CONTROLLING MINE DRAINAGE PROBLEMS IN MINNESOTA - ARE ALL THE WETLAND TREATMENT SYSTEMS REALLY ABOVE AVERAGE?[1]

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Abstract. Five surface flow wetland treatment systems were built in the 1990's to remove copper, nickel, cobalt and zinc from mine drainage in northeastern Minnesota. All but one of the drainages were neutral, and metal concentrations ranged from around 0.02 to 10 mg/l. Nickel was the primary metal generally accounting for about 90 % of the load. The one acid seep was pretreated with a peat / limestone bed prior to discharge to a surface flow wetland.

System design, maintenance and performance of the wetland systems varied. Some systems have required essentially no maintenance and have produced water that has always been in compliance, while others have required a variance to maintain compliance and have required a considerable amount of reconstruction.

All the systems included a series of berms to control the hydraulic gradient and to provide access to the wetland. Some of these berms included elaborate under drains, which were generally ineffective since only a small amount of the total flow could be transmitted. The key factor in performance was the size of the wetland. An areal nickel removal rate of about 40 mg/m^2 day was determined in pilot cell tests prior to wetland construction. In general, the systems that met this requirement produced the most consistent compliance with water quality standards.

Additional Key Words: copper, nickel, cobalt, zinc, surface flow wetlands

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Introduction

When iron ore was discovered in Minnesota in the 1880's, concern about the impact of mining on water quality was not a major issue. Fortunately, the vast majority of the rock associated with Minnesota's iron ore did not contain acid-generating minerals and, with the exception of erosion and sediment transport, there has been little impact on water resources. As a result, when the Dunka Mine was opened in 1962, little thought was given to the handling of waste rock from the operation. Unfortunately, the iron ore at this site was partially covered by an igneous intrusive rock formation known as the Duluth Complex, a gabbro, which contained disseminated copper and nickel sulfides. During the thirty years of operation, over 50 million metric tons of sulfide-containing waste were removed and stockpiled on 120 hectares of land adjacent to the mine. As water infiltrated this material, drainage with elevated copper, nickel, cobalt, and zinc was produced. Annual median concentrations in the drainage from the stockpiles of Duluth Complex have ranged from 1.5-50 mg/l for nickel, <0.1-1 mg/l for copper, <0.1-3 mg/l for cobalt and <0.1-4 mg/l for zinc. Most of the drainage had pH greater than 6.5, but one site consistently produced acidic drainage.

In 1986, LTV conducted a preliminary feasibility study to determine the best method to mitigate the drainage problem at the Dunka Mine. They examined both active treatment systems (lime treatment, reserve osmosis) and passive alternatives (limiting infiltration into stockpiles, wetland treatment; Barr Engineering, 1986). An active treatment plant, which would treat all the stockpile drainage, was projected to have a capital cost of $8.5 million and an annual operating cost of $1.2 million. The passive alternative was projected to cost $4 million to construct but only $40,000 in annual maintenance. Since mine drainage problems can persist for over 100 years, LTV decided to pursue passive alternatives.

The passive approach consisted of reducing flow from the stockpiles by modifying watersheds where appropriate, limiting infiltration into the stockpiles by capping and treating the residual drainage with wetland treatment systems (Eger et al, 1998). Five wetland treatment systems were to treat the drainage from the stockpiles.

Site Description

The Dunka Mine is a large open pit taconite mine that covers approximately 160 hectares and has a depth of around 100 m. It sits along the western edge of a small watershed (920 hectares), which is drained by a small stream (Unnamed Creek, Fig. 1). The watershed is typical for this area of Minnesota and is characterized by a series of upland ridges and low areas containing wetlands. Sulfide-containing waste material from the mine was stockpiled along the eastern edge of the mine and adjacent to these wetlands.

