenic from mine waters. *Land Contamination and Reclamation*, 11(2), 2003.
- CES, 2010. Monte Cristo Mining Area, Engineering Evaluation / Cost Analysis, March 2010.
- CES, 2011. US Forest Service Champion Mine Post Removal Action Monitoring Report, 2011.
- Costello, C. 2003. Acid Mine Drainage: Innovative Treatment Technologies. U.S. EPA Office of Solid Waste and Emergency Response.

- Doshi, S.M. 2006. Bioremediation of acid mine drainage using sulfate-reducing bacteria. .S. EPA Office of Solid Waste and Emergency Response.
- USEPA, 2002. Arsenic treatment technologies for soil, waste, and water. EPA-542-R-02-004, September 2002, [www.epa.gov/tioclu-in.org/arsenic](http://www.epa.gov/tioclu-in.org/arsenic).
- USEPA, 2003. Pilot Demonstration Project: Aquafix Water Treatment. <http://www.epa.gov/aml/tech/news/aquafix.htm>. (2003)
- Ford, K.L. 1999. Site characterization for abandoned mine/mill sites. Information Bulletin No. RS-99-108. National Applied Resource Sciences Center, Denver, CO.
- Fore, K.L. 2003. Passive treatment systems for acid mine drainage. Bureau of Land Management National Science and Technology Center, Technical Note 409.
- Fripp, J. Siemkiewicz, P.F., and Charkavork, h. 2000. Acid mine drainage treatment, ERRRP Technical Notes Collection (ERDC TN-EMRRP-SR-14), U.S. Army Engineer Research and Development Center, Vicksburg, MS. [www.wes.army.mil/el/emrrp](http://www.wes.army.mil/el/emrrp)
- Gandy, C.J. and Jarvis, A.P. 2006. Attenuation of mine pollutants in the hyporheic zone. Environment Agency, UK [www.environment-agency.gov.uk](http://www.environment-agency.gov.uk).
- Goldberg, et. al, 2008. Chemical Modeling of Arsenic (III, V) and Selenium (IV, VI) adsorption by soils surrounding ash disposal facilities. *Vadose Zone J.* 7:1185-1192.
- Grafe, M. et. al. 2002. Adsorption of arsenate and arsenite on ferrihydrite in the presence and absence of dissolved organic carbon. *J. Environ. Qual.* 31: 1115-1123 (2002).
- Griffin, B.E. 1948. The Geology of the Monte Cristo District, with special reference to ore deposits. U. of Washington M.S. Thesis.
- Gusek, J.J. 1995. Passive treatment of acid rock drainage what is the bottom line? *Mining Engineering.* Vol 47, No. 3. Pp. 250-253
- Johnson, D.B. and Hallberg, K.B. 2005. Acid mine drainage remediation options: a review. *Science of the Total Environment* 338: 3-14 (2005).
- Kadlec, R. and R. Knight. 1996. *Treatment Wetlands.* CRC Press, Boca Raton, FL.
- Krause, E. and Ettl, V.A., 1985. Ferric Arsenate Compounds: Are They Environmentally Safe?, Solubilities of Basic Ferric Arsenates, In: *Proceedings of CIM Metallurgical Society, 15th Annual Hydrometallurgical Meeting*, pp5-1 to 5-20.
- Lauzon, S. 2002. New Iron Eating Microbe Major Component of Mining Pollution and Iron and Sulfur Cycling. <http://www.who.edu/page.do?pid=9779&tid=282&cid=988&ct=162>
- MEND, 1999. Review of passive systems for treatment of acid mine drainage, MEND Report 3.14.1

Sobolewski, A. 1999. A review of processes responsible for metal removal in wetlands treating contaminated mine drainage. *International Journal of Phytoremediation*, 1:1, 19-51 (1999).

Skousen, J. 2001. Overview of passive systems for treating acid mine drainage. West Virginia University Extension Service.

