The Practical Application of Constructed Wetlands in the Philippines

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Abstract

The use of constructed wetlands to reduce acidity and remove heavy metals from acid mine drainage (AMD) water has been successfully applied in industry for many years. Considering technical research has primarily been limited to North America and Europe, we aim to broaden the research scope to the Philippines. The contrasting climate, vegetation, and geology introduce unique opportunities and constraints in support of local research initiatives. This paper presents a review of technical findings as well as preliminary experiments to establish design and operations criteria for a constructed AMD wetland at the TVIRD Canatuan sulfide mine, located on the island of Mindanao. The key objectives of this review are to optimize design and operations criteria for a passive treatment system using indigenous materials and incorporating low cost construction and minimal operations needs. Based on our review and the local AMD conditions, a Reducing and Alkalinity Producing System (RAPS) has been identified as the most promising passive treatment option. The RAPS design incorporates an anaerobic down-flow system. Water percolates downward first through organic then limestone substrate. Reduction occurs in the water and organics zone and is catalyzed by sulfate reducing bacterial processes. Subsequent dissolution of 90% CaO limestone produces alkalinity. The result is neutralization of pH and the removal of metals (As, Cd, Cu, Fe, Hg, Mn, Pb, and Zn) by (a) precipitation as metal sulfides, carbonates, and hydroxides; (b) sorption to soil substrate and plant rhizosphere; and (c) uptake into wetland plants referenced as "metal hyperaccumulators". Based on laboratory testing eight different metal hyperaccumulator plants have been identified as indigenous to the Canatuan mining area. Of these species, metal-assay analysis and plant biomass experiments have determined Gabi (Colocasia esculenta), Water Hyacinth (Eichhornia crassipes), Bugang Reed (Phragmites australis), and Vetiver Grass (Chrysopogon nemoralis) as the most effective metal hyperaccumulators with the tolerance and biomass production necessary for AMD treatment. In addition to plant-metal uptake, experiments to assess system hydraulics, metal sorption to soil and roots, and microbial processes are ongoing, and will be used to optimize the design and operations criteria for the effective long-term treatment of AMD.

Introduction

The passive, non-invasive, cost-efficient attributes of constructed wetlands present an impressive potential for mine wastewater treatment. This potential is even more attractive for remote mining companies in developing countries, where an alternative to complex infrastructure and costly maintenance is crucial. In theory, constructed wetlands can provide a long-term passive treatment solution to acid mine drainage. The successful implementation of such treatment facilities has been demonstrated in technical and academic forums of research in North America and Europe. The purpose of this paper is to document and identify the viability of passive wetland treatment for use at the Canatuan Copper and Zinc Project located in Zamboanga Del Norte, Mindanao. The paper also presents initial design and operations criteria for a constructed AMD wetland based on the current investigation activities. This extensive review will help with future constructed wetland design and implementation within the Canatuan Project and within regions of similar climate, vegetation, and geology.

Acid Mine Drainage (AMD) occurs when sulfide minerals are exposed to water and oxygen. The following equation outlines this process, where pyrite is exposed to oxygen and water, producing Fe oxyhydroxides and sulfuric acid:

$$4\ FeS_2 + 15\ O_2 + 14\ H_2O \Rightarrow 4\ Fe(OH)_3 + 8\ H_2SO_4$$

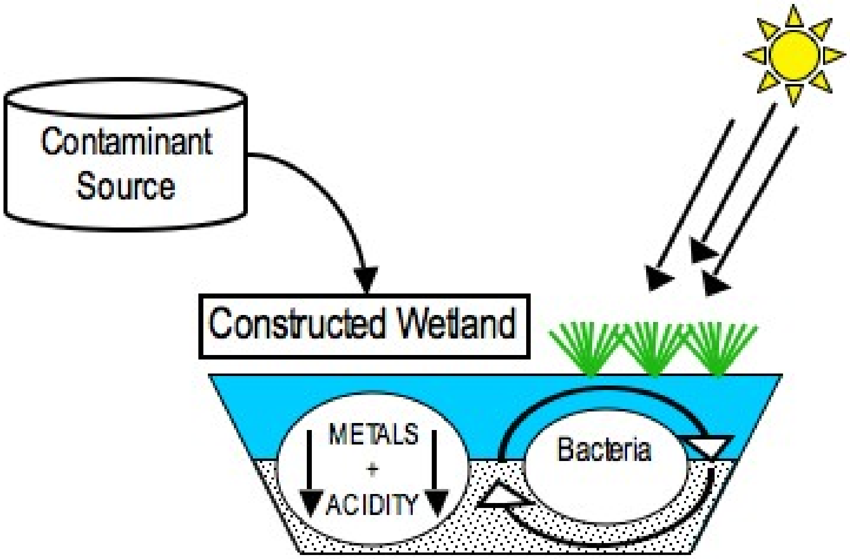
AMD is a widespread and predictable result of mining within certain geologic conditions. The more significant environmental impacts and consequences of this process consist of the following:

- Fe oxyhydroxides are deposited and tend to smother vegetation.
- Acidity dissolves and mobilizes metals such as As, Cd, Cr, Cu, Fe, Mn, Ni, Zn within the affected waterways.
- Metal and acid-contaminated water may cause serious deleterious effects to aquatic biota and water quality.

