THE DESIGN OF A WETLAND TREATMENT SYSTEM TO REMOVE TRACE METALS FROM MINE DRAINAGE[1]

by

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Abstract. Wetland treatment offers a low-cost, low-maintenance alternative to active treatment plants for treating stockpile drainage. Wetland treatment test cells built in northeastern Minnesota have been successful in removing over 80 percent of the nickel from stockpile drainage. In 1991 new peat substrate was added to one of the cells to enhance performance. After enhancement, overall annual nickel removal increased from 40 to 74%, but for most of the summer, nickel concentrations were reduced by more than 90%. Using the data from the test cells, full-scale wetland treatment systems can be designed to treat stockpile drainage. An example of this approach is presented for a stockpile which produces an average daily flow of 20 gallons per minute containing 5 mg/L nickel.

Additional Key Words: wetland enhancement, nickel

Introduction

Drainage from mineralized Duluth Complex stockpiles located at LTV Steel Mining Company's Dunka Mine in northeastern Minnesota contains elevated concentrations of nickel, copper, cobalt, and zinc. This drainage has increased metal concentrations in nearby receiving waters to levels which are as much as 500 times natural background concentrations. A feasibility analysis, conducted in 1985, concluded that although an active treatment plant could generally achieve water quality guidelines, a more cost-effective, passive approach (low cost, low maintenance) might also be successful (Barr Engineering 1986).

Wetland treatment is a crucial aspect of this passive approach; and although previous work (Eger and Lapakko 1988; Lapakko and Eger 1988; Lapakko et al. 1986) had demonstrated the effectiveness of peat to remove trace metals from mine drainage, no field data from an actual treatment system existed.

In 1986, LTV Steel Mining Company and the Minnesota Department of Natural Resources began a cooperative program to develop data on optimal wetland treatment design and system life. The goal of the program was to collect data for the design of full-scale treatment systems for the stockpile drainages at the Dunka Mine, by constructing and operating wetland treatment test plots (Eger et al. 1991).

Site Description

The Dunka Mine is a large open pit taconite operation covering approximately 160 hectares. At this location, the Duluth Complex, a metalliferous gabbroic intrusion, overlies the taconite ore and is removed and stockpiled along the east side of the open pit. The Duluth Complex material contains copper, nickel, and iron sulfides, and the stockpiles contain over 32 million tons of waste rock and cover about 120 hectares. Discrete seepages appear at the bases of the stockpiles and generally flow continuously from early April to late November. Average flows from the various seepages range from 0.5 L/sec to 14 L/sec (8 to 220 gpm), but flows

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exceeding 100 L/sec (1600 gpm) were observed after periods of heavy precipitation.

Nickel is the major trace metal in the drainages, with annual median concentrations on the order of 3-30 mg/L. Copper, cobalt, and zinc are also present but are generally less than 5% of the nickel values. Median pH ranges from 5.0 to 7.5, but most of the stockpile drainages have pH greater than 6.5.

Wetlands are located near every stockpile and appear to offer potential treatment areas for each seepage (Eger and Lapakko 1989). These wetlands are typical of the many small lowland areas in northern Minnesota and would generally be associated with any mining area.

Methods

Prior to beginning the study, each wetland was surveyed, and its capacity to treat the associated mine drainage was determined. Estimated lifetimes based on input metal load and wetland area ranged from 20 to over 700 years (Eger and Lapakko 1989). Based on the survey work, a test area was selected and cells constructed.

Four cells were designed so that a variety of water levels, vegetation, and flow regimes could be tested (Figure 1). These cells were constructed in a natural wetland. Each cell was 6 meters wide x 30.5 meters long (20 feet wide by 100 feet long) and was surrounded by a compacted peat berm. To hydrologically isolate the cells, a sand-bentonite cut-off ditch was installed in the center of the berms surrounding each cell (Eger et al. 1991).