Stanton, M. et. al. 2003. Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado (Chapter E14, Formation and geochemical significance of iron bog deposits. Professional Paper 1651, US Department of the Interior, US Geological Survey.

United States Department of Agriculture (USDA). 1995. Handbook of Constructed Wetlands. A guide to creating wetlands for: Agricultural wastewater, domestic wastewater, coal mine drainage, stormwater in the mid-atlantic region. Volume 1.

Waybrant, K. 2002. Treatment of mine drainage using permeable reactive barriers: column experiments. *Environ. Sci. Technol.* 2002, 36, 1349-1356. (2002).

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Att: Table 1. Passive Treatment Technologies  
Table 2. Water Quality Summary of 2008 – 2011 Sampling Events  
Chart 1. Total Recoverable Arsenic in Surface Water (Wetlands) – Champion Mine  
Chart 2. Total Recoverable Iron in Surface Water (Wetlands) – Champion Mine  
Att 1. Diagrams of Passive Treatment Systems  
Att 2. Typical Flowchart For Selecting Passive Acid Mine Drainage Treatment Systems  
Att 3. Engineer's Opinion of Probably Cost – Justice Mine  
Att 4. Engineer's Opinion of Probably Cost – Mystery Mine  
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**Table 1. Passive Treatment Technologies  
Monte Cristo Mining Area - Water Treatment Technologies**

Technology Name	Technology Description	Function	Selected References
Aerobic Wetlands	Shallow, surface flow wetland with emergent vegetation	Fe and Mn oxidation and precipitation; co-precipitation of metals; sorption to biomass	Eger and Wagner, 2003; USDA and USEPA, 2000
Open limestone channels	Acidic water flows over limestone, or other alkaline agent	Alkalinity addition; precipitation of Al, Fe, Mn as metal oxides	Siemkewicz et al., 1997
Anoxic limestone drains	Water flows through limestone channel under anoxic conditions	Alkalinity addition; Fe precipitation; prevention of limestone anchoring	Watzlaf et al., 2000
Anaerobic wetlands	Subsurface flow wetland, isolated from atmosphere by standing water or overlying material	Alkalinity addition; sulfate reduction and precipitation of metal sulfides; sorption or uptake by vegetation	Brenner, 2001; USDA and USEPA, 2000
Successive Alkalinity Producing Systems	Vertical flow systems that drain through layers of limestone and anaerobic organic matter	Alkalinity addition; sulfate reduction and metal precipitation	Kepler and McCleary, 1994; Zipper and Jage, 2001
Sulfate-Reducing Bioreactors	Collected water drains into anoxic chamber containing organic matter and SRB	Alkalinity addition; sulfate reduction and metal precipitation	Gusek, 2002
Permeable Reactive Barriers	Intercepted groundwater flows through permeable barrier containing reactive material	Alkalinity addition; sulfate reduction and metal precipitation; sorption	Benner et al., 1997; USDOE, 1998

NOTE:

Source: Doshi, S.M. 2006. Bioremediation of acid mine drainage using sulfate-reducing bacteria. .S. EPA Office of Solid Waste and Emergency Response.

**Table 2. Water Quality Summary of 2008 - 2011 Sampling Events  
Monte Cristo Mining Area - Water Treatment Technologies**

Location	pH	DO	Flow	Aluminum		Manganese		CaCO <sub>3</sub>		Total Arsenic		Total Iron		Ferrous Iron	Iron/ Arsenic Ratio	Sulfate	
	s.u.	mg/L	gpm	µg/L		µg/L		Alkalinity	Acidity	µg/L		µg/L		µg/L			mg/L
	mean			mean	max	mean	max	mean		mean	max	mean	max	mean			
Justice Mine	7.35	11.37	122	146	433	48	177	25.45	NM	279	712	55	1,700	NM	0.2	25.6	
Mystery Mine	3.74	10.83	114	399	473	1,226	1,840	1.05	NM	397	440	4,918	6,230	NM	12.4	76.3	
POM Mine	6.77	8.88	3.48	90	199	99	191	12.6	NM	365	1,020	744	1,920	NM	2.0	24.4	
POW Mine	4.37	10.72	0.47	3,139	6,040	389	652	1.73	NM	1,009	4,060	6,801	22,900	NM	6.7	26.9	

