Constructed Wetland Treatment Systems for Mine Drainage– Can They Really Provide Green and Sustainable Solutions?

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Abstract Constructed wetlands offer green and sustainable treatment, but how long will they really work? A wetland in northeastern Minnesota has been successfully treating mine drainage for almost 20 years. The primary removal processes include adsorption, ion exchange and complexation. These reactions have a finite lifetime since they depend on the existence of suitable removal sites. Removal will eventually cease unless new removal sites are generated or added. New sites are generated each year as vegetation dies and decomposes. For this wetland, the annual increase in metal removal capacity is about equal to the annual metal input; theoretically providing sustainable treatment.

Keywords Copper, nickel, peat, adsorption, complexation

Introduction

Wetlands have been used to treat a variety of water quality problems, including agricultural, municipal and industrial discharges (Hammer 1989, Moshiri 1993, Kadlec and Knight 1996, ITRC 2003). Wetlands have also been successful in treating coal and metal mine drainage and can be an attractive alternative to more conventional treatment methods (Hedin *et al.* 1994, Eger *et al.* 1996, Sobolewski 1997). Wetlands can be less costly to build, use processes that naturally occur to remove metals from the water (*e.g.* adsorption, filtration), and offer a system that ideally should operate with little to no maintenance for extended periods of time. Because mine drainage problems can persist for hundreds of years, the longevity of any system is a critical issue.

Surface flow wetlands were constructed to treat neutral mine drainage at the Dunka Mine in northeastern Minnesota (Eger and Eger 2005). A model was developed to evaluate treatment lifetime and the results suggest that one of the wetlands can provide a long term treatment alternative.

Wetland

The wetland treatment system was designed by STS Consultants, Ltd., and built by LTV Steel Mining Company in an existing wetland in 1992 (Frostman 1992). The wetland was originally a combination of emergent (wet meadow) and scrub-shrub type wetlands. The majority of the woody vegetation, which consisted primarily of alder (*alnus* sp.), was removed from the site. The basic design for the system included the construction of a series of soil berms, which were built to control water levels and to maximize contact between the drainage and the substrate (Fig. 1). Soil berms were built with glacial till (sandy silt) available from a surface overburden stockpile on the property. After the berms were constructed, a 30 cm layer of a mixture of local peat and peat screenings was applied to the entire area except the top of the berm. The screenings were a waste material generated during the processing of horticultural peat and consisted mostly of wood fragments and long peat fibers. This material was selected to increase the permeability of the peat to at least 10^{-3} cm/s and to provide available or-

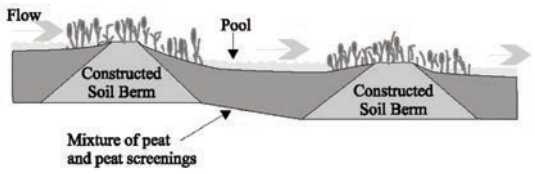

Fig. 1 *Schematic of the wetland treatment system examined in this study*

ganic carbon. In the spring of 1992, the berms were hand-seeded with Japanese Millet, while the open water areas were seeded with cattails. To obtain the cattail seeds, cattail heads were placed in a container of water with a small amount of liquid soap and several large metal bolts. The mixture was agitated until the heads broke and the seeds were dispersed. The slurry was then broadcast by hand over the wetland. The majority of the flow to this system originated from the base of a waste rock stockpile. The wetland was originally about 7000 m^2 but was expanded in 1995 by an additional 10,000 m^2.

Methods

Water samples of the inflow and outflow of the original wetland treatment system were initially collected twice a month by LTV personnel. Sample frequency from the original part of the wetland decreased to quarterly in 2004. During the initial phase of the study metals were analyzed by atomic absorption spectroscopy (AAS) but the analytical technique switched to inductively coupled plasma-mass spectrometry (ICP-MS) in about 2005. Samples were analyzed by Northeast Technical Services in Virginia, MN.

Continuous measurements of inflow and outflow water levels were made with a Steven's Model F recorder, and the flow was calculated from the standard equation for a 60 degree V-notch weir. Due to potential problems with the recording equipment under freezing conditions, continuous flow estimates were generally only available from May through October.

Results

Flow

Since continuous flow measurements were only available for May through October, the average daily flow calculated over this period has been used to compare the change in flow over time.

Average input flows ranged from 110–136 L/min for 1992 to 1994. In 1995 the top of the stockpile that provided the majority of the flow to the wetland was capped with a 40 mil LDPE liner. Flows decreased in 1995 and average flows after capping generally ranged from 22–52 L/min. Flow in 2007 was the highest of the post-closure flows (106 L/min), the result of 43.6 cm rainfall in September and October. Annual precipitation for 2007 was 100.7 cm, substantially above the long-term average precipitation of 72.4 cm.

Output flow was generally greater than input flow except during hot dry periods when evapotranspiration losses were large. During the summer of 1998 the output flow was 19–23 L/min less than the input. In July, when the input flow decreased to 15–19 L/min, there was no flow at the outlet.