Constructed wetlands (CW) are a proven passive wastewater treatment technology (Younger, 2004 and Hedin, 1994) that has been shown to mitigate these impacts for a wide range of water quality conditions. The concept of CWs is to further enhance the natural treatment process by harnessing energy and source materials from the natural environment. The objective is to promote an effective, cost efficient, low-maintenance water treatment process that can be replicated at different locations within the AMD impact areas. The use of indigenous natural materials further enhances the efficiency of the system as well as reducing capital and operating costs.

Energy within the CW is harnessed from the sun (photosynthesis), topographical relief (hydraulic gradient), and microbial metabolism (Younger, 2004). The general process is shown on Figure 1.

Figure 1: *The concept of CWs is to passively filter and treat contaminated water through vegetation and organic substrate. The natural energy of photosynthesis, topographical relief, and bacterial metabolism drive contaminant treatment processes.*



Depending on the particular CW design, natural construction materials can include:

- Organic substrate (animal manure, compost),
- Local vegetation (aquatic wetland plants, slope-stabilizing grasses), and
- Rock (limestone, river gravel/boulders)

In the case of the Canatuan Project, all the above materials were sourced from local materials and indigenous plants. Some materials showed very positive testing results while others were not as effective as originally hoped.

Constructed Wetland Types

There are 2 broad classes of constructed wetlands: aerobic and anaerobic. Aerobic wetlands are surface flow reed ponds and are generally the simplest to construct and operate. The metal removal processes are based on Fe precipitation, metal co-precipitation, plant-metal uptake, rhizome adsorption, and physical settling. Because of the simplicity of the system, design options, and in some cases operation efficiencies, are limited.

Anaerobic wetlands are somewhat more complicated to build and operate but include a wider range of design options to better suit local conditions. The most basic design is the compost wetland, which involves surface or subsurface flow of water through approximately 0.5 meters of a mixture of compost, gravel, limestone, and/or soil. A variation on the compost wetland is the Reducing and Alkalinity Producing System (RAPS) (also known as SAPS - Successive Alkalinity Producing System or VFW – Vertical Flow Wetlands). The total dimensions of the RAPS is minimum 2 meters from water surface to substrate base, and requires a minimum of 5 meters relief to attain the hydraulic force necessary for water down-flow through substrate. Fe Reduction, microbial sulfate reduction (and subsequent metal sulfide precipitation), and limestone dissolution occur as water travels down through 0.5-1.0 meter of ponded water, 0.5 meters of organic substrate, and 0.5 meters of limestone. Water is collected in perforated drainage pipes, embedded in drainage gravel along the base of the pond, (Kadlec and Knight, 1996).

Anoxic Limestone Drains (ALD), Limestone Leach Beds (LSB), Open Limestone Channels (OLC), and Slag Leach Beds (SLB) are all variations of limestone channels and are based on the generation of alkalinity by $CaCO_3$ dissolution. A key design challenge with limestone channels is to prevent the coating of limestone by iron oxyhydroxides called ‘armoring’. Armoring coats the surface of the limestone, thereby slowing the rate of dissolution. Reducing the armoring effect is achieved by creating a buried anaerobic channel to prevent the oxidation of Fe (ALD), or by using the force of steep slopes and hydraulic friction to inhibit the buildup of the Fe oxyhydroxide solid (OLC) (Lorion, 2001).

Constructed Wetland Selection Criteria

When deciding which type of wetland design to choose, local topography, geology, hydrology, and influent water chemistry must all be taken into consideration. In the case of a treatment area with generous relief and limited area, RAPS is the preferred anaerobic system as it can treat metals at a higher rate. Conversely, in the case of insufficient relief, or in areas of unstable base material creating slope stabilization challenges, the compost wetland is the preferred anaerobic system.

Guidelines based on contaminant removal rates provide an estimate of minimum size requirements to achieve target contaminant levels. The following sizing calculation is the accepted guideline to date (Hedin, 1994):

$$A = Q_d\,(C_i - C_t)\,/\,R_A \qquad \text{(Eq. 1)}$$

Where ;

