Controlling Metal and Acid Release by Reclaiming Tailings as Wetlands

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Abstract
A small plot experiment was begun in 1997 to examine the effectiveness of creating wetlands to mitigate acid and metal release from tailings. Unsaturated controls were established and five treatments were applied to the tailings. Saturated treatments included 61 cm covers of peat, overburden, tailings, and 71 cm of water. Aquatic macrophytes were included in one of the water covers, while cattails were included with the peat, overburden and tailings and covers. Controls produced highly acidic drainage with an average pH of 2.88, acidity over 18,000 mg/L and 5,400 mg/L Zn. The pH in the treated tailings ranged from 6.4 to 6.8, and average Zn concentrations ranged from 0.02 to 0.03 mg/L. As long as a water cover over the tailings was maintained, pH remained circumneutral. Surface waters associated with the tailings cover produced the highest concentrations of Zn and sulfate. No transport of sulfate or Zn from the tailings to surface water was observed with peat and overburden covers. Treatments containing aquatic macrophytes had the lowest sulfate release, and Zn concentrations in surface water decreased with time. The presence of the macrophytes also increased surface water pH and produced a cover of organic detritus on the surface of the tailings, which consumed oxygen and limited sulfate oxidation in the underlying tailings.

Key Words: water cover, zinc, sulfate

Introduction
Environmental problems caused by acid generating tailings have occurred throughout the world. Many of these mining sites were developed before the magnitude of the acid generating problem was identified, and today control of acid generating tailings is a critical component in the development of any new mine. Extensive testing is required to identify acid generating waste, and reclamation plans must include provisions to prevent or treat any acid produced at the site.

Acid generation occurs when the residual iron sulfide minerals in the tailings are exposed to oxygen and oxidize. This reaction can be represented as:

$$2\ FeS + 3\ H_2O + 9/2\ O_2 = 2\ FeOOH + 4\ H^+ + 2\ SO_4^{-2}$$

If the tailings do not contain an excess of neutralizing minerals (i.e. calcium carbonate), drainage from the tailings will be acidic and may contain elevated concentrations of trace metals. The production of acidic drainage requires iron sulfides, oxygen, and water. To stop the production of acid, at least one of these three components must be controlled or eliminated.

One of the most effective methods to control acid generation is to limit oxygen diffusion into the tailings by utilizing a water cover (GARD Guide, 2009). Oxygen concentrations in water are generally less than 10 mg/L or a factor of about 300 less than the mass concentration in air and the diffusion rate is about 10,000 times slower than in air. General recommendations call for a water cover of at least 1 meter in depth (Feasby et al., 1997). Although this approach has drastically reduced the oxidation of the tailings, and has generally prevented acid conditions, metal release has still occurred (Aubé et al., 1995). While keeping the tailings totally submerged during operation is achievable, long-term maintenance of water holding dams becomes a concern when mining is completed (Aubertin et al., 1997).

In Minnesota, the maximum depth of water that can be left in a tailings basin at the end of operation is 2 meters, due to dam safety rules. While this may be sufficient to minimize acid production in the center of the tailings basin, it will not provide protection for the tailings along the perimeter of the basin, or on beach areas. Creating a wetland over these areas could produce an anoxic layer above the tailings and minimize acid generation with minimal maintenance. Additionally, wetland plants are capable of sequestering metals in roots and senescent vegetation. Metals in litter and roots are not readily dissolved, thus reducing metal concentrations in the overlying water.

Wetland plants are known to accumulate metals (Jackson 1998). *Typha latifolia*, a common biomass dominant plant in wetlands, is known to be tolerant of heavy metals (McNaughton et al. 1974, Ye et al. 1997), concentrating metals in the roots with limited translocation to shoots (Ye et al. 1997). Cardwell et al. (2002) found that *T. latifolia* concentrated Cd, Zn, Cu and Pb in roots and rhizomes. Boyd (1970) found that as biomass of *T. Latifolia* increased, metal concentrations in the plant decreased, but total metal content increased. However, McNaughton et al. (1974) found that *T. latifolia* growth was reduced in the presence of pollution from a Zn smelter with elevated Zn, Cd, and Pb. Manios et al. (2003) found that *T. latifolia* metal concentrations increased with metal concentration in irrigation water.

Although most studies have focused on *T. latifolia*, studies of other emergent plant species have found similar patterns of metal concentration in roots (Ye et al. 2001, Stolz and Greger 2005). Collins et al. (2005) found that metal content of plants generally increased with substrate metal concentrations. Jackson (1998) stated that metals bioaccumulated within floating vegetation will likely remain in the treatment system via senescence.

The ability of wetland plants to transport oxygen into anoxic sediments (Bedford et al. 1991) is also important in forming metal oxides, which exhibit reduced bioavailability and hence toxicity. Although plant uptake of metals is a small portion of the amount of metals retained in wetlands constructed to treat metal-contaminated waters (O'Sullivan et al. 2004), plants do contribute to metal retention in soils. Plants are able to form organic soils (Goulet and Pick 2001, O'Sullivan et al. 2004), contributing to the formation of metal sulfides through lowered redox potential and providing a carbon source for sulfur reducing bacteria.

Objectives

- Establish wetland vegetation over acid generating tailings.
- Measure the effectiveness of the wetland to reduce acid generation and metal release.
- Compare the effectiveness of the various treatments to the unsaturated controls.

Methods

Five treatments were chosen to examine not only the effect of a substrate cover and wetland vegetation, but also the effect of water covers alone. In general monthly precipitation exceeds evaporation in northeastern Minnesota, although periods of drought can occur. Annual precipitation exceeds evapotranspiration by about 25 cm, so over the long term, a lined tailings basin should always remain saturated. Locally available soils, both wetland and mineral soil, were used to create a favorable growth media as well as provide a barrier between the acid generating tailings and the surface water. The five treatments were:

1. Water cover
2. Water cover with submerged macrophytes
3. Peat planted with cattails
4. Glacial till planted with cattails
5. Acid generating tailings planted with cattails

Water levels in northern Minnesota peatlands typically do not fluctuate more than 30 cm annually and the roots of wetland species are generally confined to the upper 30 cm of the soil (Melchert et al., 1997). A 60 cm cover was chosen to protect the underlying tailings from root contact and unsaturated conditions.