Stockpile drainage was collected near the toe of the stockpile (Site W3D), piped to the plots, and dispersed across each cell with a perforated PVC pipe, then collected with an open half pipe at the outflow. In 1991, the collection point was moved closer to the stockpile to increase the nickel concentration in the input water to the treatment cells. Based on the results of previous laboratory studies

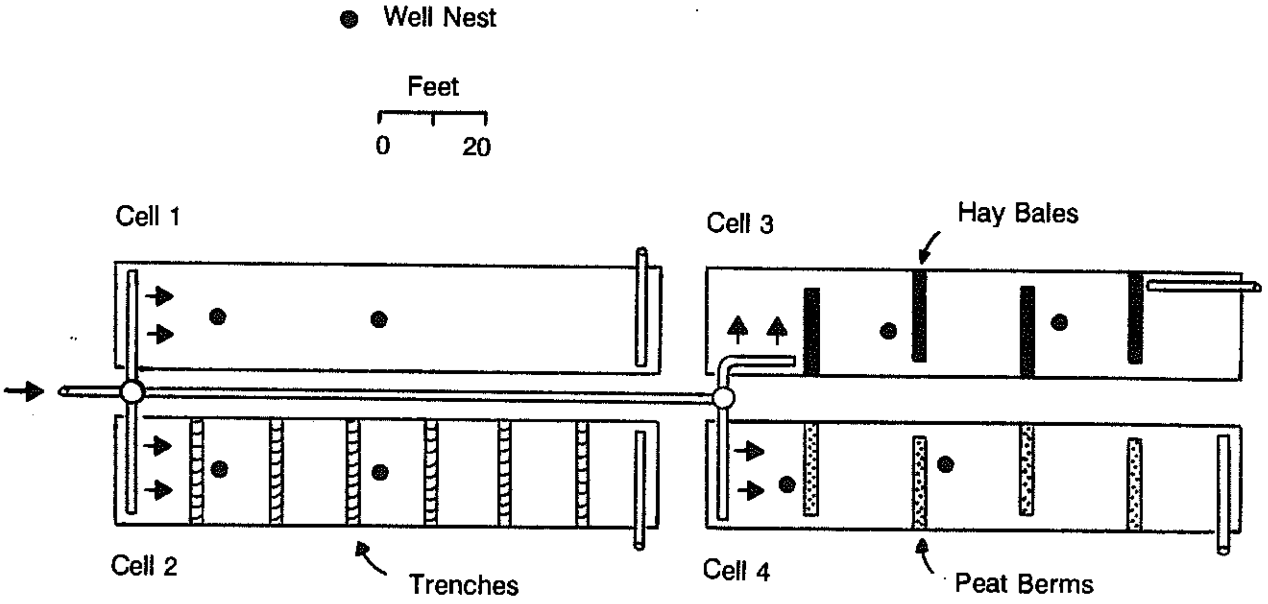

Figure 1. Wetland treatment test cells.

(Lapakko et al. 1986), a design residence time of 40-48 hours was selected for the cells.

The initial residence time in each cell was estimated from the volume of water above the peat surface. Tracer studies using rhodamine WT dye and iodide were conducted to measure the actual residence time in each cell (Eger et al. 1992).

Specific cell designs were as follows:

Cell 1: Unmodified natural wetland; water dispersed across natural wetland; vegetation primarily sedges (Carex sp.) and grasses (Calamograstis sp.); water depth was 5 cm (2 inches).

Cell 2: Modified wetland; shallow trenches were constructed with a backhoe; these trenches were spaced about 4.5 meters apart and were about 60 cm deep (15 feet by 2 feet) and were dug perpendicular to the flow path; spoil material from the trench was cast downstream; sedges and grasses from the surrounding area were transplanted into the cell; water depth was 5 cm (2 inches).

Cell 3: Modified wetland; hay bales placed to create serpentine flow, 5 cm (2 inches) of straw placed on the bottom of the entire cell to encourage sulfate reduction; cell planted with cattails (Typha latifolia, 1 per square meter); water depth was 15 cm (6 inches).

Cell 4: Modified wetland; peat berms constructed across the cell, perpendicular to flow; cattails planted (1 per square meter); water depth was 15 cm (6 inches). In 1991 six inches of a mixture of 1 part well decomposed reed sedge peat from an unimpacted wetland to 2 parts peat screenings from a sphagnum peat processing facility was added to the cell. The outlet elevation was set to allow 5 cm (2 inches) of water depth, assuming that the peat would settle about 50%. Complete settling did not occur during 1991, and the water depth varies in the cell from 0 to about 5 cm.