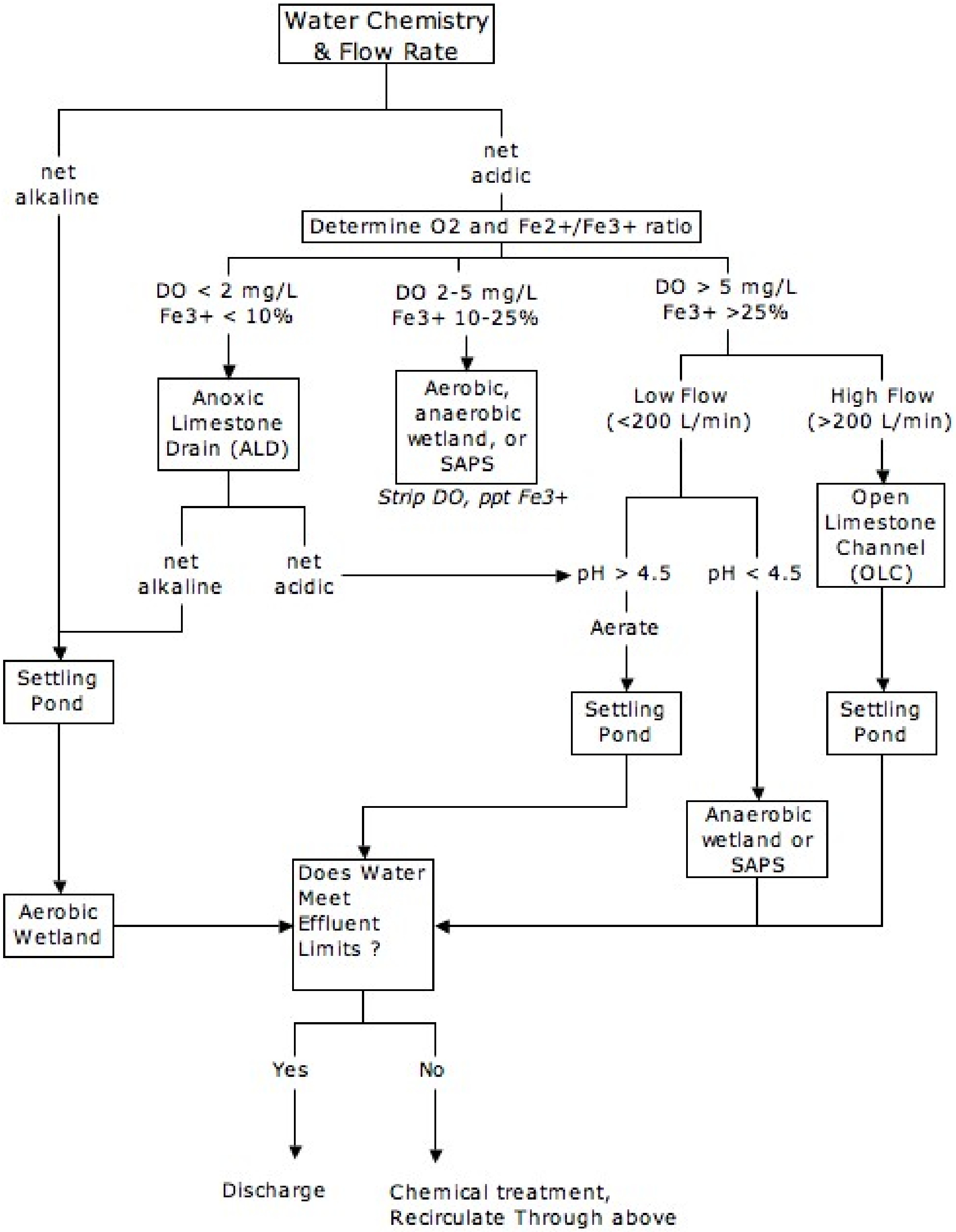
A is the wetland area (m^2),
Q_d is flow rate (L/d),
C_i is influent contaminant concentration (mg/L),
C_t is target contaminant concentration (mg/L), and
R_A is a sizing factor that varies with design and contaminant.

The most applicable R_A factors are the following:

- R_A Fe (aerobic wetlands) = 10 $g^{-}d^{-}\cdot m^{-2}$
- R_A Acidity as $CaCO_3$ (Compost wetland) = 3.5 $g^{-}d^{-}\cdot m^{-2}$
- R_A Acidity as $CaCO_3$ (RAPS) = 40 $g^{-}d^{-}\cdot m^{-2}$

The most important water quality parameters considered when deciding on a CW design are pH and dissolved oxygen (DO). A generalized flow chart for water conditions simplifies these factors and is shown in Figure 2 (Hedin et al., 1994).

Figure 2: *Guideline to choosing best constructed wetland design based on pH, dissolved oxygen, and Fe concentration. (Adapted from Hedin et al., 1994).*



In the case of the Canatuan Project, the AMD waters generally have a pH ~ 3 and DO > 5mg/L. According to the Hedin et al. flowchart, this condition indicates the more applicable CW evaluation for the Project should focus on compost wetlands and RAPS, and ALD/OLC limestone channels.

Constructed Wetland Components

Each of the three wetland systems selected include similar components that affect the design, construction and operation of the system. These include substrate materials, vegetation, microbial activity and hydrologic conditions. Discussion of each within the context of the Canatuan project and local conditions are provided below.

Substrate

The substrate serves as the biodegradable carbon source and is important as both a source of bacteria, as well as a quick food source for sulfate-reducing bacteria (SRB) activity. The recalcitrant carbon source can be considered a "time release" source of carbon, important to insure carbon source is sustained over a longer time period (Neculita et al., 2007; Stottmeister et al., 2003; and Lasat, 2002).

The key objectives for substrate selection include:

- Low cost/easily available local products.
- Introduction of sulfate-reducing bacteria (SRB) from manure.
- Grain size distribution (permeability) in the range of 0.06-10 mm, enabling a permeability of >10-5 m/s. The target grain size distribution will ensure a preferential condition for root penetration and water/contaminant infiltration.
- Sources of biodegradable (manure) and recalcitrant (forest litter and sawdust) are organic carbon sources for SRB metabolism.