Each treatment was initially applied in duplicate. In previous experiments with fairly uniform material, duplicate treatments provided data that were sufficient to determine the effectiveness of the mitigation approach (Lapakko and Eger, 1981; Eger et al., 1984). A split block design was used to randomly assign the location of each treatment (Figure 1). Beginning in 2003, sampling was reduced and only one of the treatments was sampled to investigate long-term performance.

The wetlands were constructed in cylindrical polyethylene open top tanks with a diameter of 117 centimeters and a depth of 163 cm. An ultraviolet-resistant Supralloy PVC liner (0.76 mm thick) was fitted inside each tank for double containment. The tanks were installed in the ground to simulate natural thermal conditions.

Each tank was filled to a depth of 61 cm with tailings. In order to minimize the variability between the tanks, tailings were shovelled into 20-L buckets from various portions of the pile and manually placed in the tanks. A sampling well constructed from 1.27 cm schedule 40 PVC well screen was installed horizontally 23 cm above the bottom of the tank. Sand was placed on the sides of the well screen to cover the slots, and then the tanks were filled with approximately 38 cm of tailings. The tailings were then covered with 61 cm of reed sedge peat, glacial overburden, tailings, or 71 cm of water.

For the tanks with soil covers, a 1.27 cm PVC well was installed horizontally 30.5 cm below the surface. Riser pipes extended above the top of the tanks. In order to minimize the chance of water movement down the riser pipe, a 7.5 cm acrylic flange was installed about 18 cm below the tailings surface. After the flange was in place, moist bentonite (with the consistency of putty) was placed over the flange to seal it to the pipe. The top of the pipe was equipped with a ball valve which remains closed, except when sampling, to prevent direct oxygen transport into the bed. The valve was fitted with a 6 mm hose adaptor to facilitate sampling with a peristaltic sampling pump. Slotted well screens (12-mm diameter) were installed vertically 61 cm into the substrate and approximately 10 cm in from the tank wall in the shallow water tanks, so water levels could be measured when no surface water was present.

Eighty grams of inorganic fertilizer containing 10% nitrogen, 10% phosphorus, and 10% potassium were incorporated to a depth of 5 cm in the substrates of the shallow water tanks. Sixteen mature cattails (*Typha sp.*), collected from a constructed wetland used to treat mine drainage at the Dunka Mine in northeastern Minnesota , were transplanted in each of these tanks on 30 cm centers. Prior to planting, the cattails were rinsed to remove the soil and the tops were cut off to leave a 23 cm stem.