The input stockpile drainage can be characterized as a high hardness neutral drainage whose primary contaminant is nickel. Nickel concentrations into the cells have ranged from 0.11 to 3.8 mg/L. In 1991 after the collection point for the stockpile drainage was moved, average nickel concentrations of the input water increased from 0.66 mg/L in 1989 and 1990 to 2.0 mg/L in 1991. Average hardness is around 2300 mg/L as $CaCO_3$, with a pH range of 6.5 - 7.9. Copper and zinc generally meet water quality criteria, while cobalt and nickel routinely exceed the criteria, sometimes by more than an order of magnitude.

Data collection began in August 1989. Water quality samples of the inflow and outflow were collected about twice per week and analyzed for pH, specific conductance, alkalinity, acidity, calcium, magnesium, sodium, potassium, sulfate, copper, nickel, cobalt, zinc, iron, and manganese. Input and output flows from each cell were measured with Data Industrial electronic flow meters and recorded with a Campbell Scientific micrologger, which also recorded precipitation, temperature, and relative humidity.

Results

Nickel Removal

In 1989 and 1990, the largest reduction in nickel concentration occurred in the shallow water (5 cm water depth) cells (Cells 1 and 2). Outflow concentrations were generally reduced by about 80-90%, and the overall mass removal of nickel exceeded 80% (Table 1). Cells 3 and 4, with 15 cm of water, reduced nickel concentrations by 19-63% in 1989 and 46-77% in 1990. Cell 4 consistently had the lowest nickel removal. When the peat mixture was added to Cell 4 in 1991, nickel removal increased dramatically. Nickel concentrations were reduced by over 90% from input values of over 2 mg/L to outflow values of less than 0.2 mg/L, which met the water quality standard (Figure 2). Nickel removal remained acceptable until the middle of October, when outflow concentrations exceeded the water quality standard, and the nickel removal decreased from about 90% to a minimum of about 25% in early November. The sharp rise in outflow concentration corresponded to an increase in flow rate through the cell from 1.3 to 3.1 gpm.

Table 1. Nickel removal in wetland treatment cells, 1989-1990.

Cell	Description	Vegetation	Water Level (cm)	Average Outflow Nickel Concentration mg/L	% Reduction in Concentration	Overall Mass Removal %
1	unmodified natural wetland	primarily grasses and sedges	5	0.10	85	83
2	modified wetland with trenches	primarily grasses and sedges	5	0.09	87	86
3	modified wetland serpentine flow straw addition	cattails with open water	15	0.23	66	68
4	modified wetland serpentine flow	dense stand of cattails	15	0.46	32	40

Average input nickel concentration was 0.66 mg/L, input concentration ranged from 0.11 to 2.1 mg/L.