Mineral precipitation is expected to occur (metal sulfides, hydroxides, and carbonates), therefore metal sorption to the soil substrate surface will result. This will eventually lead to clogging of pore space within the substrate. Long-term studies of the RAPS design show that metal sulfides do not pose a long-term performance failure (Ziemkiewicz et al., 2003). However, to achieve the anaerobic sulfate reduction and metal-sulfide sink, anaerobic conditions must be created and maintained. Water transport is therefore a key component of assuring the long-term performance of anaerobic wetlands. Clogging of water pipes, preferential flow pathways, and low-flow conditions are all factors that could lead to a loss in anaerobic conditions.

There are three ways to maintain substrate performance: Regular observation of metal-partitioning in substrate (sampling and soil-metal analysis); the installation and rigorous maintenance of water distribution systems (to maintain a predictable, constant flow); and the addition of C-substrate which can be achieved by regular addition of organic substrate, or by the natural decomposition of vegetation.

Vegetation

In addition to aesthetics, vegetation in constructed wetlands serves many other important purposes. These include soil stabilization/flow moderation, oxygen transport, metal-rhizome adsorption, carbon source, and metal uptake into plant tissue. Aquatic plants can assist in the ‘baffling’ of water flow to assist in even infiltration of water into substrate and to prevent preferential flow pathways. This is important in order to maintain desired oxygen concentrations and to maximize substrate particle contact with contaminants (Stottmeister et al., 2003).

In aquatic plants, oxygen transport from the aboveground plant tissue into the submerged rhizosphere is a survival adaptation. Moreover, oxygen exuded within the rhizosphere can create a coating that protects the root surface from the harsh, often anoxic and toxic wastewater (Stottmeister et al. 2003). The rhizosphere also provides the microenvironment in which aerobic microbial processes can occur. This protective coating and microbe layer further influences the potential for metal-rhizome adsorption of metal contaminants. As vegetation dies and biodegrades, carbon is released and made available to SRB thereby providing a natural source of carbon with the potential to replace what has been consumed in the organic substrate.

Plants with the ability to accumulate metals to greater than 0.1-1 % of their total mass are termed metal hyperaccumulators and are important vegetation components within the CW system (Van Rensburg and Morgenthal, 2003). Phytofiltration is the term given for the process of using metal hyperaccumulator plants in a saturated (aquatic) environment to treat contaminated water. Key qualities for the aquatic plant species used for phytofiltration within CWs include the following:

- Can be sourced locally
- Have known metal hyperaccumulating capability
- Can tolerate acidic pH
- Have the ability to store metals mainly in roots rather than shoots

There are well over 80 different plants (*Pteridophytes* and *Aquatic macrophytes*) with resistance to heavy metals. Of these 80, and with cross reference to known aquatic plants of the Philippines, 6 aquatic metal hyperaccumulator plants are known to exist within and around the Canatuan Project area (Gangstad, 1972).

Microbial Activity

Microbial activity can be a positive or negative factor in water treatment processes. In the case of AMD, acidophilic bacteria catalyze acid-formation by the oxidation of Fe. However, the activity of bacteria can also be harnessed in reductive pathways, providing the ability to reverse the acid-generating process of sulfide oxidation to sulfate reduction. Sulfate reducing bacteria (SRB) catalyze the reduction of sulfate to sulfide, producing carbonate alkalinity and soluble sulfide, according to the following reaction:

$$2\,CH_2O + SO_4^{2-} \Rightarrow 2HCO_3- + H_2S \qquad \text{(Eq. 2)}$$

Soluble sulfide reacts with metals to form metal sulfides, thus removing soluble metals from the mine influent according to the following:

$$H_2S + M^{2+} \Rightarrow M_eS\downarrow + 2H^+ \qquad \text{(Eq. 3)}$$

Where ;

M_e is the cationic metal Cd, Fe, Ni, Cu, or Zn.

SRB populations are present in manure, and so are easily introduced to constructed wetlands, (Neculita et al, 2007 and Stottmeister et al., 2003). The requirements for SRB activity within a CW are sufficient carbon substrate and anaerobic conditions. For this reason, long-term treatment with a CW may require the carbon substrate to be replenished. The main limiting factor for SRB activity, however, is that water conditions remain anaerobic. It is therefore important to design an anaerobic CW for low-flow conditions, which requires a comprehensive knowledge of historical hydrology and trends.

Hydrologic Conditions

Sizing the CW requires an estimate of the AMD flow rate and operation of the CW requires data relative to water budgets, evapotranspiration and seasonal variations in the expected AMD flow rates. As indicated above the hydraulic operation of the CW and sustainability of the hyperaccumulators requires a consistent water supply. Given the wet season and dry season variations this can be a significant factor in the CW design process.