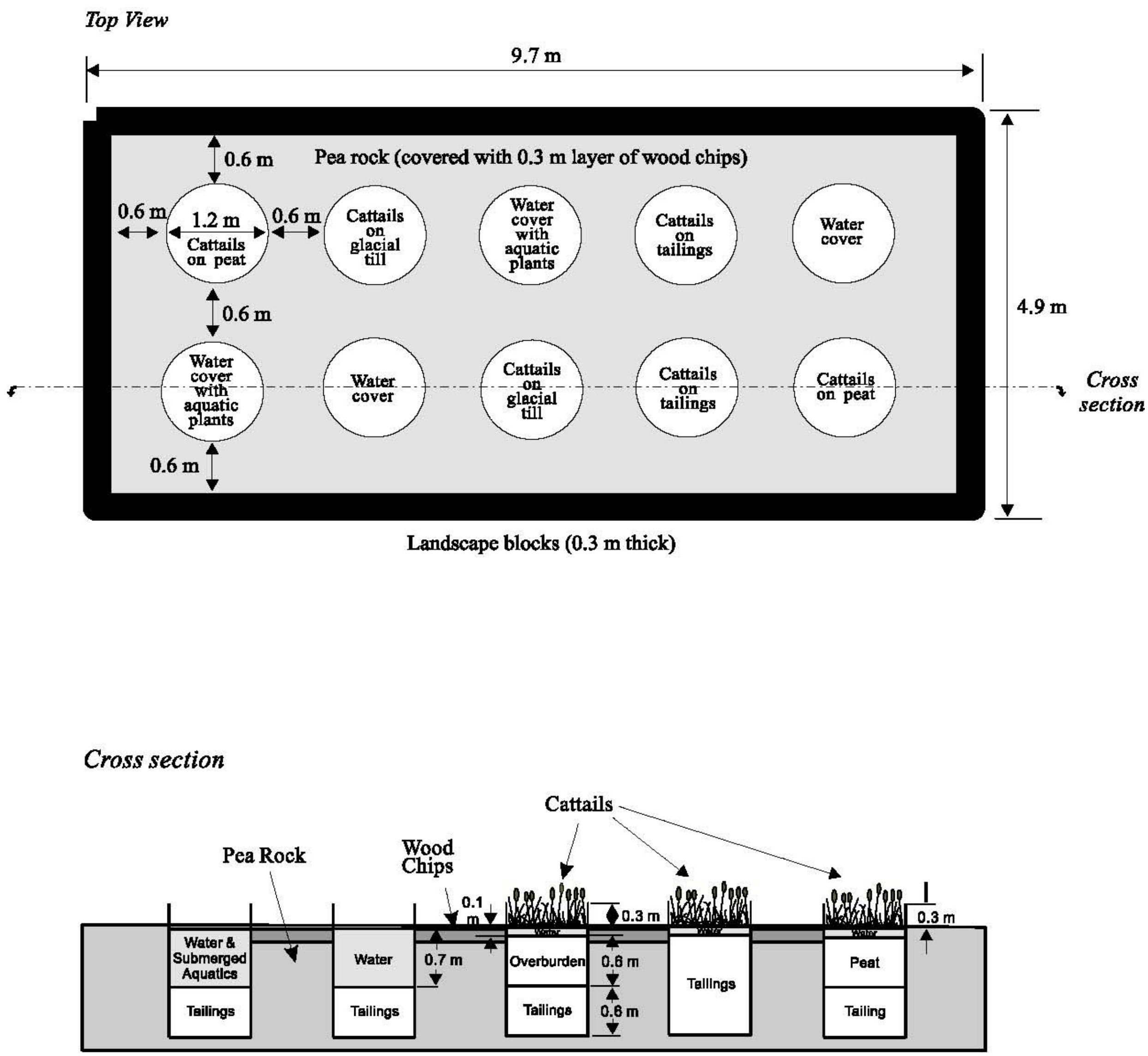

Figure 1. Experimental design, top view and cross section

On-land control tanks

Two cylindrical polyethylene tanks (d = 122 cm, h = 107 cm) were initially set up in duplicate as controls to simulate an unsaturated beach area. These tanks were equipped with a 1.27 cm half-slotted PVC well screen (0.3 mm slots) covered with a geotextile sock, placed at the bottom of the tank for sample collection. Two 3.8 cm thick layers (68 kg) of industrial silica sand were placed in the bottom of the tank to serve as a filter for the well screen. The lower sand layer had an effective filtration size of 0.25 mm (Unimin 4030) and the higher layer had an effective filtration size of 0.45 mm (Unimin 4075). These tanks are freely draining. Ninety-one cm of acid generating tailings were added to the tanks.

Water sampling

Sampling procedures

Water samples were collected about once per month from the surface water and the shallow and deep wells in the wetland tanks. A portable Masterflex (Model 7570-10) sampling pump, equipped with 6 mm ID Tygon tubing, was used to pump surface water and well water into a flow cell, where temperature, dissolved oxygen (DO), pH, and Eh readings were taken. Surface water samples were drawn from about 2.5 cm below the surface. Most of the metal samples collected from the surface and all of the subsurface samples were filtered in an onsite laboratory. Flow weighted composite samples were collected from the on-land controls which flowed sporadically based on precipitation.

Water analyses
A Beckman Eh/pH meter (Model 11) equipped with an Orion combination redox electrode (Model 9678BN) was used for Eh analysis, the same meter with a Ross combination pH electrode (Model 8165) was used for pH analysis and with a Beckman (Model 5981150) probe for temperature analysis, a Yellow Springs dissolved oxygen meter (Model 57) was used to measure dissolved oxygen. The samples were analyzed in the laboratory for specific conductance using a Myron L model EP conductivity meter. Alkalinity and acidity were measured using standard titration techniques (APHA et al., 1992). Sulfate and metals samples were filtered through a Gelman Supor 0.45 micron filter. Metals samples were preserved with 0.2 mL of Baker Instr-Analyzed nitric acid per 50 mL of sample.

Sulfate was analyzed at the Minnesota Department of Agriculture (MDA) laboratory using the Ion Chromatographic Method (Wastewater Method 4500-SO_4 B) with a Dionex DX300 IC in 1997 and 1998 but was changed to a Lachat QuickChem 8000 using the same method starting in 1999. Metals samples were analyzed at MDA using a Varian 400 SPECTRAA atomic absorption spectrophotometer in the flame mode or a Zeeman GFAA graphite furnace.

Statistics
Statistical analysis of treatment effect was performed on the treatments that were continued for the entire course of the experiment. ANOVA and Tukey *post-hoc* tests were performed using Systat version 13. All significant results are reported at $p \leq 0.05$.

Results
Results for this paper will focus primarily on long-term performance of the treatments. Data from the start up of the experiment are available in previous reports (Eger et al*, 2000*).

Water levels
Initially water levels were allowed to fluctuate naturally in response to precipitation and evapotranspiration. However, the summer of 1998 was unusually dry and, as a result, all the surface water in the tanks with substrate covers evaporated in July. Water levels continued to fall throughout July and August until there was no water in the shallow wells. Water balances were conducted on the treatments and showed that evapotranspiration was 92 percent of average lake evaporation in the tanks with water cover, 104 percent in the tanks with cattails planted directly on the tailings, 177 percent for the glacial till and 210 percent for the peat.

Starting in August and September of 1998, groundwater was added to three tanks; one of the tanks with peat (tank 6), one with glacial till (tank 8) and one with cattails planted directly on tailings (tank 7). The objective of the water additions was to minimize the amount of oxygen entering the underlying tailings. These additions continued throughout the course of the study, although in 2003, distilled water replaced groundwater as the replenishing solution. The distilled water was a better surrogate for natural precipitation than the previously used local groundwater.

Since evapotranspiration in the tanks with water covers was much less than that measured in the tanks with cattails, water levels decreased more slowly and then increased with above normal precipitation in 1999. As a result, water was periodically removed from these treatments in order to avoid overflow.

Water quality

Control tanks

The untreated tailings (control) produced extremely acidic and contaminated water. Over the thirteen years of the study, the drainage had an average pH of 2.88and around 33,500 mg/L sulfate (Table 1). Zn was the major cation in solution, with an average concentration of about 5440 mg/L. Cu concentration was also elevated with an average value of 137 mg/L.

Table 1. Drainage quality; average concentrations for untreated control compared to samples from the tailings layer in the wetland cells 1997-2009.

Tank	SC	pH	DO	SO_4	Cu	Zn	Ca	Mg
Control	21345	2.88	NA	33496	137	5439	415	2195
Water cover	3932	6.63	1.7	2384	0.019	0.024	505	216
Water cover and submerged aquatics	3853	6.75	1.3	2301	0.019	0.021	503	204
Cattails on peat	3958	6.48	1.3	2293	0.018	0.033	525	236
Cattails on tailings	4183	6.78	1.2	2540	0.019	0.019	485	250
Cattails on glacial till	3658	6.66	1.1	2282	0.017	0.028	505	209

Notes: Specific conductance reported in umhos/cm, pH in standard units and all other concentrations in mg/L.