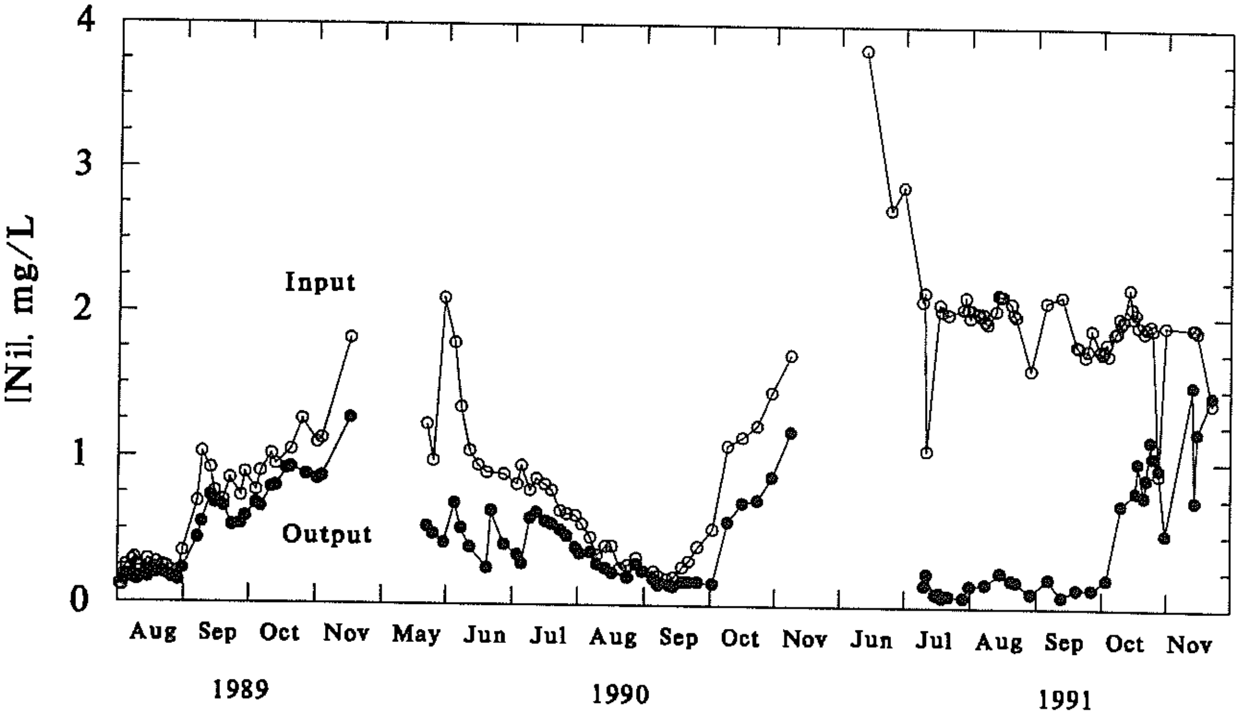

Figure 2. Water quality results for Cell 4, 1989-91. Additional peat was added to the cell prior to the 1991 field season.

Residence Time

Residence time was defined by

$$\text{Residence Time (hrs)} = \frac{\text{Effective Volume of the Cell (gal)}}{\text{Outflow (gal/hr)}}$$

The effective volume was determined from tracer studies

Effective volume (gal) = outflow rate (gal/hr) x time for tracer concentration in outflow to peak (hr.)

In general, for the shallow water cells, residence times of 48 hours provided good removal although adequate removal was observed at residence times as low as 18-24 hours (Eger et al. 1991). Additional residence time studies were conducted during 1991, and the data will be presented in future reports (Eger et al. 1992). Residence times were varied in Cell 4, from around 31 to 12 hours. During the initial part of the study, nickel removal exceeded 90%, and outflow samples met the water quality standards at residence times of both 20 and 30 hours (Table 2). However, when residence time was decreased to 17 hours in October, nickel removal decreased dramatically from 93% to 55% and decreased further to 38% when the residence time was decreased to 12 hours (Table 2).

Seasonal Variations

Reduction in nickel concentration also appears to be dependent on time of year. Even though input nickel concentrations were approximately equal throughout the year, nickel removal not only decreased in the enhanced wetland during the fall but also in all the other cells. Removal in the unmodified natural wetland cell (Cell 1) was highest in July and decreased as residence time decreased (Table 3, Figure 3). Nickel removal improved slightly when residence time was increased to 96 hours in October. Outflow nickel concentrations in October and November were almost an order of magnitude higher than those measured in June and July, even though the residence time was doubled (Table 3, Figure 3).

Design

A conceptual design was performed for one of the neutral stockpile seepages at the Dunka Mine (W1D). This seepage has reported annual average daily flows in the range of 20-40 gpm with an average nickel concentration of around 5 mg/L. Peak flows as high as 300 gpm have been reported, and nickel concentrations of 15 mg/L have been measured.