Both meteorologic and hydrologic data specific to the Canatuan Project have been collected since 1994 and 2003 respectively. The mean annual rainfall within the area is approximately 3,064 mm and the mean annual evaporation is approximately 1,203 mm. Monthly water balance studies have indicated a mean annual net rainfall depth of 2,056 mm and a mean annual evapotranspiration of 1,008 mm.

Hydrologic studies during the period 2004-2009 indicate a wide range of base-flow within the local streams. Monthly unit base flow ranges from 800 m^3/ha/month to nearly 2,000 m^3/ha/month. Short-term high intensity storm events show an even greater range of flows.

Both the meteorologic and hydrologic data suggest the need for parallel CW treatment considerations to better match the climate and flow rate variations.

Pilot Testing and Preliminary Results

The conditions and concepts for many of the key processes in the successful performance of CWs, as discussed in this review, are simple in theory but difficult in actual implementation. How CW concepts and theory can be applied to the conditions at the Canatuan Project is currently under pilot testing and evaluation. Preliminary results and potential opportunities and constraints are discussed within the following sections.

Pilot Testing Locations

Water quality monitoring within the Canatuan Project area has identified four small watershed streams that have recently exhibited signs of AMD. This is evident by a decreasing trend in pH and an increase in some metals concentrations. Three of the streams are perennial and the fourth is an intermittent stream that flows only after rainfall events. Two of these streams were selected for pilot studies and are known locally as Manhattan Creek and Small Scale Mining Creek. The first drains an area of approximately 11 ha of which 8 ha is drainage from the active surface mine area. The second stream drains an area of approximately 6 ha which was previously a portion of a small scale mining area prior to the TVIRD operation. Both streams are tributaries to Canatuan Creek that drains the majority of the Canatuan Project.

The fourth stream drains an area of approximately 30 ha which includes one overburden waste disposal stockpile. This area is also affected by construction activities associated with a new tailings storage facility. Because of the ongoing activity this area and associated impacts, this particular stream was not selected for the initial pilot studies.

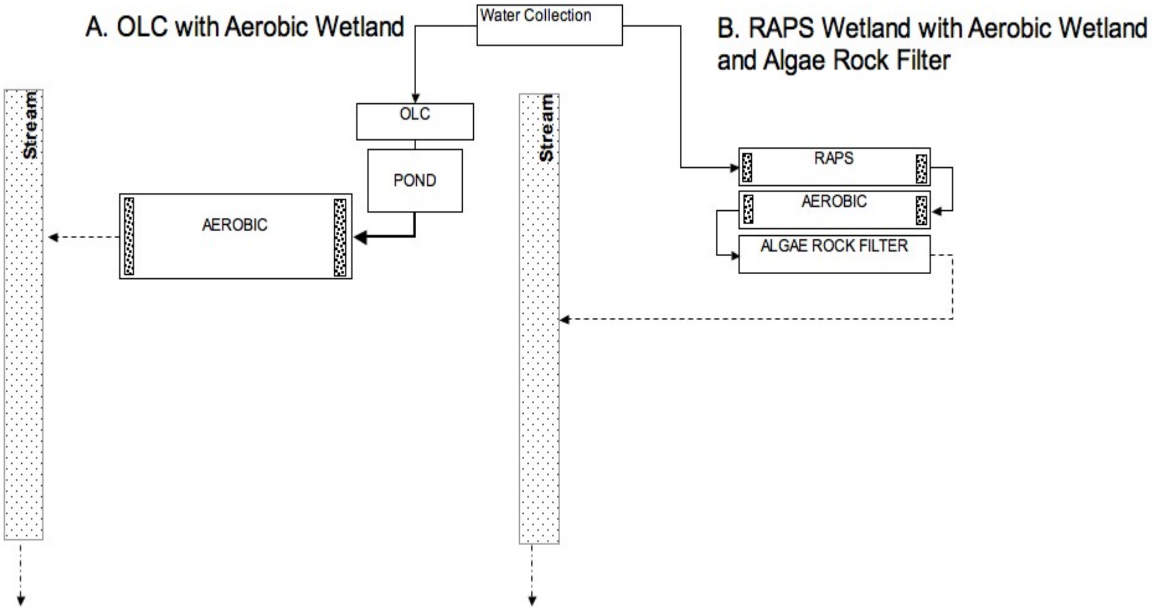
Pilot studies initially started with the Small Scale Mining Creek drainage in August 2009. A pilot CW facility was constructed adjacent to the Small Scale Mining Creek and water from the creek was used as the influent source. The water supply was subsequently increased in September 2009 by including the Manhattan Creek. The Small Scale Mining Creek water supply alone was unable to fully meet the needs of the pilot facility. This increased the influent AMD supply from approximately 0.1 L/s to 0.4 L/s.

Pilot Test Constructed Wetland Facilities

Two pilot constructed wetland facilites were constructed at the Small Scale Mining Creek location to evaluate and compare the treatment efficiencies and provide a basis for development of future design critera.

A schematic diagram of the two systems is shown on Figure 3. System A consists of an open limestone channel with aerobic wetland. System B consists of a RAPS wetland followed by a polishing aerobic wetland and an algae rock filter.