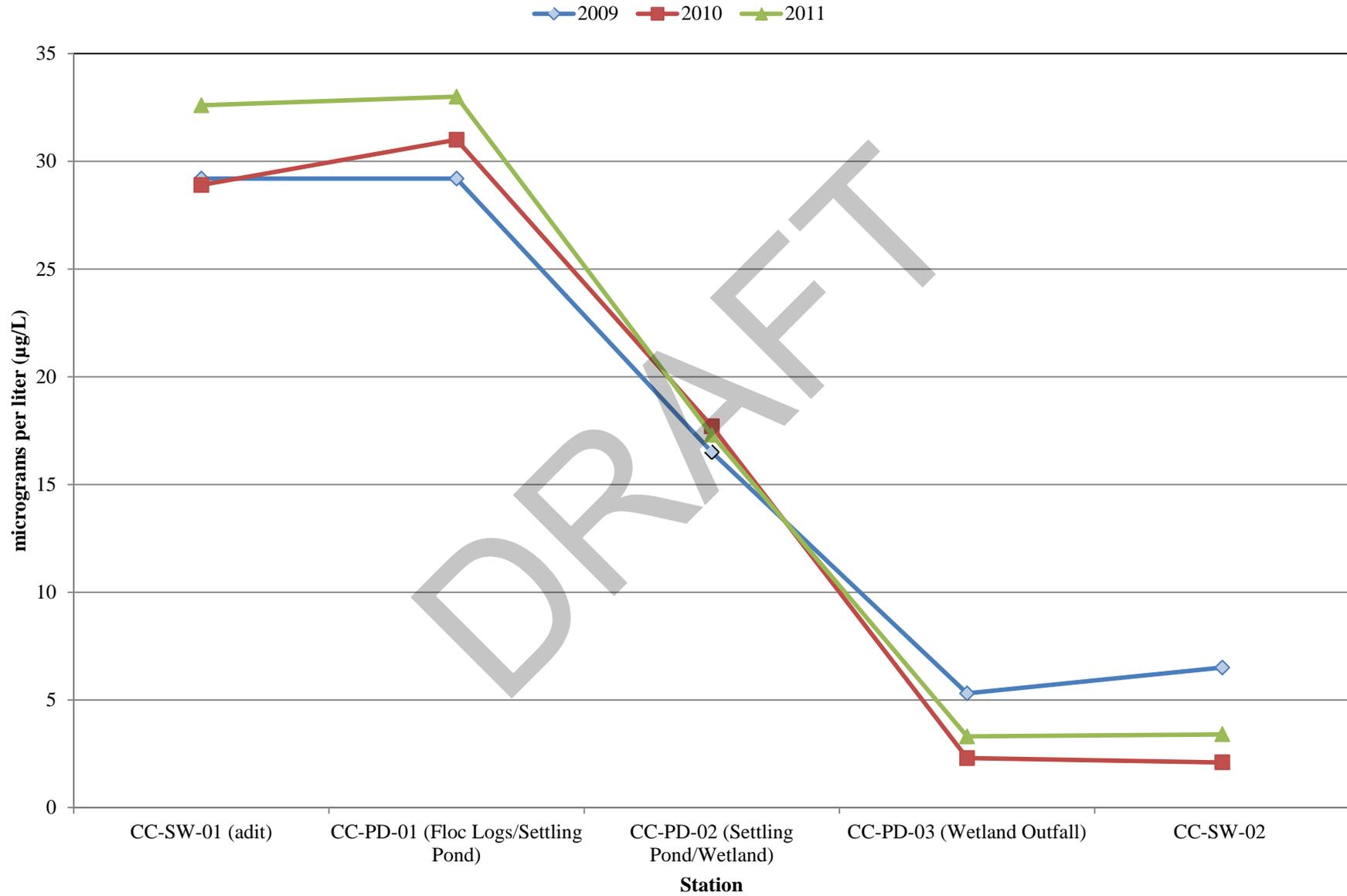
NOTES:

Data compiled from the 2008, 2010, and 2011 sampling events conducted by Cascade Earth Sciences.

