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Wetlands for the Treatment of Mine Drainage

There is considerable interest in the problem of contaminated mine drainage - and acid mine drainage specifically - within the mining and environmentalist communities. This web site gives examples of wetlands cleaning up contaminated mine water, describes how they do it, and discusses environmental consequences of this. The information is presented in several sections, all of which are initially linked to this page.

This site is designed and maintained by Dr. **André Sobolewski**. My qualifications to talk about wetlands are presented here. I would sincerely appreciate receiving your thoughts and comments, as well as your contributions. Feel free to write me a note.

Introduction

The largest single environmental problem facing the mining industry is Acid Mine Drainage. More information on this topic is found on this excellent web site.

Two key features of AMD should be understood to appreciate why:

1. Rainwater flowing over unearthed sulphide minerals may become acidic. When water becomes acidic, it dissolves toxic metals.
2. As yet, we cannot predict whether or not water will become acidic, when acid-generation will start, nor whether it will continue for months or decades.

Thus, AMD may be a liability for mines long after they cease to operate. The environmental impact it causes can be severe. In my own backyard, British Columbia, Canada, the former Mt. Washington copper mine has been releasing an acidic, copper-contaminated discharge into the Tsolum River for over 20 years. The Tsolum used to be a very large salmon-bearing rivers on Vancouver Island, but salmon no longer spawn there. Copper released from the site is primarily responsible for this (Deniseger and Pommen, 1995). Salmon will not return to the river as long as the AMD remains untreated.

Wetlands have the ability to remove metals from mine drainage and to neutralize AMD. Since wetlands are self-sustaining ecosystems, they may be able to remediate contaminated mine drainage as long as it is generated. Thus, they may represent a long-term solution to AMD, and to contaminated mine drainage in general.

There isn't a single "shining example" which demonstrates that wetlands uniformly ameliorate degraded mine drainage. On the contrary, there are small examples from many sources generally supporting this idea. This includes the experience accrued over the past 15 years using wetlands to treat AMD from abandoned coal mines in the Eastern United States. There are also sobering examples of failed designs of wetland treatment systems. I will present as much of this information as possible. To facilitate its presentation, I have divided the information into separate topic areas, as follows:

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- **Are We Creating Toxic Wetlands?**
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Knowledge from Exploration Geochemistry

Exploration geologists have long known that "swamps and bogs" (to use their parlance) are natural sinks for metals. Many copper bogs were mined in late Neolithic Europe for copper (Brooks *et al.*, 1995). This section reviews some of that (apparently forgotten) knowledge and will examine well-documented cases of wetlands retaining metals in highly mineralized areas.

Reports of wetland retention of metals by exploration geologists

Exploration geologists have known for many years that metals, most commonly copper, iron, manganese, uranium, and zinc, frequently accumulate in swamps and bogs located in mineralized areas (Levinson, 1980; Brooks *et al.*, 1995). I've spoken to a few old-timers, such as Lew Green and Bob Boyle [retired geologists with the Canadian Geological Survey], who told me that they would regularly come upon bogs high in arsenic, copper, pyrite, or uranium.

Some of these sites have been investigated, and the results have been published in the literature or as theses (e.g., Cannon, 1955; Horsnail *et al.*, 1969; Lett, 1978). I will discuss two examples of such reports on this page.

Case Study 1 - The Tantamar cupriferous bogs Two small cupriferous bogs have been reported in the Sackville area of New Brunswick, Canada (See map here). The northern bog was first noticed in 1898 by the farmer who owned the land, when vegetation failed to re-establish itself after a forest fire. Its high copper content was discovered when the farmer applied sediments to fertilize his cucumber patch: the black muck proved lethal!

This 2.5 acres (1 hectare) wetland was staked out in 1950, and though it is estimated to contain 300 tons of copper (Fraser, 1961), an economic method to recover the copper has not been found to date. The wetland sediments contain 3 to 6% copper (dry weight). Fraser reports that the wetland is largely devoid of vegetation, except for mosses growing by seepages of water. The moss *Pohlia nutans* dominates areas of high copper concentrations, with liverworts growing in areas where copper falls to 0.1-1%. The moss reportedly contains up to **12% copper** (this is not a typo!) (Boyle, 1977).