Table 2. Outflow water quality of enhanced wetland (Cell 4) as a function of residence time and time, 1991

Time Period	Average Flow Rates (gpm)		Average Residence Time (hrs)	Average Nickel Concentrations (mg/L)		Average Reduction in Nickel Concentration (%)
	In	Out		In	Out	
7/10-7/30	1.3	1.3	28	1.9	0.11	94
7/31-8/21	2.0	1.8	20	2.0	0.18	91
8/22-10/9	1.3	1.2	31	2.1	0.15	93
10/10-10/24	2.2	2.1	17	2.0	0.9	55
10/25-11/22	3.1	3.1	12	1.7	1.1	38

Note: for period 7/10 to 7/30 outflow = inflow because of 3.75" of rain during this period.

Table 3. Outflow water quality of unmodified wetland (Cell 1) as a function of residence time and time, 1991

			Average Nickel concentrations mg/L		
Time Period	Average Outflow Rate gpm	Average Residence Time	In	Out	Average reduction in nickel concentration (%)
6/13 - 8/1	1.0	40	2.241	0.147	93
8/2 - 9/6	1.4	29	2.058	0.318	85
9/7 - 9/27	1.9	21	1.950	1.150	41
9/28 - 10/9	.9	44	1.820	1.670[1]	8
10/10 - 11/13	.6	67	1.878	1.251	33

[1] only one data point

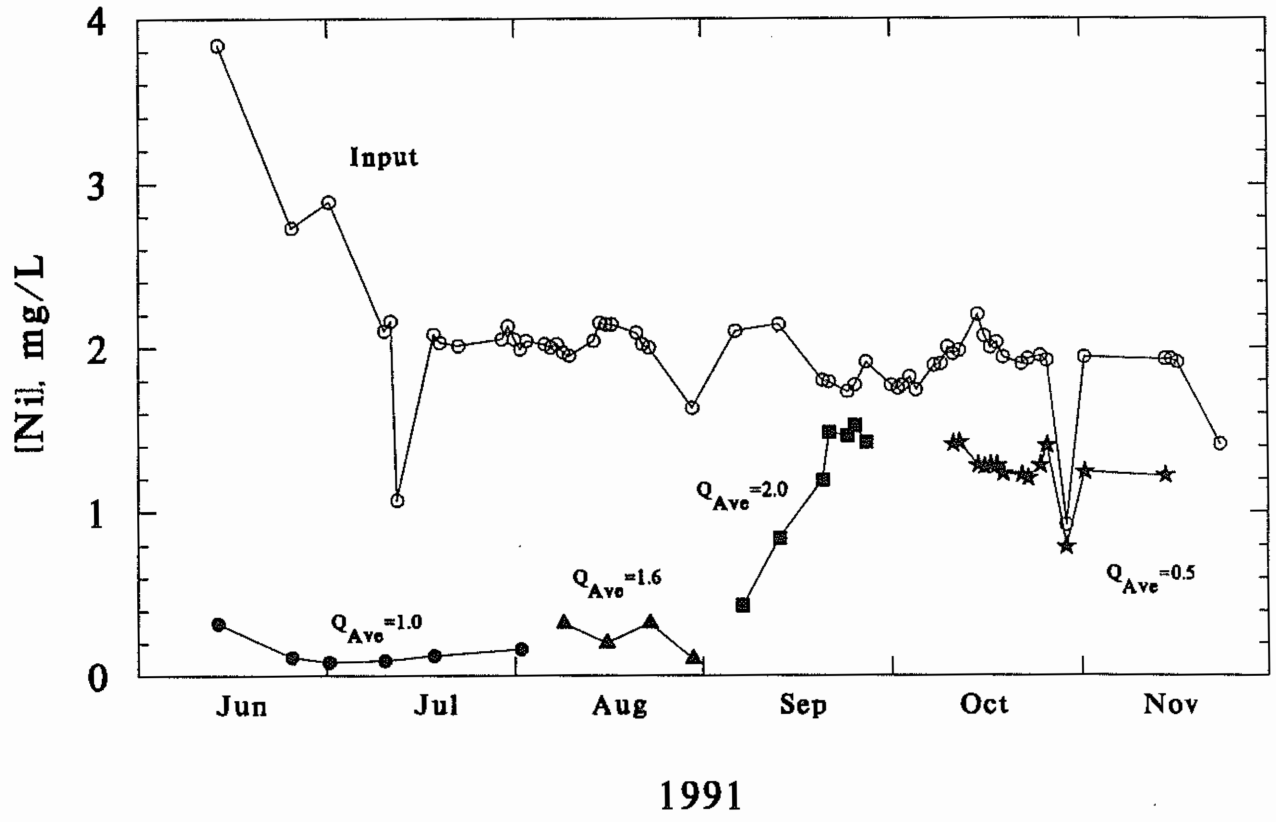

Figure 3. Water Quality results for unmodified wetland (Cell 1), 1991. Flow rates (Q_{Ave}, gpm) were changed to study the effects of residence time on nickel removal.