Figure 3*: Schematic diagram showing the Aerobic (A) and Anaerobic (B, RAPS) pilot constructed wetlands to be tested for this study.*



Water Quality Baseline Conditions

Sampling and testing of the water quality for the Small Scale Mining Creek AMD source was done during a four-month monitoring period from June 2009 to September 2009. Seven sampling events occurred during this period and testing was done by ICP at the onsite TVIRD Assay Laboratory. Testing and sample preparation was done in accordance with USEPA protocols.

The results of the tests are presented in Table 1 and indicated the metals of concern are As, Cd, Cu, Fe, Hg, Mn, Ni, and Pb. Of the eight metals, Cd, Cr and Pb have the highest concentrations of concern relative to the Philippine water quality standards. Similarly, the pH values are low as expected for AMD waters. Evaluation of the effectiveness of the CW treatment for AMD water will focus on the eight metals and the pH.

There was no baseline data established for the Manhattan Creek water supply during the initial months of study since this source was not originally used. However, field testing of the water for pH was done during this period as part of the normal water quality monitoring within the Canatuan Project area. The pH values showed the same 3 to 4 range as those exhibited by the Small Scale Mining Creek. Additional sampling and testing of the Manhattan Creek water supply will be integrated into the future monitoring and testing of the CW systems.

Table 1: *Monitoring results for metal concentration (ppm) of source AMD water over a 4-month period.*

Sampling Date	pH	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn	TSS
Detection Limit	-	0.002	0.001	0.01	0.1	0.5	0.001	0.1	0.1	0.003	0.02	-
11-Jun	3.04	0.021	0.005	0.03	4.10	23.6	ND	4.3	0.4	0.029	0.57	35
7-Jul	3.05	0.009	0.016	0.04	11.16	37.0	0.002	6.2	0.5	0.566	1.53	33
14-Aug	3.33	ND	0.004	0.03	2.57	27.2	0.002	8.4	0.4	ND	0.97	1
23-Aug	3.35	ND	0.022	0.09	16.02	26.5	0.003	51.0	1.2	0.063	3.38	3
7-Sep	3.72	ND	0.009	ND	1.52	ND	ND	5.8	0.1	0.103	0.85	32
11-Sep	3.93	ND	0.007	0.07	1.31	20.6	ND	ND	0.2	ND	0.57	1
18-Sep	3.48	ND	0.024	0.50	19.16	53.1	ND	22.1	1.2	0.488	2.85	3
Mean	3.41	0.006	0.012	0.107	6.99	24.12	0.002	12.73	0.52	0.16	2.59	24

ND = Non Detection, below the laboratory detection limit.

Pilot Constructed Wetland Results – A. Aerobic Wetland and Open Limestone Channel

Construction and testing of the Aerobic Wetland was done first and is representative of the simplest passive treatment system that could be used for long term AMD treatment.

Taro, Bugang, and *Vetiver*, are three emergent aquatic plant species (roots penetrate into saturated soil substrate) that were found to be capable of accumulating As, Cd, Cu, Mn, Ni, and Pb. Water hyacinth and Kankong are floating aquatic plant species (roots are suspended in the water column, just below the surface) and were found to be capable of accumulating Cu, Hg, and Pb. All of the five plant species have the potential for metals uptake. A summary of the metals accumulation by the four plant species is shown in Table 2.

Results of initial plant-metal analysis indicate all metals of concern for the pilot constructed wetland have the capacity to be removed by phytofiltration.

Table 2: *Plant identification and taxonomy, and metal accumulation potential for the four aquatic plants source locally, and chosen for use in the constructed wetlands. * Kankong is cited as having metal tolerance, but has not, to our knowledge, been used in metal hyperaccumulation studies.*

AQUATIC PLANT SPECIES NAME			METALS ACCUMULATED									
LOCAL (TAGALOG)	COMMON (ENGLISH)	TAXONOMY										
			As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
Gabi	Taro	*Colocasia esculenta*	●	●							●	
Water Hyacinth	Water Hyacinth	*Eichhornia crassipes*	●	●	●	●		●		●	●	●
Bugang	Common Reed	*Phragmites australis*	●	●		●				●	●	●
Vetiver	Vetiver	*Chrysopogon nemoralis*		●		●			●		●	●
Kankong*	River Cabbage	*Ipomoea aquatica Forssk*										