Water Quality

There was little variation in pH in the wetland. Both input and output pH generally ranged from 6.7 to 7.6. From 1992 to 1994, the input nickel concentration to the wetland treatment system was typically on the order of 1 mg/L in the spring, and then increased to approximately 6 mg/L in early summer. Concentrations then remained relatively constant until the seep froze in late fall (Fig. 2).

In 1995, input nickel concentrations decreased substantially. The nickel concentrations in the input to the wetland remained low in the spring, but only increased to 2–3 mg/L in the summer. Maximum concentrations gradually decreased to less than 1 mg/L by 1999. Concentrations remained in this range until high rainfall occurred in the fall of 2007 when concentrations increased to over 3 mg/L.

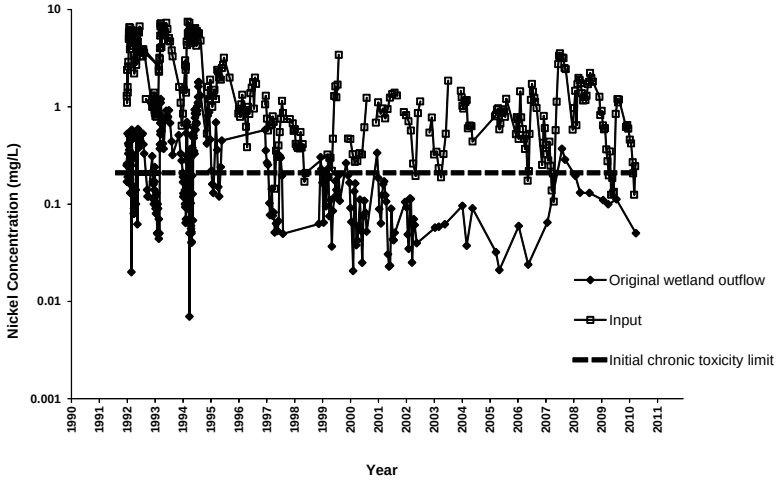

Fig. 2 *Nickel concentration, input and outflow, over time*

Outflow nickel concentrations were about 90 % lower than the input values (Fig. 2). Prior to capping the stockpile, outflow concentrations exceeded the initial chronic toxicity limit of 0.213 mg/L more than about 50 % of the time. As flow decreased, the frequency of compliance increased and outflow concentrations were generally below the initial limit.

Mass Removal

Overall mass into and out of the wetland was calculated by multiplying the average concentration for the month by the average daily flow for that month. Daily flow data were generally available from May through October, but for April, November and December, there were only a few individual flow readings. Since both flow and precipitation in November and December tended to be low, the average of the limited individual measurements was assumed to be a reasonable estimate of flow. An average value may not provide a reasonable estimate of spring melt flow, since the volume and timing of flow depends on the amount of moisture in the snow pack, temperature and rainfall. However, metal concentrations during April were about one-half the summer values, so the total mass input during April, even with higher flows, would tend to be lower than summer months. From 1992 through 1995, when input load was the highest, the May to October input mass accounted for 86 % of the annual load (Eger *et al.* 2000).

After 2000, data collection from the original portion of the wetland was reduced. As a result, the overall mass removed in this portion of the wetland was estimated from the total removal for the entire wetland based on area. The estimated mass removal ranged from about 1 – 27 kg/a with an average of about 5 kg/a.

Discussion

The lifetime of a wetland treatment system is a function of the metal removal processes, the size of the wetland and the input load. For surface flow wetlands, the primary metal removal processes are a combination of adsorption, ion exchange and complexation with the organic substrate (Eger *et al.* 1994). Removal occurs as water contacts the substrate with most of the removal occurring in the top 20 cm of the wetland (Eger *et al.* 1994). The removal capacity has been estimated from laboratory and field measurements to be on the order of 10,000 mg Ni/kg dry peat (Eger and Lapakko 1988, Eger *et al.* 1996). When the wetland was first built, the design was based on average input values for 1990–1991. For this time period, average daily flow was 78 L/min and the average nickel concentration was 5.4 mg/L (Eger *et al.* 1996). Based on a wetland area of 7000 m^2, an effective re-

moval depth of 20 cm, a peat bulk density of 0.1 gm/cm^3, a maximum removal capacity of 10,000 mg nickel/kg dry peat, and flow from April through November (245 days), the design lifetime t was calculated from:

$$t = \frac{R_R}{M} \quad (1)$$

with

t Lifetime [a]

R_R total removal capacity of the wetland [kg Ni]

M load [kg Ni/a]

This calculation assumed that all the input nickel is removed and provided an initial lifetime estimate of about 10 years (Eger and Wagner 2002).