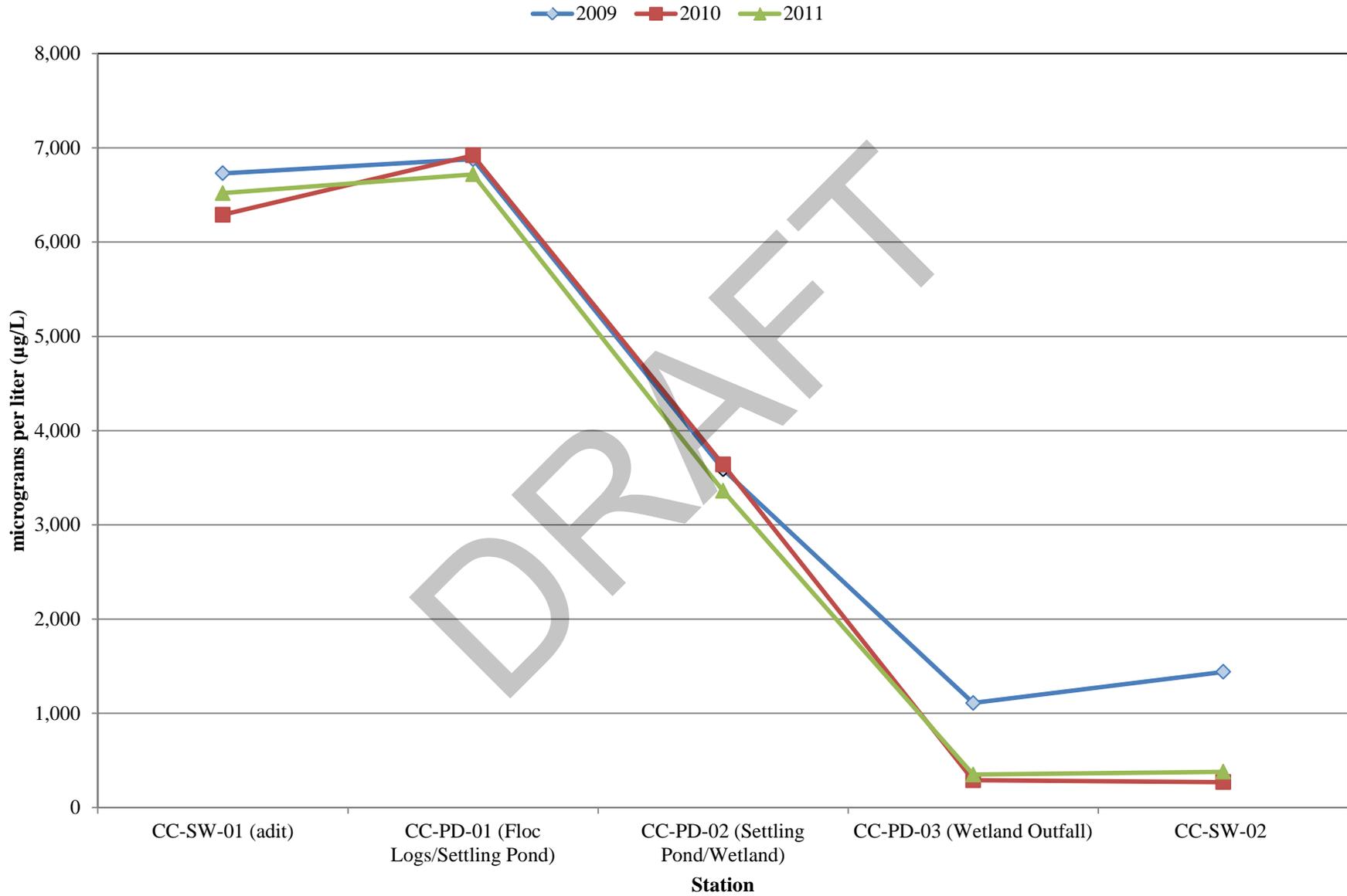
Abbreviations: µg/L = micrograms per liter, CaCO<sub>3</sub> = calcium carbonate, DO = dissolved oxygen, gpm = gallons per minute, max = maximum, mg/L = milligrams per liter,