Due to shallow water tables, precipitation that infiltrates the stockpiles appears as seepage in many places along the toes of the stockpiles. Although some of this seepage is diffuse, the majority of the flow occurs as discrete flow, which generally flows continuously from spring melt in April till freeze up in late November. Average flows from the various seepages prior to closure ranged from 3 L/min to 840 L/min, but flows exceeding 6000 L/min had been observed after periods of heavy precipitation.

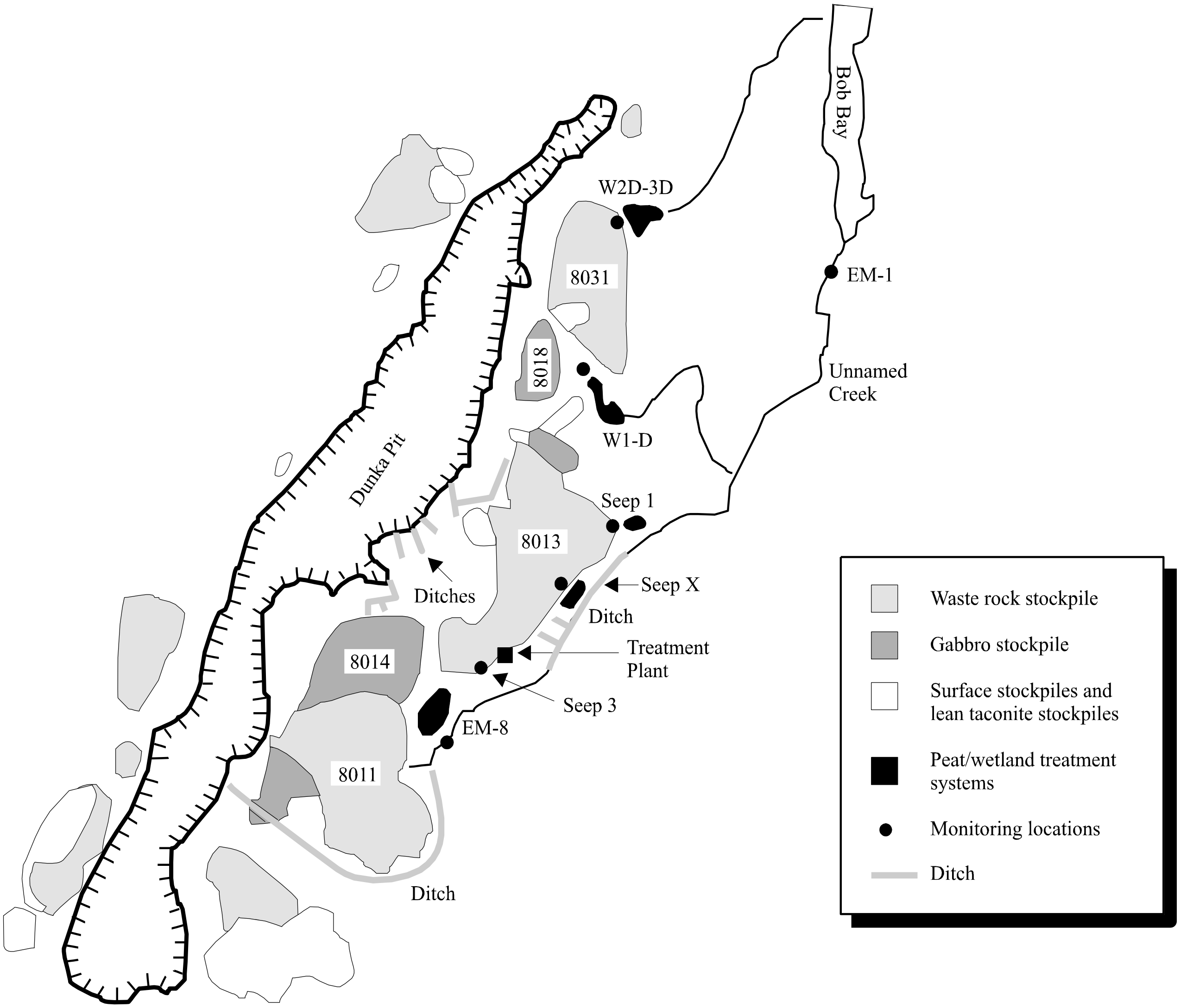

Figure 1. LTV's Dunka Mine, Babbitt, Minnesota.