Tailings layer (deep wells)

All the treatments had significantly less acid and metal release than the controls and there was little difference between treatments. The average pH ranged from 6.48 to 6.78, and the average sulfate concentration ranged from 2282 to 2540 mg/L. Average Zn concentrations were all less five orders of magnitude less than the controls and varied from 0.019 to 0.033 mg/L (Table 1).

Cover layer (shallow wells)

Water quality from the shallow wells varied between treatments, but in general the differences appeared related to the chemistry of the substrate rather than release from the underlying tailings (Table 2). The average pH was lowest in the naturally acidic peat (5.22)and averaged between 6.72 and 6.81 in the glacial till and the tailings (Table 2). The average Zn concentrations were highest in the peat (0.129 mg/L) and lowest in the glacial till (0.011).

Sulfate concentrations varied widely between treatments. Initially sulfate was <10 mg/L in the peat cover and <100 mg/L in the glacial till. Sulfate concentrations increased markedly in both the peat and till covers after the water level decreased in the summer of 1998 and allowed oxygen to enter the lower tailings layer. Sulfate increased from <10 mg/L in the peat tank to 150-300 mg/L, and in the glacial till tank from <100 mg/L to around 1900 mg/L. Concentrations slowly decreased in the glacial till tank but dropped much more rapidly in the peat tank when the water used to maintain water levels was switched from well water to distilled (Figure 2). Sulfate concentrations in the tailings cover increased from around 2100 mg/L at the start of the study to around 2700 mg/L after the water levels dropped in 1998. Concentrations slowly decreased to around 2000 at the end of 2009. ANOVA results showed that over the course of the entire experiment, floating vegetation, glacial till and peat cover treatments all reduced sulfate concentrations when compared to the water cover alone.

Table 2. Drainage quality; average concentrations for untreated control compared to samples from the cover layer in the wetland cells 1997-2009

Tank	SC	pH	DO	SO_4	Cu	Zn	Ca	Mg
Control	21345	2.88	NA	33496	137	5439	415	2195
Cattails on peat	432	5.22	0.8	112	0.026	0.129	28	20
Cattails on tailings	3719	6.81	1.3	2242	0.016	0.016	500	237
Cattails on glacial till	1977	6.72	1.6	700	0.015	0.011	353	121

Notes: Specific conductance reported in umhos/cm, pH in standard units and all other concentrations in mg/L.

Figure 11. Sulfate concentration vs. time in the substrate layer of the tanks with peat cover (tank 5,6), glacial till (tanks 4,8) and tailings cover (tanks 2,7) 1997 to 2009.

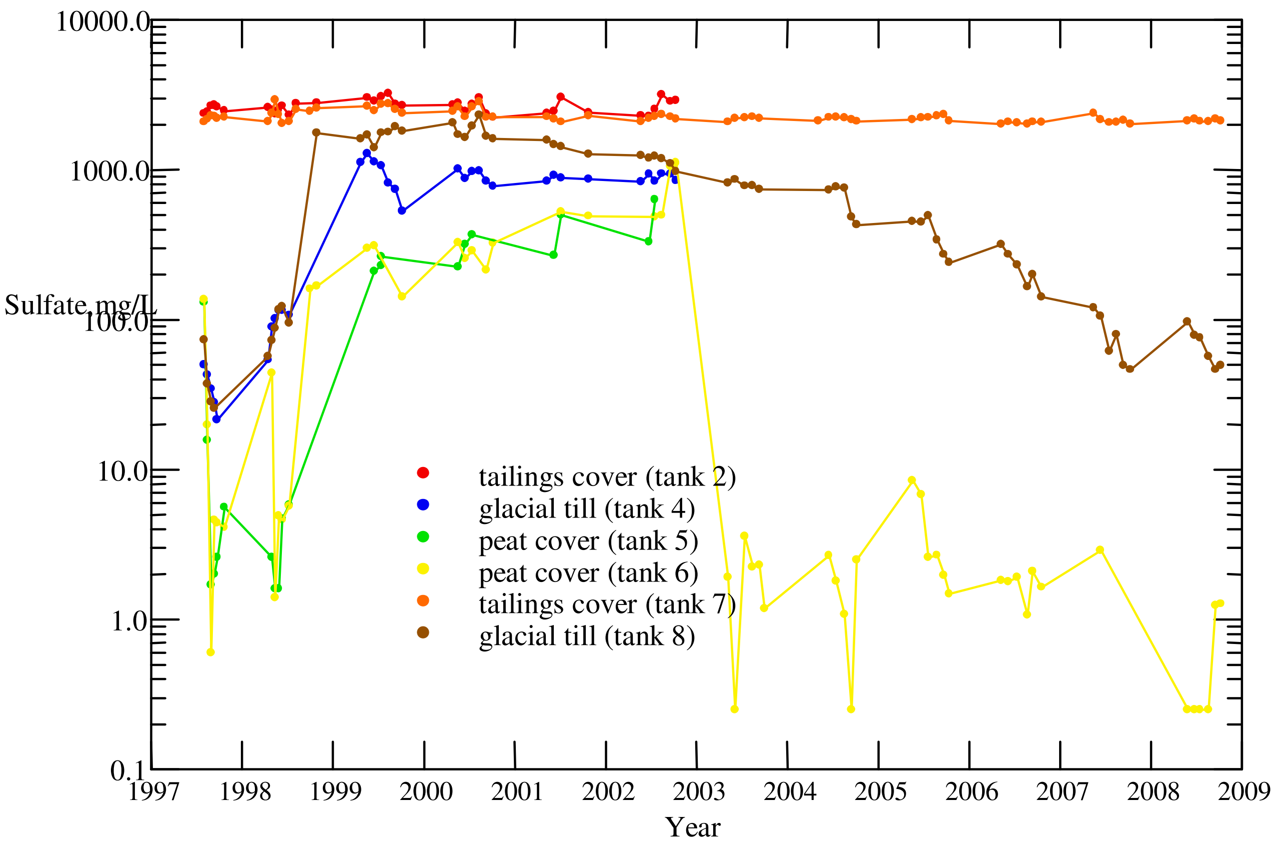

Figure 2. Sulfate concentration vs. time in the cover layer.