NM = not measured, POM = Pride of the Mountains, PW = Pride of the Woods, s.u. = standard units.

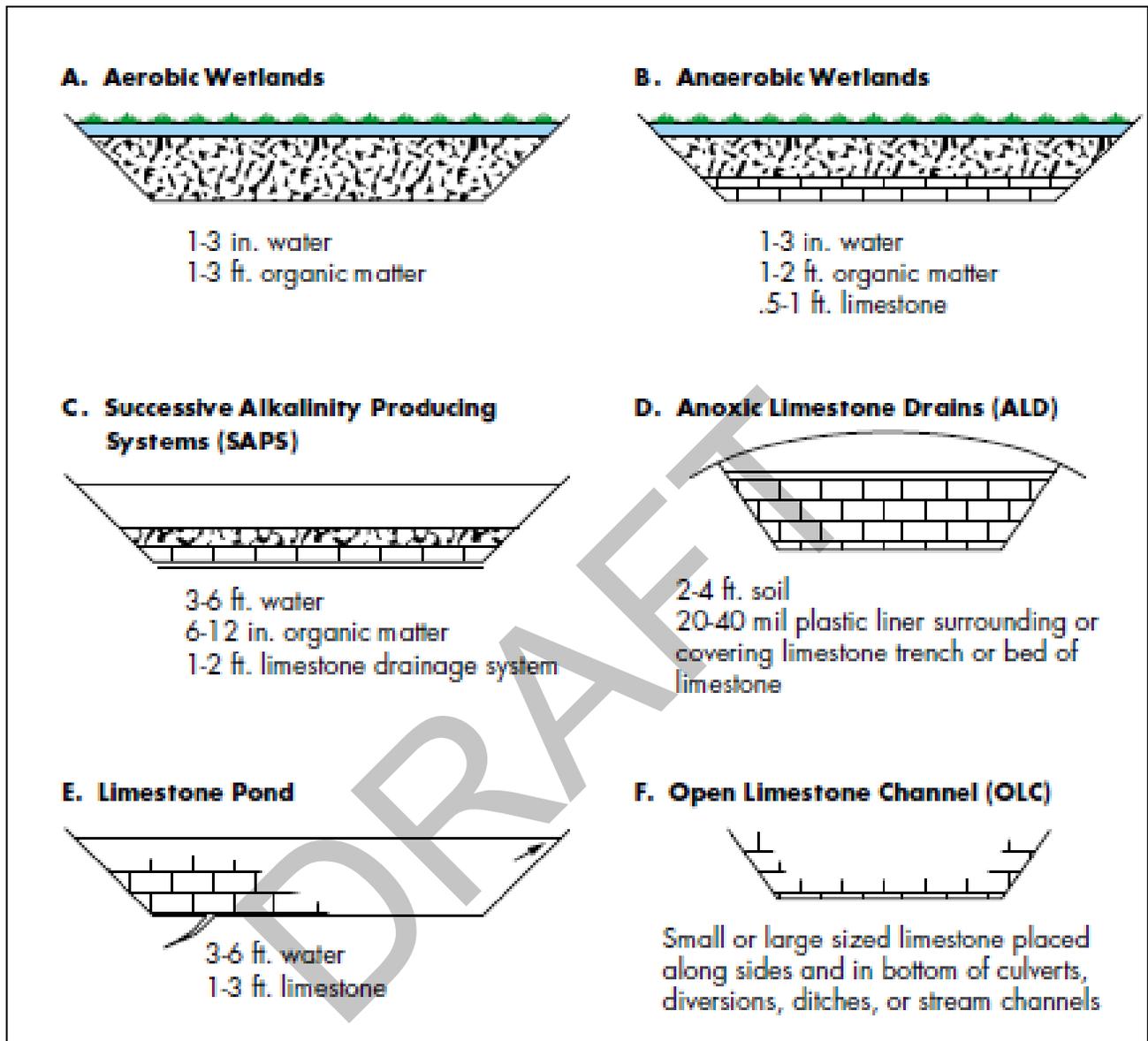
**Chart 1. Total Recoverable Arsenic in Surface Water (Wetlands)  
Champion Mine**