The other wetland is much less well studied. It was only found in the late 1950's through a copper anomaly in sediments of a creek draining its southerly end (Smith, 1960).

Fraser (op. cit.) indicates that the pH in sediments of the northern wetland varies from 5.5 to 8.1, depending on the time of sampling. This is unlike native copper bogs, which are normally acidic (pH 4 to 6). The Eh in the wetland sediments varies from 0.08 to 0.23.

Copper enters the wetland through the bottom, emerging as distinct seeps containing 0.005 to 1.0 mg/L. Its source appears to be copper mineralization associated with the Boss Point Formation (Boyle, 1977). The copper is retained in wetland sediments soon after the seepage emerges. Fraser (1961b) demonstrated that it is attenuated predominantly through association with organic matter, which in the wetland sediments reaches 10-20% (Boyle, 1977).

Fraser determined that accumulating 300 tons of copper in the wetland would require approximately 4,000 years. He notes that the wetland can't be older than that, because sea water retreated from the area 4,000 years ago. Therefore, he concludes that this wetland has been removing copper from solution since the time it was formed.

This example shows that wetlands have an extraordinary capacity to accumulate copper. In this wetland, the copper is retained by forming extremely stable complexes with organic matter (prolonged acid attack or boiling in aqua regia for three hours does not remove all the copper). Its most remarkable aspect is that it has apparently been accumulating copper for 4,000 years, longer than any mine abandonment plan I've seen!

Case Study 2 - The Uraniferous Bogs in the Western United States

Uranium has a strong affinity toward organic matter (Szalay, 1964), suggesting that it should easily be retained in the organic-rich sediments of wetlands. Another process in wetland sediments, the microbial reduction of uranyl ions [U(VI)] to the less mobile U(IV) (Lovley *et al.*, 1991), may also be important for its retention. Given this, it would be expected that uranium should be commonly retained by wetlands. Indeed, uraniferous "bogs" are reported from Scandinavia, Canada, the former Soviet Union, and the western United States Zielinski *et al.* 1987).

Beginning in 1982, the U.S. Geological Survey conducted reconnaissance work in mountain wetlands located in the Western United States to determine whether they accumulate uranium (Owen and Otton, 1995). Among other things, it was found that of the 145 wetlands investigated in the Front Range of Colorado, approximately half were enriched to some degree for uranium, with 15% being highly enriched (100-1,000 ppm U, dry weight) and 1% being very highly enriched (over 1,000 ppm U, dry weight). Based on this work, several wetlands were investigated to understand in detail their underlying geology and geochemistry.

The north fork of Flodelle Creek, in northeastern Washington, U.S.A., harbours uraniferous wetlands which were investigated. The creek is fed by water draining a highland area underlain by uraniferous granite (See map here).

Wetlands on the Flodelle occupy two areas. In the upper part of the creek, a five to thirty (5-30) metre wide valley floor supports wetlands. They are fed by seeps and spring highly enriched in uranium (50-318 ppb; Zielinski *et al.* 1987). Uranium accumulates in their organic-rich sediments, reaching up to 8,960 ppm (average 1,243 ppm in one stratigraphic unit; Johnson *et al.* 1987).

Other wetlands in the broader, central part of the drainage basin were formed after beavers occupied the valley 5,000 years ago. Organic-rich sediments accumulated behind the dams they built, eventually giving rise to the wetlands. The wetlands occupied nearly 4 acres when investigated in 1984, and they contained on average 300 ppm uranium (they were stripped mined at the time of the investigation, which may have skewed downward their average uranium content).

Leach tests were conducted to determine how strongly the uranium is retained in wetland sediment. These tests revealed that uranium will be retained under normal environmental conditions. It's release required leaching with sulfuric acid or with a concentrated bicarbonate solution (Zielinski and Meier, 1988). The latter information supports the idea that wetlands could be used to remove uranium from contaminated mine drainage. Indeed, there are examples of both natural and constructed wetlands used for this purpose (e.g., Cluff lake, described in Table 1 below, and ERA Ranger Mine (Shinners, 1996).