In 1995 the entire top of the stockpile was covered with a 40 mil low density polyethylene liner (LDPE). The cover prevented water from contacting most of the reactive material in the stockpile. Flow dropped about 62 %, from an average May to October flow of 125 L/min during 1992–1994, to 47 L/min for the post-closure period (1996–2011).

By preventing precipitation from infiltrating the stockpile and contacting the reactive material, the transport of reactive products was significantly reduced. Nickel concentrations decreased from an average of 3.98 mg/L for 1992–1994 to 0.92 mg/L for 1996–2011. Since both flow and nickel concentrations decreased, the overall load to the wetland decreased by about 90 %. By reducing the load, the estimated lifetime was increased by about a factor of 10, from the initial design lifetime of 10 years to around 100 years.

The "ideal" passive treatment system will provide permanent treatment with little to no maintenance. However, in this system over 90 % of the nickel removal occurs within the substrate, through a series of reactions (adsorption, ion exchange, chelation) associated with the organic fraction of the peat. These types of removal mechanisms have a finite capacity and the wetland will have a fixed life unless new removal sites can be generated at a rate greater than or equal to the incoming metal load.

New sites are generated as vegetation dies and new organic substrate accumulates. The average rate of peat accumulation in northern wetlands is about 1 mm/year (Craft and Richardson 1993). If the removal capacity of the newly accumulated material is assumed to be 10,000 mg nickel/kg, the wetland would add 7 kg of nickel removal capacity each year as calculated from (2):

$$\Delta R_R = f_{PA} \times R_{Ni} \times A \quad (2)$$

where

ΔR_R Increase in removal [kg/a]

f_{PA} rate of peat accumulation [–]

R_{Ni} nickel removal capacity

A wetland area

Since the average rate of mass removal was 5 kg/a and the estimated increase in capacity is 7 kg/a, the wetland is generating excess removal capacity and therefore in theory should be able to provide sustainable treatment (Fig. 3).

If the treatment is to be sustainable and effective, not only must there be new metal removal capacity generated, but the metal must be retained within the wetland. Mass balances calculated on wetland test cells demonstrated that over 99 % of the removed metals were associated with the substrate and less than 1 % of the total removal occurred in the vegetation (Eger *et al.* 1994). These results were consistent with earlier studies on metal removal in a white cedar wetland (Eger and Lapakko 1988) and with data reported by others (Skousen *et al.* 1992, Wildeman *et al.* 1993). Sequential extraction tests, conducted on a series of substrate samples collected from test cells constructed at the Dunka Mine, demonstrated that only 1–2 % of the nickel was water soluble and could, therefore, be easily removed from the substrate (Eger *et al.* 1994, Eger *et al.* 1996).

Additional evidence for the permanent nature of the removal in the wetland is that nickel removal continued despite a decrease in

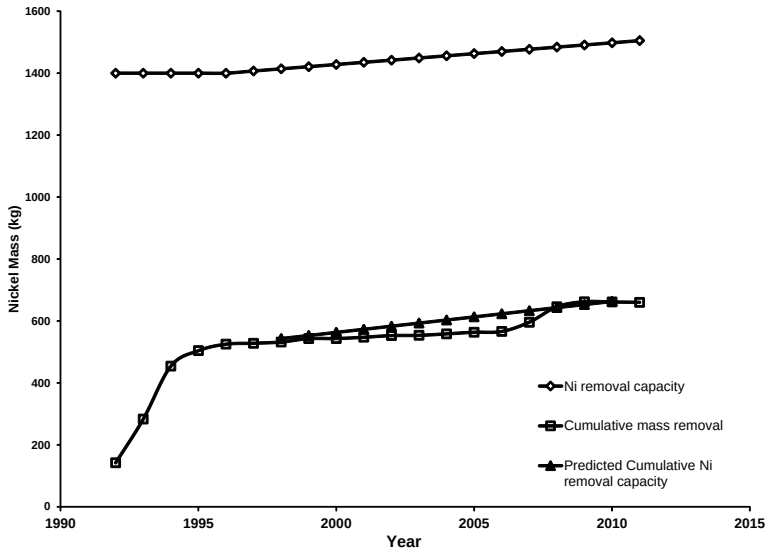

Fig. 3 *Nickel mass removal in the wetland system and projected nickel removal capacity.*

the input concentration of about a factor of five. If the nickel was weakly bound to the substrate, nickel would be released from the substrate as nickel concentrations in the water decreased, and no removal would occur. Although continuous flow data is only collected from May through October, water quality samples are collected whenever there is water flowing into or out of the wetland. Over the twenty years of operation, output concentrations have rarely exceeded input values, and there has always been nickel removal in the wetland (Fig. 2).

Conclusions

Since 1995, when the Dunka mine was closed and the stockpiles capped, nickel loads into the W1D wetland have dropped by an order of magnitude. Nickel has been removed every year and there has been no evidence of nickel release from the wetland. The annual nickel removal in the wetland is now about the same as the estimated annual production of new removal sites. If conditions remain unchanged, treatment could continue indefinitely.

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