Surface water

Concentrations in surface water varied over time due to water level fluctuations, release from the substrate, and the effect of biological activity. All treatments had substantially higher pH, lower sulfate and lower Zn concentrations than the control. Average pH varied from 6.37 to 8.55, and sulfate varied from 24 to 428 mg/l (Table 3). Treatments that had tailings exposed directly to water (water cover and cattails on tailings) had the highest sulfate and Zn concentrations. Although the water cover with submerged aquatics also had tailings directly exposed, sulfate and Zn were much lower than the other 2 treatments. ANOVA results showed that pH was significantly higher in the floating vegetation treatment than any other treatment. Additionally, the floating vegetation and glacial till treatments had significantly lower Zn concentrations than the water cover.

Table 3.Drainage quality; average concentrations for untreated control compared to samples from the surface water in the wetland cells 1997-2009.

Tank	SC	pH	DO	SO_4	Cu	Zn	Ca	Mg
Control	21345	2.88	NA	33496	137	5439	415	2195
Water cover	652	6.82	7.1	302	0.016	0.098	100	21
Submerged aquatics	373	8.55	8.7	82	0.017	0.012	36	17
Cattails on peat	275	6.37	4.6	31	0.019	0.035	20	14
Cattails on tailings	911	6.95	7.0	428	0.021	0.429	182	34
Cattails on glacial till	331	7.31	7.3	24	0.018	0.010	37	16

Notes: Specific conductance reported in umhos/cm, pH in standard units and all other concentrations in mg/L

Sulfate mass release

The amount of sulfate released to the surface water was estimated for the treatments with water covers by multiplying the surface concentration in the fall by the volume of water. Based on specific conductance vs. depth profile data, the water column was stratified in the early spring but essentially well mixed by the fall. As a result, when the mass was calculated from the surface sample, there is a sinusoidal pattern in mass over time (Figure 3). Mass balances were calculated only for the tanks with water covers and were adjusted for the volume of water that had to be removed to prevent the tanks from overflowing. Analyzing the treatments with cover layers is much more complex since there is a significant flux of water and solutes into and out of the substrate as water levels fluctuate.

Sulfate release was substantially lower in the treatments with aquatic plants (Figure 3). From 1997 to 2009, the estimated mass release from the tailings with aquatic plants was about 115 grams or about 15% of the 700 grams that were released in the water cover.

Sulfate mass for the unsaturated control was calculated by multiplying the flow weighted concentration times the total volume of flow for the sampling period. Mass release from the control was about two orders of magnitude greater than the release in the tanks with water covers.

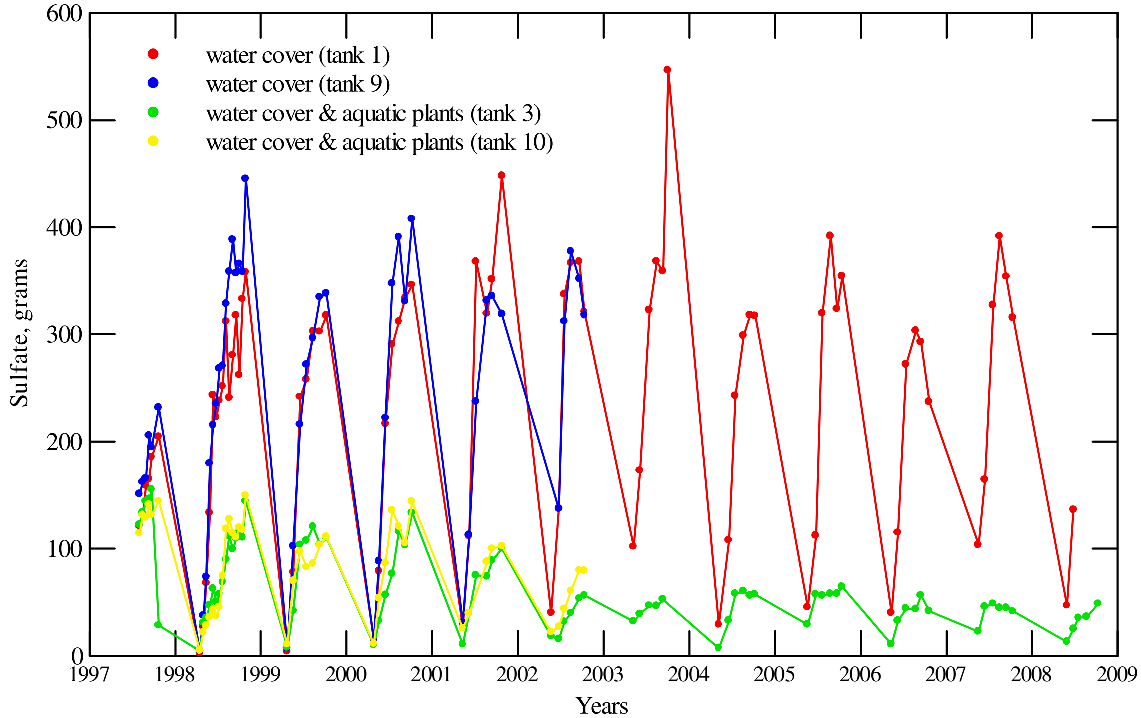

Figure 3. Mass of sulfate in surface water vs. time for water cover and water cover with aquatic plants.