To me, these case studies indicate that processes exist in nature which can be used to help solve current environmental problems. With good science, such as the body of work described above, natural treatment systems can be designed rationally and predictably. The challenge for us is to put all these pieces together.

Attenuation of Contaminated Mine Drainage by Natural Wetlands

The evidence that natural wetlands can improve the quality of mine drainage is dispersed and largely unpublished. The case for wetland treatment systems becomes more compelling when this evidence is assembled, as I have done here. Two case studies of operating mines are also presented.

Mining operations often introduce or redirect the flow of water in their immediate vicinity. Occasionally, these discharges flow into existing natural wetlands, or into creeks where wetlands develop in flat reaches or depressions. In a surprising number of instances, these wetlands improve the quality of the mine water.

Insofar as I know, Bob Boyle was the first to report on this property of wetlands. In **1965**, he wrote:

> "Streams and springs that dissipate their water into bogs have their zinc (as well as other metals) largely removed. Initially this zinc is loosely bound (but) with aging, the zinc partakes of the organic colloidal complexes and is then (...) unavailable to most extractants. Numerous bogs that extract the zinc from surface waters were observed in the Keno Hill area. One of these into which the mine water from the Hector-Calumet mine flows, effectively removes all of the zinc (40 ppm) in less than 2,000 feet."

GSC Bulletin 111. 1965. Geology, Geochemistry, and Origin of the Lead-Zinc-Silver Deposits of the Keno Hill-Galena Hill area, Yukon Territory, by R.W. Boyle.

Two examples of natural wetlands treating mine drainage are provided. These wetlands receive fairly large discharges from currently operating mines. The first is associated with the Woodcutters Mine, which is located in Northern Territory, Australia. The second is associated with the Birchtree Mine, in Thompson, Manitoba, Canada.

You'll note that these are tropical and northern boreal mines, respectively. The number of natural wetlands which have been documented to ameliorate mine drainage is quite lengthy, covers many climactic regions, and is growing. Table 1 below summarizes the information I have on hand. Additional contributions would be greatly appreciated. Simply write me a note.

Table 1. Documented Cases of Natural Wetlands Ameliorating Mine Drainage

Mine	Location	AMD	Contaminants	Reference

			removed	
United Keno Hill Mines	Yukon Territory, Canada	No	Zn	Boyle, 1965
Unnamed coal mine	West Virginia, USA	Yes	Fe, Mn	Wieder and Lang, 1982
Mt. Washington	British Columbia, Canada	Yes	As, Cu, Zn (Limited)	Erickson and Deniseger, 1987 Kwong and Van Stempvoort, 1994
Carbonate Mountain	Montana, USA	Yes	Al, Fe, Pb	Dollhopf *et al.*, 1988
Dunka Mine	Minnesota, USA	No	Cu, Ni	Eger and Lapakko, 1988
Star Lake, Jolu Mines	Saskatchewan, Canada	No	Cu, cyanide	Gormely, 1990
Natural wetlands at 35 coal mines	Pennsylvania, USA	Yes	Al, Fe, Mn	Stark, 1990
Unnamed coal mine	Pennsylvania, USA	Yes	Fe, Mn	Tarutis *et al.*, 1992
Con Mine	Northwest Territories, Canada	No	As, Cu, cyanide	Ball, 1993
Quirke Mine	Ontario, Canada	No	Fe, Ra-226	Davé, 1993
Ranger Mine	Jabiru, Australia	No	U	Noller *et al.*, 1994 Woods and Noller, 1995
Tom's Gully Mine	100 km S.E. of Darwin, Australia	No	As, Cu, Co, Fe, Mn, Ni, Pb, U, Zn	Noller *et al.*, 1994 Woods and Noller, 1995
Hilton Mine	Mt Isa, Queensland, Australia	No	Fe, Mn, Tl, Zn	Jones and Chapman, 1995
Woodcutters Mine	80 km south of Darwin, Australia	No	Cd, Mn, Pb, U, Zn	Noller *et al.*, 1994 Woods and Noller, 1995
United Keno Hill Mines	Yukon Territory, Canada	No	Zn	Sobolewski, 1995 See also this page
Birchtree Mine	Manitoba, Canada	No	Ni	Hambley, 1996
St. Kevin Gulch	Colorado, USA	Yes	Fe yes, Zn no	Walton-Day, In Press
Cluff Lake McLean Lake	Saskatchewan, Canada	No	U	Len Sinclair, Saskatchewan Pollution Control, Prince Albert, SK. Personal Communication
Silver Queen	British Columbia, Canada	No	Zn	T.W. Higgs, H.A. Simons, Vancouver, B.C. Unpublished Observation