The key factors in any design include the following:

Drainage Characteristics
1. Flow
    a. average flows
    b. peak flows
2. Water quality
    a. average concentration
    b. peak concentration
3. Mass loading, both average and peak
4. Anticipated changes over time

Wetland Characteristics
1. Size
2. Type of system
    a. overland
    b. subsurface
3. Type of substrate

Design Factors
1. Effluent requirements
    a. average
    b. maximum allowable concentration
2. Residence time
3. Performance data
    a. Metal removal
        (1) average
        (2) minimum
    b. Seasonal effects
4. Lifetime

Drainage Characteristics

In order to size a wetland treatment system properly, input flow and water quality should be well characterized. Historical data can provide averages and ranges for these input parameters. Since the goal of wetland treatment is to provide a system which will perform long term with low maintenance, projections on the variability of flow and water quality must be made. These projections could be based on past maximum values or on projections. For example, contaminant concentrations could be projected from chemical characteristics of the mine waste or from accelerated laboratory tests on rock dissolution. Flow projections could be made from predicted response to certain design storms, e.g., 10 yr. - 24 hr. storm. The choice of values will also be dependent on other mitigative activities that are planned for the waste. Flow may be reduced if infiltration into the waste is reduced.

For illustrative purposes, the design presented here is based on an average flow of 20 gal/min with 5 mg/L nickel. Although this does not consider peak flows or loads, an extensive infiltration reduction program is planned for the stockpile within the next two years. Flow reductions of around 80% may be achievable. This would reduce average flow to around 4 gal/min and peak flows to around 60 gal/min. Initially, the system may not provide complete treatment for flows exceeding about 40 gal/min, but it should function optimally for the long term once capping is in place.

Wetland Characteristics

The wetland model for this design is the enhanced treatment cell. Enhancing the wetland with a new peat mixture provides 1) a substrate which has lower metal content and therefore higher metal uptake potential than the peat at the mine, much of which already has elevated metal content (Eger and Lapakko 1989); 2) a more permeable substrate which should help encourage subsurface flow; 3) a material which can be replaced when the removal capacity is exhausted.

The total area available for wetland treatment of this drainage is about 11 acres (Figure 4). However, regulatory requirements demand that to the maximum extent possible, treatment must occur near the stockpile. One of the purposes of the design calculation is to determine the appropriate treatment bed size.

Design Factors

Effluent requirements. The main contaminant is nickel, and this must be reduced to an average monthly value of 0.213 mg/L at the outflow of the system. Maximum allowable nickel concentration in any one sample is 4.6 mg/L.

Residence Time. Although adequate nickel removal occurred at residence times as low as 20 hours in the summer, this residence time was not sufficient to produce acceptable quality water in the fall. Cells with residence times of 48 hours have generally produced acceptable effluent, although the data from 1991 suggest that as temperatures decrease in the fall, treatment may also decrease. The existing average flow rate of 20 gal/min was used to size the system to provide an average residence time of 48 hours.