Discussion

Disposal of acid generating materials below a water cover is one of the most effective methods for limiting sulfide oxidation. The effectiveness is the result of the low solubility of oxygen in water (~ 10 mg/l vs. 21% in air) and the much slower transport of oxygen to the sulfide surface. For example, the diffusive transfer of oxygen in water is on the order of 10,000 times slower than diffusive transfer in air (GARD, 2009). The effect of a water cover on reducing sulfide oxidation was evident in the results of this study as surface water in the treatments with water and/or soil covers met surface water quality criteria for pH, Zn and copper (Table 4). Despite limiting sulfide oxidation, there was some release of all constituents and metal concentrations were about an order of magnitude higher than natural background.

Table 4. Comparison of average concentrations in treatments with water and/or soil covers to Minnesota water quality standards and natural background

Treatment	pH	Cu	Zn
Water cover	6.82	0.016	0.098
Submerged aquatics	8.55	0.017	0.012
Cattails on peat	6.37	0.019	0.035
Cattails on glacial till	7.31	0.018	0.010
Water Quality Standards	6.5-8.5	0.023	0.343
Natural Background	6.5-7.5	0.001	0.001

Notes: pH in standard units and metal concentrations in mg/L. Minnesota standards are from MN Rules Chapter 7050, and are for the protection of cool and warm water fisheries. Metal limits are calculated at a hardness of 400 mg/l as $CaCO_3$. Natural background concentrations are typical values for unimpacted streams in northeastern Minnesota (Thingvold et al 1979).

The presence of aquatic plants substantially decreased the release of sulfate and metals. Long term sulfate release was about 15% of the release in the water cover alone and is probably due to the build-up of organic material on the surface of the tailings. Over the long term, the aquatic macrophytes were replaced by filamentous algae which were probably the result of excess fertilizer added during start-up. A visible mat of organic matter could be seen covering the tailings and dissolved oxygen was substantially lower at the interface, dropping to around 1 mg/l during the summer. Oxygen was consumed as the plant material decayed and, as a result, the rate of oxygen transport to the tailings decreased.

Similar results were observed by St. Germain and Kuyucak (1997). The introduction of submerged aquatic plants into the water cover produced an oxygen consuming layer above the tailings. The plants supplied organic matter to cover the tailings and created a biologically active layer where not only was oxygen consumed, but sulfate was reduced to sulfide. The sulfide can react with metal ions present in the water to form insoluble metal sulfides, which are stable under anaerobic conditions (Kuyucak et al., 1991).

Wetland vegetation will provide organic material to the surface of the substrate, as well as sequestering metals in biomass. By establishing vegetation directly on the tailings, a layer of organic material should eventually accumulate and restrict oxygen transport to the tailings. Emergent wetland macrophytes generally concentrate metals in the roots and rhizomes, and metals bioaccumulated within floating vegetation will likely remain in the treatment system via senescence (Jackson 1998).The treatments in which cattails were planted directly on the tailings were not successful in maintaining acceptable water quality. Vegetation appeared stressed (yellow, stunted) and produced much less biomass than the plots with either peat or glacial till soil covers. When the surface dried, the tailings oxidized and acidified the surface water when the water level increased. In a wetland that naturally developed on a tailings spill, oxidation of the tailings also occurred in the areas with vegetation, although due to the fine grain size and high degree of saturation, the overall rate was low (Davé 1994). When water was supplied to maintain the water level above the tailings, pH could be maintained, and Zn concentrations decreased. Supplementing the tailings with organic matter and limestone would have been beneficial in maintaining pH and improving vegetation. Biosolids additions have been successful in improving vegetation in various tailings applications (Svendson et al, 2007, Bengson, 2000)

Covering the tailings with a substrate such as glacial till or peat should not only provide a better growth medium for vegetation, but also should reduce oxygen transport to the underlying tailings. In natural wetlands, when the soil is saturated, anoxic conditions typically develop within several cm of the surface. The organic soil layer is instrumental in reducing sulfide oxidation by contributing to the formation of metal sulfides through lowered redox potential and providing a carbon source for sulfur reducing bacteria (Goulet and Pick 2001, O'Sullivan et al. 2004).A cover of 61 cm of substrate should have been sufficient to maintain saturation above the tailings since typical water level fluctuations in precipitation-dependent wetlands in northern Minnesota are on the order of 30 cm (Boelter and Verry, 1977, Melchert et al., 1997).

The dramatic decrease in water levels in the tanks with glacial till and peat in this experiment was not expected, and would not be expected to occur in an actual tailings basin with a substantial amount of open water. Kadlec and Knight (1996) concluded that evapotranspiration in wetlands characterized by nonwoody emergent vascular plants is about equal to lake evaporation. In northeastern Minnesota, annual lake evaporation is around 56 cm, and in normal years precipitation exceeds lake evaporation by about 22 cm (USDA-SCS, 1975). The tanks in this study are lined and have no interaction with runoff or groundwater, and are a model for any future lined tailings basins in Minnesota. Water levels depend solely on precipitation and evapotranspiration, and should eventually overflow due to the excess precipitation.

Water levels in all the tanks with water covers increased over the course of the study, and starting in 1999 water was periodically removed to prevent overflow.

In a large tailings pond, water from the open water area would supply water to the cattails growing along the shore and prevent water levels from dropping substantially. In normal years, water levels in the open water portion of the basin would increase and replenish water lost in the wetland portion of the basin.

Given the large water level fluctuations in the peat and till tanks, water was periodically added to maintain a saturated barrier above the tailings layer. By maintaining the water level, sulfate and Zn concentrations were similar to the water used to replenish the tanks and decreased when the replacement water was switched to distilled water in 2003(Prior to 2003, well water was used to maintain water levels and simulated water from the interior of a tailings pond. The distilled water was a better analogue for precipitation input).