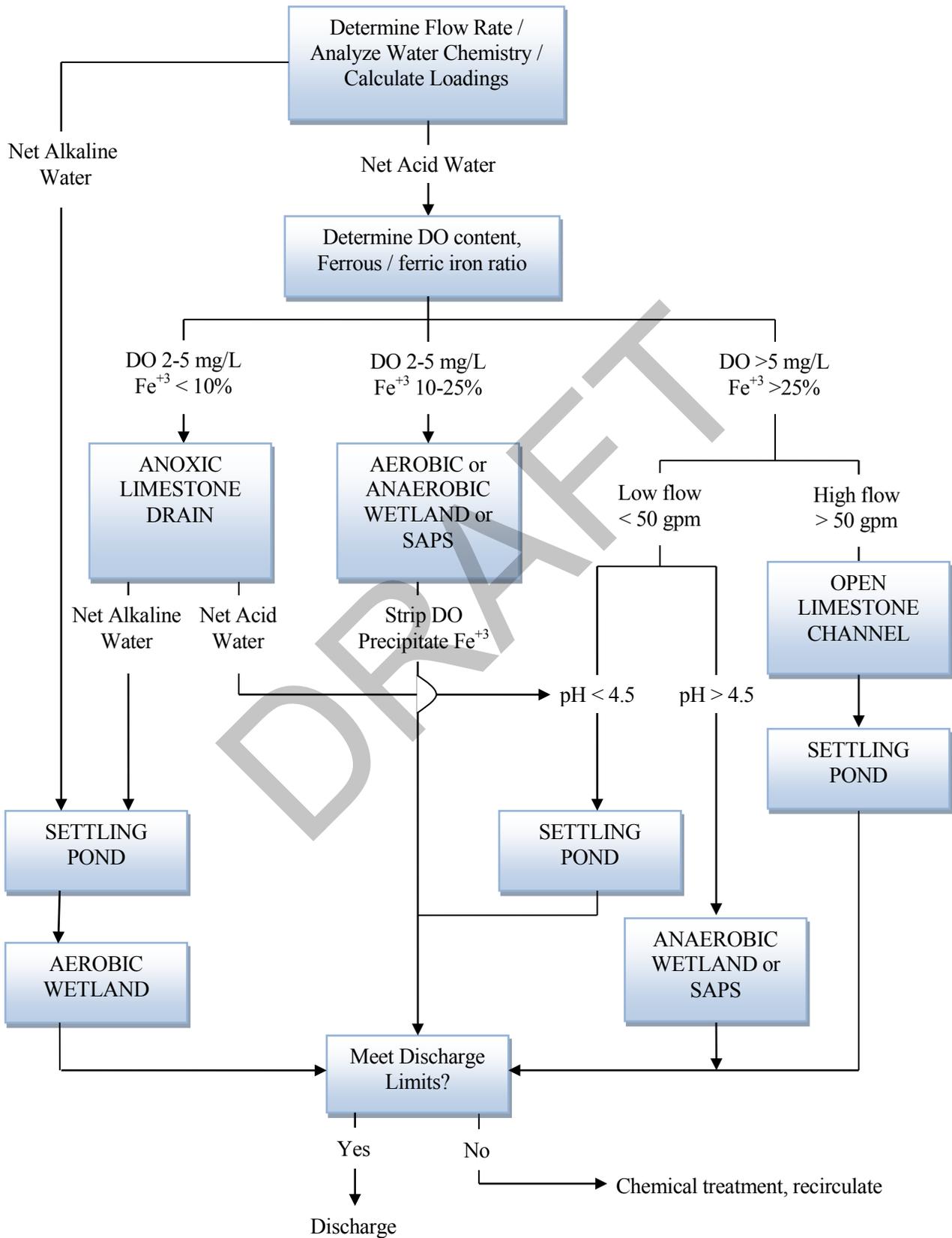
**Chart 2. Total Recoverable Iron in Surface Water (Wetlands)  
Champion Mine**