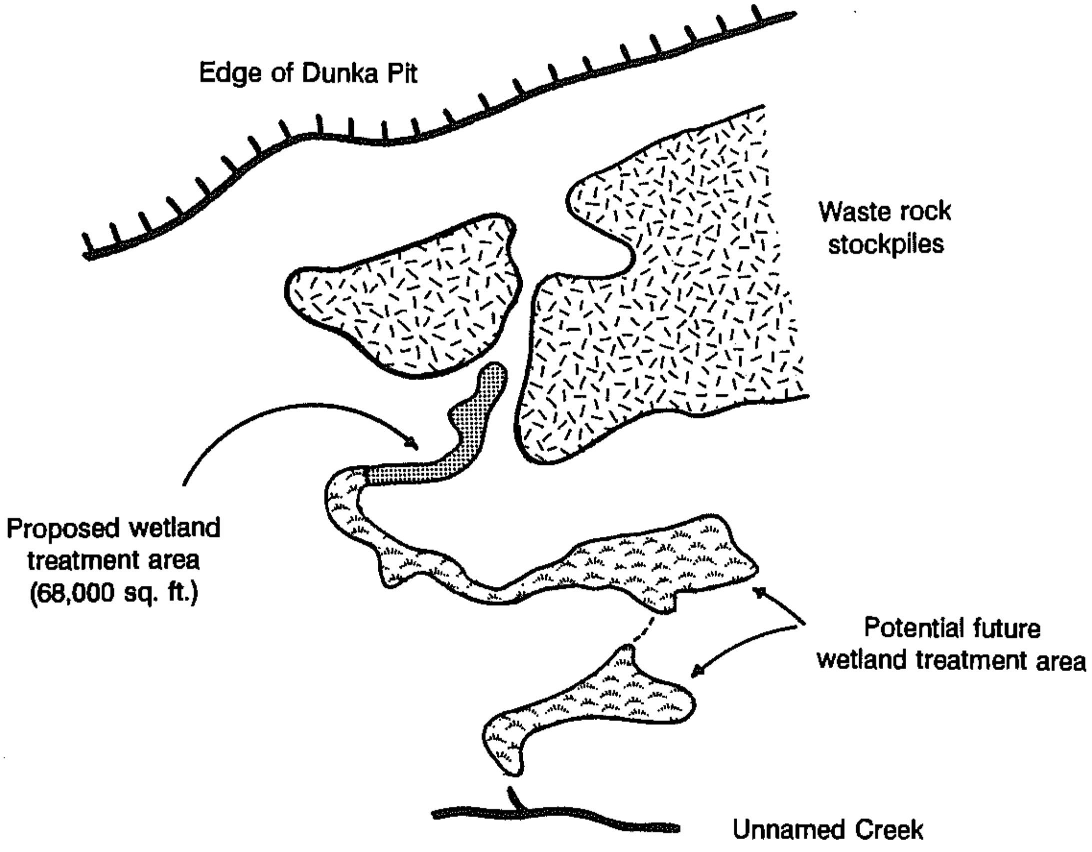

Figure 4. Conceptual wetland treatment area.

After infiltration into the stockpile is reduced, the average residence time could increase by around a factor of 5 to 240 hours.

Performance Data. During the summer, at input flows from 1 - 2 gpm, the enhanced cell generally produced acceptable effluent. The full-scale system was sized by determining both a hydraulic loading factor, expressed in units of gpm input/ft ^{2} of wetland and an areal nickel loading factor, expressed in units of mg nickel input/ft ^{2} wetland/day.

For the hydraulic loading of the full-scale treatment system to be comparable to the enhanced cell, a treatment area of 2000 ft^2/gpm input should be provided. Although this cell usually provided acceptable treatment for input flows of 2 gpm in August (a hydraulic loading of 1000 ft^2/gpm), the data suggests effluent limits probably will be difficult to meet in the colder months at the higher flow rate.

For an average flow of 20 gpm, the area required to treat the drainage adequately would be 40,000 ft^2. The outlet should be set to maintain 2 inches of water above the peat, and then the residence time in the surface water will be about 48 hours. (This was the approximate water level in the enhanced treatment cell.)

For the system to have an areal nickel loading (mg/ft ^{2} day) comparable to the enhanced cell during 1991 (~ 8 mg/ft^2 day), the area required would be as follows:

$$\text{Treatment Area} = \frac{545{,}000 \text{ mg Ni/day}}{8 \text{ mg/ft}^2 \text{ day}} \cong 68{,}000 \text{ ft}^2$$

To provide a margin of safety, the larger area should be used. For a system this size, with an average water depth of 2 inches, the residence time would be approximately 72 hours. Since this system employs overland flow, most of the metal removal will occur in the aerobic zone and result from adsorption, chelation and ion exchange.