Note: the wetlands listed above ameliorate mine drainage to varying degrees. Some, such as the wetlands at Mount Washington or St. Kevin Gulch, do not improve the mine discharge to an acceptable degree. Others, like the wetlands at Star Lake or Birchtree Mine, are (were) actually used for treatment, and remove all the contaminants of concern.

In the course of my field work in the Keno Hill area, I was able to investigate a number of wetlands naturally remediating contaminated mine drainage. Two simple cases are presented. A tiny wetland was found which neutralizes a highly acidic seep. This wetland is quite remarkable, as it neutralizes mine water from a pH 1.1 to 6.6, all within a distance of 10 feet!

Another small natural wetland removed zinc and other metals from contaminated mine drainage. Despite elevated metal concentrations in the wetland sediments, there was no metal uptake by plants.

Constructed wetlands for treatment of mine drainage

There are two fundamentally different types of constructed wetlands: those dealing with coal-generated mine drainage, and those dealing with drainage from metal mines. We know a great deal more about the former than the latter. Therefore, I will deal separately with systems treating mine drainage from coal mines and metal mines. Only general information on constructed wetlands will be here.

Features common to every wetland treatment system can be seen in the system (for a moderately small site) shown below. The photograph, looking downward from the top of a slope, shows a series of wetlands treating the acidic discharge from an abandoned underground coal mine. The wetlands are visible as dark green patches on the lighter-coloured grassy slope. The mine water is gravity-fed from an adit near the top of the hill, and the treated water is discharged at a site near the car stationed to the right of the house.

Note the following features of this system. The wetlands are *integrated* within the landscape: looking at them, you wouldn't know they're acting as treatment systems for mine drainage. Several wetlands are used for treatment, rather than a single one. This is due to restrictions imposed by the landscape and the need to achieve a specified surface area for treatment. Furthermore, their elongated shape maximizes contact between the water and the wetland surface.

Surprisingly, plants do not remove metals to a significant degree. However, iron plaques forming on plant roots will retain arsenic and other metals (Otte *et al.*, 1995). Metal adsorption onto detritus is also important. Chemical reactions (hydrolysis) and biologically-driven reactions (formation of insoluble sulphides and carbonates) primarily account for the removal of metals and their retention in sediments. Neutralization of acidic water within wetlands results from biological production of bicarbonate. The only maintenance these otherwise "passive treatment systems" may require is the periodic removal of precipitates accumulating in sedimentation ponds.

The challenge in designing a wetland treatment system is to assemble several elements (such as anoxic limestone drains, ponds, and wetlands) and size them properly to produce biogeochemical processes which treat the mine drainage to the desired water quality on a consistent basis. The following pages will describe systems designed to treat drainage from coal mines and metal mines.

Are We Creating Toxic Wetlands?

Although wetlands may naturally accumulate metals, are we creating highly polluted environments by developing wetland treatment systems? This is an important question to consider and resolve. The (limited) information available on this topic will be reviewed in this section.

Simply diverting contaminated mine water to a wetland may do more harm than good. For instance, Kalin and co-workers (1991) reported that acidic bogs in Nova Scotia, Canada, receiving AMD were severely injured, despite their alleged tolerance of acidic water. Similarly, Carlson and Carlson (1994) documented the severe impact of coal pile leachate (very similar to AMD) on a forested wetland. Interestingly, their analysis indicated that low pH and high salinity were primarily responsible for plant dieback, whereas high aluminum and manganese concentrations in the leachate played a less important role. However, other natural wetlands receiving contaminated mine water have been unimpacted by it (Dollhopf *et al.*, 1988; Hambley, 1996). So the issue is not a simple one.