The effect of a prolonged drop in water levels was observed in the duplicate tanks prior to 2003. Tank 6 supplemented water to maintain water above the tailings while no water was added to Tank 5.When the water dropped below the top of the tailings in one of the peat treatments, oxygen was introduced and additional oxidation occurred. When the water level was allowed to remain below the top of the tailings, oxidation increased and sulfate concentration increased by more than a factor of two, from around 3100 mg/L to about 7700 mg/L (Figure4).

Figure 9. Sulfate concentration vs. time in the tailings layer of the tanks with peat cover (tanks 5,6), 1997 to 2009. Due to dry conditions, water was periodically added to tank 6, see table A6.4.

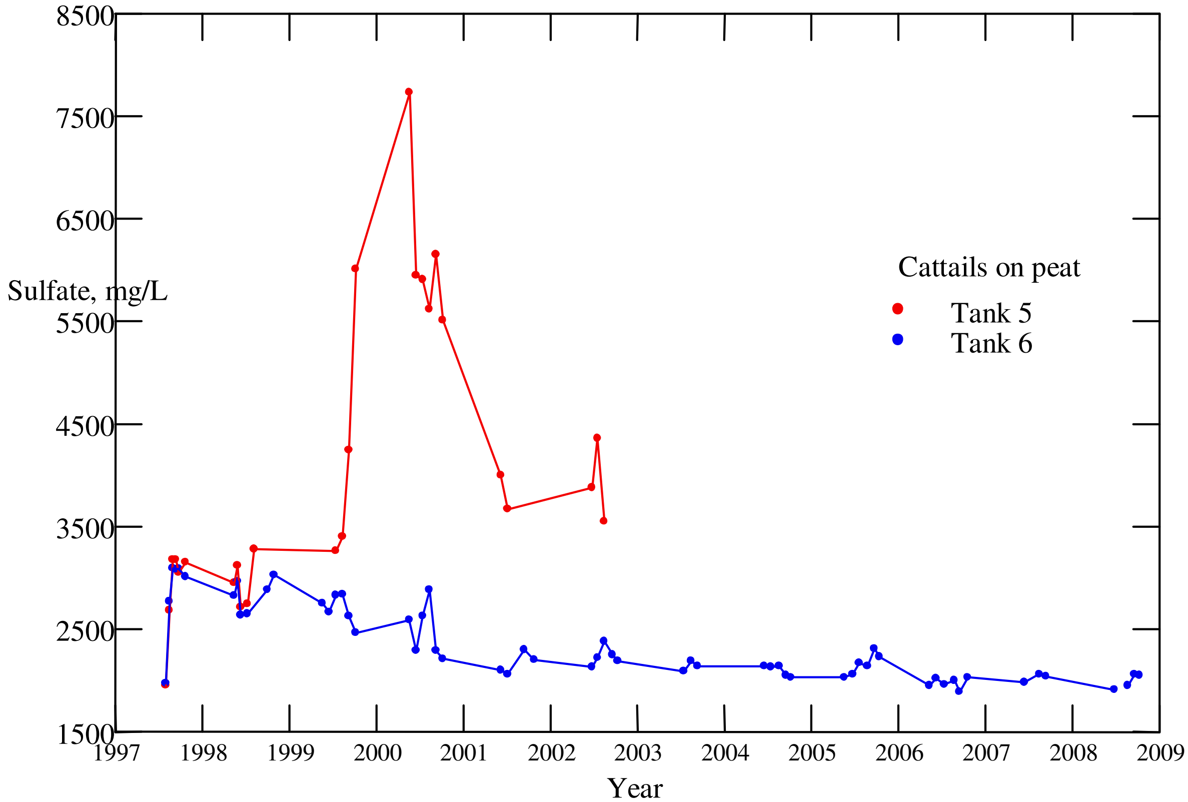

Figure 4.Sulfate in tailings, peat cover.

Conclusions

Permanent water covers, either as open water ponds or wetlands were successful in maintaining a circumneutral pH, and minimizing sulfate and metal release. Surface water quality met water quality guidelines but was above natural background as some low level release still occurred. For successful treatment, the water level must be maintained above the reactive tailings to minimize oxygen transport and subsequent sulfide oxidation. Aquatic plants should be included in the water cover not only for ecological diversity, but also because their presence decreased release from the tailings. The long term nature of this study (12 years) indicates that as long as water levels are maintained, this approach is a successful long term strategy for the management of acid generating tailings.

References

Aubé, B. C., St-Arnaud, L. C., Payant, S. C., and Yanful, E. K. 1995. Laboratory evaluation of the effectiveness of water covers for preventing acid generation from pyritic rock. In *Proceedings of the Sudbury 95, Conference on Mining and the Environment* May 28-June 1, Sudbury, Ontario, Canada.

Aubertin, M., Dionne, J., and Marches, L. 1997. Design guidelines and stability criteria of engineering works for water covers. In *Proceedings of the Fourth International Conference on Acid Rock Drainage*, May 31-June 6, 1997, Vancouver, British Columbia, Canada. p. 1849-1866.

Boelter, D. H., and Verry, E. S. 1977. Peatland and water in the northern lake states. USDA Forest Service Gen. Tech. Rep. NC-31. 22 p.

Bedford, B.LL., Bouldin, D.R. and Beliveau, B.D. (1991) Net oxygen and carbon-dioxide solutions bathing roots of wetland plants. The Journal of Ecology, Vol. 79, pp. 943-959.

Bengson, S.A. (2000) Reclamation of copper tailings in Arizona using biosolids. Paper presented at the Mining, Forest and Land Restoration Symposium and Workshop, Golden, CO, July 17-19, 2000.

Boyd, C.E. (1970) Production, mineral accumulation and pigment concentration in typha latifolia and Scirpus americanus. Ecology, Vol. 51, pp. 285-290.

Cardwell, A.J., Hawker, D.W. and Greenway, M. (2002) Metal accumulation in aquatic macrophytes from southeast Queensland, Australia. Chemosphere, Vol. 48, pp. 653-663.