Some metal removal will also occur due to sulfate reduction. Although the enhanced cell did show evidence of sulfate reduction (Eger et al. 1992), removal by sulfate reduction is probably limited. To have significant sulfate reduction, the following must occur:

a. An anaerobic zone must be established.
b. A source of readily decomposable organic matter must be present.
c. Elevated sulfate concentrations must occur in the drainage.
d. Transport of the mine drainage to the anaerobic zone must occur.

Adequate sulfate occurs in the drainage, and although the wood fragments in the screenings will more readily decompose than the peat, the overall rate of decomposition will probably be slow. However, due to the neutral pH and low concentrations of trace metals in the drainage, high rates of reduction may not be needed to remove the metals.

Although the screenings alone are quite porous when mixed with a well-decomposed reed-sedge peat, the estimated hydraulic conductivity of the mixture is about 10^{-3} cm/sec. Given the low hydraulic gradients present in natural wetlands (slopes < 1%), most of the flow in the enhanced system will be surface flow. Based on the estimated cross-sectional areas and gradients, about only 1 percent of the overall flow will be subsurface (Table 4). Removal by sulfate reduction will be limited by the rate at which metals can diffuse to the anaerobic zone.

At an input concentration of 5 mg/L nickel and an average flow of 20 gallons per minute, the input of metals is 6.5 mmoles/min. To remove this metal by sulfate reduction would require at a minimum the reduction of an equal number of moles of sulfate. Since the input concentration is 5 mg/L or 0.85 mmoles/L, the decrease in sulfate concentration would be about 8 mg/L. Since the sulfate input concentrations are about 2000 mg/L, this small change could not be detected. Additional work is underway to better estimate the amount of metal removal that occurs by sulfate reduction in overland flow systems. In order to transmit a significant volume of water through the peat and achieve some metal reduction through sulfate reduction, a vertical bed would be needed. Although a vertical downflow system may be slightly more difficult to construct and maintain, this type of system provides a better method of obtaining significant sulfate reduction. The vertical system shown in the design modification table (Table 4) can treat about 500 times more flow than a bed with a horizontal gradient, due to a higher hydraulic gradient and larger cross-sectional area for flow, even though it covers one-third the area of the overland flow design.

Lifetime. Initial lifetime measurements were made based on nickel concentrations measured during laboratory and field studies (Lapakko and Eger 1988, Eger and Lapakko 1988). A nickel capacity of 10,000 mg nickel/kg dry peat and an effective removal depth of 20 cm were used to estimate the total mass of nickel that could be removed (Eger and Lapakko 1988). Additional studies are underway to refine estimates of both the depth of removal and the maximum uptake. For this design,

Table 4. Flow through treatment cell, horizontal and vertical

Flow type	Cross sectional area (ft^2)	Estimated hydraulic conductivity cm/sec	Gradient	Flow gal/min	% of average input flow
horizontal	50[1]	10^{-3}	.02	.02	1%
vertical	20,000[2]	10^{-3}	.33[2]	100	500%

[1] based on a bed 100' wide x 600' long x .5' deep.
[2] based on a bed 100' wide x 200' x 3' deep with 1 ft. of standing water.

it is assumed that all metal removal occurs in the added substrate (15 cm) and that the maximum capacity is 10,000 mg nickel/kg dry peat.

Using these estimates and the treatment area requirement based on nickel loading, the lifetime of the system under present conditions is estimated to be approximately 7 years. Once infiltration reduction measures on the stockpile are completed, the estimated lifetime would increase to around 35 years if an 80% reduction in flow and nickel load are achieved.

Conclusions

Wetland treatment appears to be an acceptable treatment alternative for stockpile drainage at LTV's Dunka Mine. A conceptual approach, using an enhanced wetland design with overland flow, should provide treatment from the unaltered stockpile for around 7 years. As the stockpile is reshaped and capped to reduce infiltration and thereby decrease the volume of contaminated drainage, the lifetime of the wetland treatment system will increase to around 35 years. LTV plans to construct a full-scale system for this drainage in 1992.

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