Assuming that a wetland treatment system has been properly designed, what evidence is there that it lessens the overall impact on the environment?

Since treatment wetlands receive contaminated mine drainage, it would be expected that animals living in them will be adversely impacted. Remarkably, this doesn't usually appear to be the case. Albers and Camardese (1993) demonstrated that, in a constructed wetland treating AMD, metal concentrations in wetland invertebrates were independent of water chemistry (metal concentrations or pH), even when the water pH was artificially acidified. Pascoe and co-workers (1994) found that neither plants nor small mammals living in a wetland overlying mining waste (tailings) accumulated toxic elements (As, Cd, Cu, Pb, and Zn). Lacki and co-workers (1992) found that wetlands treating mine drainage provided valuable habitat to reptiles and amphibians, without any deleterious impact on their populations. On the other hand, a report indicated that the caddisfly *Limnephilus indivisus* experienced greater mortality in a wetland impacted by AMD from a strip mine (Usis and Foote, 1991). Another report suggested that crabs in a freshwater wetland bioaccumulated metals, but the metal sources included mine, industrial and municipal wastewater, confounding the significance of these data (van Eeden and Schoonbee, 1991).

Metals uptake by wetland plants is one potential point of entry into the food chain. In the Carbonate Mountain study (Dollhopf *et al.*, 1988), aluminum, arsenic, cadmium, copper, iron, lead, manganese, nickel, and zinc concentration in the sedge *Carex rostrata* fell within the ranges reported by Hutchinson, 1975. However, lead in plant leaves was reported to exceed these concentrations.

In my investigations, I found that, typically, wetland plants do not take up metals which are accumulated in sediments. For example, the table below (Table 2) compares metal concentrations in two natural wetlands receiving metal-contaminated water.

Table 2. Metal concentrations (mg/dry kg) in sediments and plant tissues of wetland receiving metal-contaminated or uncontaminated water.

	S. McQuesten wetland	No Cash wetland	Galkeno wetland	Non-impacted sites
Metal	Sediments/Plants	Sediments/Plants	Sediments/Plants	Plant tissues
	n=2	*n=1*	*n=2*	Mean/Range
Cadmium	23 / <0.50	227 / 0.78	66 / <0.50	8.0 / 2.6-28
Copper	46 / 4.27	238 / 3.19	110 / 2.81	48 / 2.5-243
Lead	<50 / 4.7	1,760 / 7.2	98 / <2.5	11 / 2.0-53
Zinc	1,114 / 132	12,200 / 185	10,345 / 102	143 / 26.5-1,000

South McQuesten wetland provides background metal concentrations in the area. It has the same vegetation as the No Cash and Galkeno wetlands, but does not receive mine water. Ranges and mean metal concentrations in aquatic grasses and forbs from non-impacted sites, are from Hutchinson, 1975.

Notice that the No Cash and Galkeno wetlands have accumulated metals in their sediments, indicating they removed metals from mine water. Yet metal concentrations in plant tissues from these wetlands are comparable with those from the South McQuesten wetland, and fall within the range of those from unimpacted site. Thus, there is no significant metal uptake by plants in these wetlands.

How Do We Design a Wetland Treatment System?

Two case studies are provided to illustrate how wetland treatment systems can be designed.

- Design of a wetland system to treat mine drainage at United Keno Hills Mines
- Use of mesocosms in a wetland removing zinc from mine drainage.

I believe that wetlands will play an increasingly prominent role in remediating contaminated mine drainage, as we learn more about them and as our designs improve. There are certainly signs that the technology is gaining in acceptance, such as the report by Van Zyl (1996) that coal mines in South Africa are testing wetland treatment systems.

This document should be cited as:

Sobolewski, A. 1996. Wetlands for Treatment of Mine Drainage. WWW document located at URL http://technology.infomine.com/enviromine/wetlands/Welcome.htm

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