Collins, B.S., Sharitz, R.R. and Coughlin, D.P. (2005) Elemental composition of native wetland plants in constructed mesocosm treatment wetlands. Bioresource Technology, Vol. 96, pp. 937-948.

Davé, N.K., and Vivyorka, A.J. 1994. Water cover on acid generating uranium tailings - laboratory and field studies. In Proceedings of International Land Reclamation and Mine Drainage Conference/Third International Conference on the Abatement of Acid Drainage, April 25-29, Pittsburgh, PA. p. 297-306.

Eger, P., Lapakko, K., and Chamberlain, P. 1984. Mixed disposal of waste rock and tailings to reduce trace metal release from waste rock. Presented at *1984 Symposium on Surface Mining, Hydrology Sedimentology, and Reclamation*, University of Kentucky, Lexington, Kentucky. p. 49-55.

Eger, P., Antonson, D., Folman, J., Wagner, J., Melchert, G. 2000. Creating wetlands on acid-generating tailings: maintenance free reclamation? In: Proc. Fourth International Conference on Acid Rock Drainage, Denver, CO, May 22-24, p.1149-1158

Feasby, D. G., Tremblay, G. A., and Weatherell, C. A 1997. Decade of technology improvement to the challenge of acid drainage - a Canadian perspective. In *Proceedings of the Fourth International Conference on Acid Rock Drainage*, May 31-June 6, Vancouver, British Columbia, Canada.

Goulet, R.R. and Pick, F.R. (2001) The effects of cattails (*Typha latifolia* L.) on concentrations and partitioning of metals in surficial sediments of surface-flow constructed wetlands. Water, Air, and Soil Pollution, Vol. 132, pp. 275-291

Jackson, L.J. (1998) Paradigms of metal accumulation in rooted aquatic vascular plants. The Science of the Total Environment, Vol. 219, pp. 223-231.

Kadlec, R. H., and Knight, R. L. 1996. *Treatment Wetlands*. Lewis Publishers, New York. 893p.

Kuyucak, N., Lyew, D., St-Germain, P., and Wheeland, K.G. 1991. In situ bacterial treatment of AMD in open pits. In *Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage*, *Volume 1,* September 16-18, Montreal, Quebec, Canada. p. 335-355.

Lapakko, K., and Eger, P. 1981. Trace metal removal from mining stockpile runoff using peat, wood chips, tailings, till and zeolite. In *Proceedings of the 1981 Symposium on Surface Mining Hydrology, Sedimentology and Reclamation,* Lexington, KY. p 105-114.

Manios, T., Stentiford, E.I. and Millner, P. (2003) Removal of heavy metals from a metaliferous water solution by *Typha latifolia* plants and sewage sludge compost. Chemosphere, Vol. 53, pp. 487-494.

McNaughton, S.J., Folsom, T.C., Lee, T., Park, F., Price, C., Roeder, D., Schmitz, J. and Stockwell, C. (1974) Heavy metal tolerance in Typha latifolia without the evolution of tolerant races. Ecology, Vol. 55, pp. 1163-1165.

Melchert, G., Berglund, E., Lapakko, K. A. 1997. Baseline water quality assessment of the Pine Island peatland, Koochiching County, MN DNR. p. 42.

Melchert, G., Eger, P., Kassa, Z., and Dewar, S. 1994. Reclaiming coarse taconite tailings with municipal solid waste compost. International Land Reclamation and Mine Drainage Conference/Third International Conference on the Abatement of Acidic Drainage, April 25-19, Pittsburgh, PA. p. 175-183.

St-Germain, P., and Kuyucak, N. 1997. Biologically supported water covers - a laboratory assessment. In Mineral Processing and Extractive Metallurgy Review. Special Issue on the 3rd International Conference on Minerals Bioprocessing, Biorecovery/Remediation in Mining, August 25-30, 1996, Big Sky, MT.

O'Sullivan, A.D., Moran, B.M. and Otte, M.L. (2004) Accumulation and fate of contaminants (Zn, Pb, Fe and S) in substrates of wetlands constructed for treating mine wastewater. Water, Air, and Soil Pollution, Vol. 157, pp. 345-364.

Stolz, E. and Greger, M. (2005) Effects of different wetland plant species on fresh unweathered sulphidic mine tailings. Plant and Soil, Vol. 276, pp. 251-261.

Svendson, A., Henry, C., Brown, S (2007) Revegetation of High Zinc and Lead Tailings with Municipal Biosolids and Lime: Greenhouse Study, J. Environ. Qual. 36:1609–1617

Swanson, D. A., Barbour, S. L., and Wilson, G. L. 1997. Dry-site vs. wet-site cover design. In *Proceedings of the Fourth International Conference on Acid Rock Drainage*, May 31-June 6, Vancouver, British Columbia, Canada. p. 115-130.

Thingvold, D., Eger, P., Hewett, M. J., Honetschlager, B., Lapakko, K., Mustalish, R. 1979. Water resources. In Minnesota Environmental Quality Board Regional Copper-Nickel Study 3 (4): 217 p

USDA-SCS. 1975. Hydrology Guide for Minnesota. Chapter 8. p. 8.1 - 8.16.

Wilson, G. W., Newman, L., Barbour, S. L., O=Kane, M., and Swanson, D. A. 1997. The cover research program at Equity Silver Mine Ltd. In *Proceedings of the Fourth International Conference on Acid Rock Drainage*, May 31-June 6, Vancouver, British Columbia, Canada. p. 197-210.

Ye, Z.H., Baker, A.J.M, Wong, M.H. and Willis, A.J. (1997) Zinc, lead and cadmium tolerance, uptake and accumulation in Typha latifolia. New Phytologist, Vol. 136, pp. 469-480.

Ye, Z.H., Whiting, S.N., Qian, J.H., Lytle, C.M., Lin, Z.-Q and Terry, N. (2001) Trace element removal from coal ash leachate by a 10-year-old constructed wetland. Journal of Environmental Quality, Vol. 30, pp. 1710-1719.