Attachment 1. Diagrams of Passive Treatment Systems (Skousen, 2001)



**Attachment 2. Typical Flowchart For Selecting Passive Acid Mine Drainage Treatment Systems (Skousen, 2001)**



**Attachment 3. Engineer's Opinion of Probable Cost - Justice Mine**

**Cascade Earth Sciences**  
 3511 Pacific Blvd SW, Albany, OR 97321  
 Tel: (541) 926-7737 Fax: (541) 967-7619  
**Engineer's Opinion of Probable Cost**



**Design & Install Passive Treatment Technologies for Justice Mine** 28-Aug-12  
 Monte Cristo Mining Area TLO

NO.	Description	Estimated Quantity	Units	Unit Price	Total Cost
1	<b>CONTRACTOR IN-DIRECT COSTS</b>				
2	Mobilization	1	LS	\$ 20,000.00	\$ 20,000.00
3	Bonding and Insurance	1	LS	\$ 5,000.00	\$ 5,000.00
4	<b>CONTRACTOR DIRECT COSTS - SETTLING POND</b>				
5	Excavation	2,600	CY	\$ 15.00	\$ 39,000.00
6	Bentonite Mat & Cutoff Wall	362	CY	\$ 50.00	\$ 18,200.00
7	8" Adit Collection Piping	800	FT	\$ 35.00	\$ 28,000.00
8	Soil media Iron reaction cell	4,400	CY	\$ 10.00	\$ 44,000.00
9	Outlet Structure	1	LS	\$ 5,000.00	\$ 5,000.00
10	<b>CONTRACTOR DIRECT COSTS - AEROBIC WETLAND</b>				
11	Excavation	7,000	CY	\$ 15.00	\$ 105,000.00
12	Substrate (Peat)	1,000	CY	\$ 60.00	\$ 60,000.00
13	Substrate (Hay, Manure)	500	CY	\$ 40.00	\$ 20,000.00
14	Planting	500	HR	\$ 35.00	\$ 17,500.00
15	Supervision	100	HR	\$ 100.00	\$ 10,000.00
16	8" Distribution Piping (Inlet and outlet)	100	FT	\$ 35.00	\$ 3,500.00
17	Outlet Structure	1	LS	\$ 3,500.00	\$ 3,500.00
18	<b>Sub-Total</b>				\$ 378,700
19	Contingency	25.0%			\$ 95,000
20	<b>Total Construction</b>				\$ <b>473,700</b>
21	<b>INCIDENTALS</b>				
22	Administrative Services	2%	L.S.		\$ 9,500
23	Pilot Testing	6%	L.S.		\$ 28,400
24	Engineering Design	8%	L.S.		\$ 37,900
25	Engineering Construction Services	8%	L.S.		\$ 37,900
26	<b>TOTAL PROJECT COST</b>				\$ <b>587,400</b>
27	<b>ANNUAL OPERATION AND MAINTENANCE</b>				
28	Inspection - Trained 2-person Field Crew	80	HR	\$ 50.00	\$ 4,000.00
29	Fertilizer Applications/Plant Maintenance	1	EA	\$ 1,000.00	\$ 1,000.00
30	Piping and Structural Maintenance	1	LS	\$ 5,000.00	\$ 5,000.00
31	Annual Sampling and Lab Testing	1	LS	\$ 3,000.00	\$ 3,000.00
<b>TOTAL ANNUAL O&amp;M COST</b>				\$ <b>13,000.00</b>	