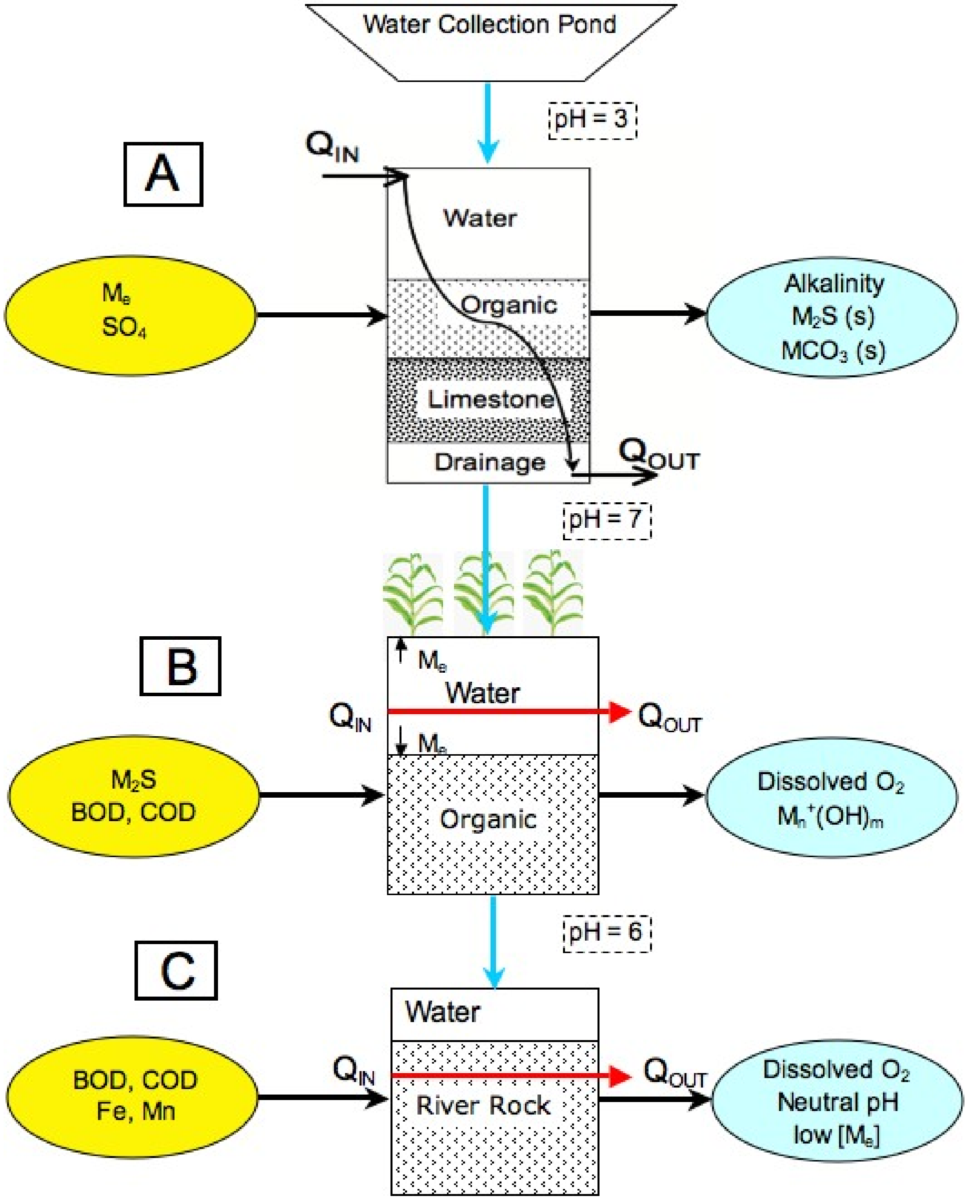
Results of initial plant-metal analysis indicate all metals of concern for the pilot constructed wetland have the capacity to be removed by phytofiltration under the conditions less controlled than the batch experiments.

Pilot Constructed Wetland – B. Anaerobic RAPS Wetland

Construction and testing of the Anaerobic RAPS system was constructed after the aerobic system. It is a more complicated system from both construction and operation standpoints but has been shown to be a more effective long term AMD passive treatment system at other AMD treatment projects.

Experiments have yielded positive results using the RAPS system (Younger, 2004; Wildeman et al., 1994; Hedin et al., 1994). In comparison to an anaerobic wetland, the limestone layer of the RAPS adds additional alkalinity, which is pertinent with highly acidic influent water. It is important to pass RAPS-treated water through an aerobic wetland to remove residual metals (mobilized in their reduced form) and add oxygen/remove chemical oxygen demand (COD) (necessary for plant and animal life in receiving water pathways). Figure 4 presents a schematic diagram describing the principle chemical processes involved in the RAPS-Aerobic-Rock Filter design.

Figure 4: *Diagram for the chemical theory of our proposed RAPS-Aerobic Wetland-Rock Filter design.*



Within the RAPS Pond (Pond A) four processes occur; generating alkalinity and removing metals at metal sulfides and carbonates:

- Uptake of heavy metals into wetland plants.
- Fe Reduction; $Fe^{3+} + 1/2\ H_2O \rightleftharpoons Fe^{2+}\ 1/4\ O_2 + H^+$
- Microbial Sulfate Reduction; $SO_4 + 2CH_2O + 2H^+ \rightleftharpoons H_2S + 2H_2CO_3$

  $Me^{2+} + S^{2-} \rightleftharpoons FeS$ (s)

- Limestone Dissolution; $CaCO_3+CO_2 + H_2O \rightleftharpoons Ca^{2+} + 2HCO_3^-$

Within the Aerobic Pond (Pond B) the following four processes occur, resulting in the removal of iron, heavy metal co-precipitation, and metal uptake into emergent vegetation:

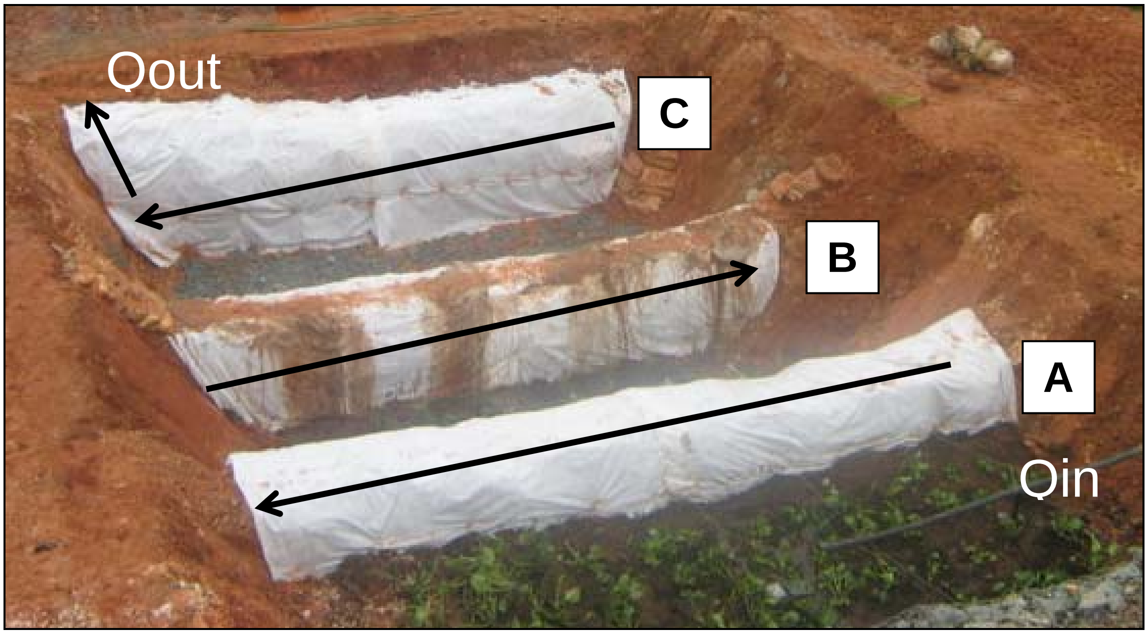
- Fe Oxidation; $Fe^{2+}\ 1/4\ O_2 + H^+ \rightleftharpoons Fe^{3+} + 1/2\ H_2O$
- Fe Hydrolysis; $Fe^{3+} + H_2O \rightleftharpoons iFe(OH)_3\ (s) + 3H^+$
- Metal Sorption to organic substrate, plant rhizome.
- Metal uptake into hyperaccumulator plants.

Within the final Rock Filter Pond (Pond C) the following four processes occur, providing the final removal of metals and oxygen restabilization (from BOD/COD conditions, to re-oxygenated).

- Phyto (algal) increase in pH,
- Residual metal sorption to algae surface
- Phyto re-oxygenation
- Chemical Oxygen Demand (COD) removal

A photograph of the complete 3-cell anaerobic wetland design is shown on Figure 5. Pond A, a RAPS system, is filled with 0.35 m limestone, and 0.35 m organic material. Water hyacinth grows on the surface of the ponded water. Pond B, an aerobic system, is filled with 1 meter of organic substrate, and planted with 1/3 Gabi, 1/3 Vetiver, and 1/3 Bugang. Pond C, a rock filter system, is filled with 0.65 m of 15-30 cm diameter river rock. Pond C will be ‘inoculated’ with algae. Pond A and Pond C are ‘down-flow’ systems with perforated pipes for subsurface drainage. Each pond is 8 x 2 meters in area, with varying depth.

Figure 5: *RAPS-Aerobic-Rock Filter 3-cell wetland. Arrows denote water flow direction.* Q_{IN} *is the water inflow area, and* Q_{OUT} *is the outflow area.*



Conclusions and Further Studies

Metal analysis for plant tissue and inflow/discharge water to both the Aerobic and the Anaerobic RAPS wetland is ongoing. Hydraulic balance has been achieved using the two AMD water supply sources. Hydraulic controls have also been installed on influent and discharge pipes so that hydraulic retention time can be measured and controlled to optimize contaminant interaction and treatment by the two processes.

A monitoring schedule for both Aerobic and Anaerobic Pilot CWs for the Canatuan study includes testing of the following parameters:

- Daily inflow and discharge flow rates, pH, and dissolved oxygen.
- Weekly water samples taken for heavy metal analysis, total suspended solids, sulfate, BOD/COD and acidity/alkalinity as $CaCO_3$.
- Monthly plant tissue and soil metal digestion and analysis.
- Monthly plant biomass measurements including the measurement of shoot (maximum plant height above soil/water) and root (maximum root depth below soil/water) growth.

Although the Canatuan Project data collected to date is limited, the preliminary results indicate both the constructed wetland passive treatment systems are achieving good results in the treatment of AMD. With the continued research and monitoring of the pilot system, design optimization will be determined to enable the construction of a full-scale, effective long term (~20 year), self-sustaining, and cost efficient AMD water treatment facility for the Canatuan Mine.

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