**Attachment 4. Engineer's Opinion of Probable Cost - Mystery Mine**

**Cascade Earth Sciences**  
 3511 Pacific Blvd SW, Albany, OR 97321  
 Tel: (541) 926-7737 Fax: (541) 967-7619  
**Engineer's Opinion of Probable Cost**



**Design & Install Passive Treatment Technologies for Mystery Mine** 28-Aug-12  
 Monte Cristo Mining Area TLO

NO.	Description	Estimated Quantity	Units	Unit Price	Total Cost
1	<b>CONTRACTOR IN-DIRECT COSTS</b>				
2	Mobilization	1	LS	\$ 3,500.00	\$ 3,500.00
3	Bonding and Insurance	1	LS	\$ 1,000.00	\$ 1,000.00
4	<b>CONTRACTOR DIRECT COSTS - ANOXIC LIMESTONE DRAIN</b>				
5	Excavation	100	CY	\$ 10.00	\$ 1,000.00
6	Bentonite Mat & Cutoff Wall	10	CY	\$ 30.00	\$ 400.00
7	4" Adit Collection Piping	50	FT	\$ 20.00	\$ 1,000.00
8	Gravel	20	CY	\$ 50.00	\$ 1,000.00
9	4" Distribution Piping (Inlet)	300	FT	\$ 20.00	\$ 6,000.00
10	<b>CONTRACTOR DIRECT COSTS - AEROBIC WETLAND POND</b>				
11	Excavation	200	CY	\$ 10.00	\$ 2,000.00
12	Substrate (Peat)	100	CY	\$ 60.00	\$ 6,000.00
13	Substrate (Hay, Manure)	100	CY	\$ 40.00	\$ 4,000.00
14	Planting	60	HR	\$ 35.00	\$ 2,100.00
15	Supervision	10	HR	\$ 100.00	\$ 1,000.00
16	4" Distribution Piping (Inlet and outlet)	300	FT	\$ 20.00	\$ 6,000.00
17	Outlet Structure	1	LS	\$ 1,300.00	\$ 1,300.00
18				<b>Sub-Total</b>	\$ 41,100
19	Contingency	25.0%			\$ 10,300
20				<b>Total Construction</b>	\$ <b>51,400</b>
21	<b>INCIDENTALS</b>				
22	Funding, Permitting & Administrative Services	4%	L.S.		\$ 2,100
23	Pilot Testing	8%	L.S.		\$ 4,100
24	Engineering Design	10%	L.S.		\$ 5,100
25	Engineering Construction Services	10%	L.S.		\$ 5,100
26				<b>TOTAL PROJECT COST</b>	\$ <b>67,800</b>
27	<b>ANNUAL OPERATION AND MAINTENANCE</b>				
28	Inspection - Trained Field Crew	80	HR	\$ 50.00	\$ 4,000.00
29	Fertilizer Applications/Plant Maintenance	1	EA	\$ 250.00	\$ 250.00
30	Maintenance	1	LS	\$ 1,500.00	\$ 1,500.00
				<b>TOTAL ANNUAL O &amp; M COST</b>	\$ <b>5,750.00</b>