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

In 1988, four overland flow test cells were built to investigate methods to optimize metal removal and to provide design data for the ultimate implementation of wetland treatment at this facility (Eger and Lapakko, 1989; Eger et al., 1991, 1993, 1994, 1996a). Based on the results of this study, two full-scale wetland treatment systems were built in March of 1992 (Eger et al., 1996b). In 1995, two additional systems were built and one of the original systems was enlarged. The final wetland was constructed in 1997. Wetland locations are shown in Fig. 1.

General Construction

All of the treatment systems have been built in existing wetlands. The first 4 wetland systems were designed by STS Consultants (Frostman, 1992), while the last system was designed by LTV Steel Mining Company.

In general the original wetland areas were a combination of emergent (wet meadow) and scrub-shrub type wetlands, and the majority of the woody vegetation, which consisted primarily of alder, was removed from the site. The basic design for each 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. 2). 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 centimeter layer of a mixture of local peat and peat screenings was applied. The screenings are a waste material generated during the processing of horticultural peat and consist 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/sec and to provide available organic carbon. 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 bolts, and then the mixture was agitated until the heads broke and the seeds were dispersed. The slurry was then broadcast over the wetland.

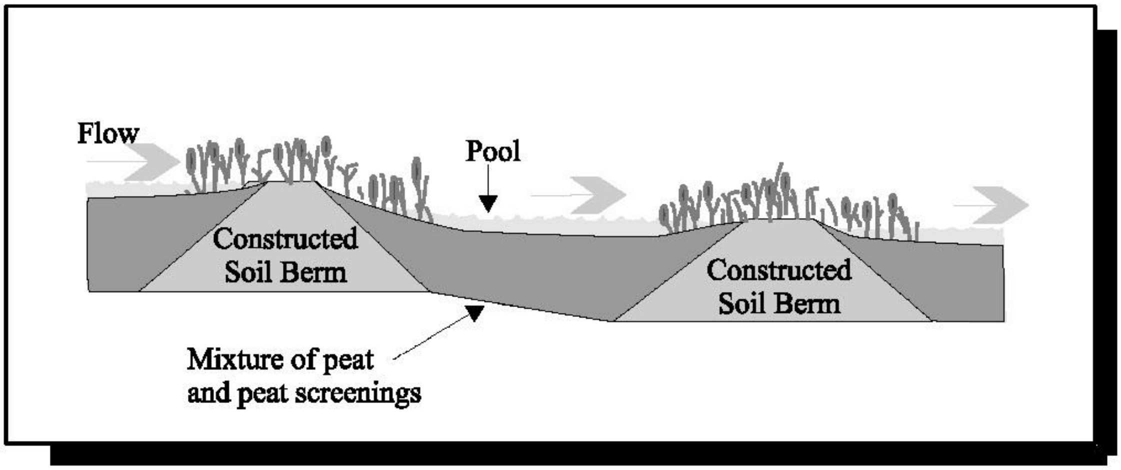

Figure 2. Schematic of berms used in wetland treatment systems.

Wetland Treatment Systems

W2D/3D system

This system covers 4200 m^2, contains 6 berms, and treats the drainage from two seepage areas which are associated with waste rock stockpile 8031 (Fig. 3). Originally flow could be observed at the toe of the stockpile but after the berms were constructed the water level at the toe increased and the seeps were covered. As a result only limited data exists for the inputs to the system. The average flow from the stockpile, based on original data, has been estimated to be on the order of 75 L/min. From 1992-94, the input to the wetland was estimated to have an average pH of 7, with mean metal concentrations of 1.92 mg/L nickel, 0.05 mg/L copper, 0.05 mg/L zinc and 0.02 mg/L cobalt (Table 1).

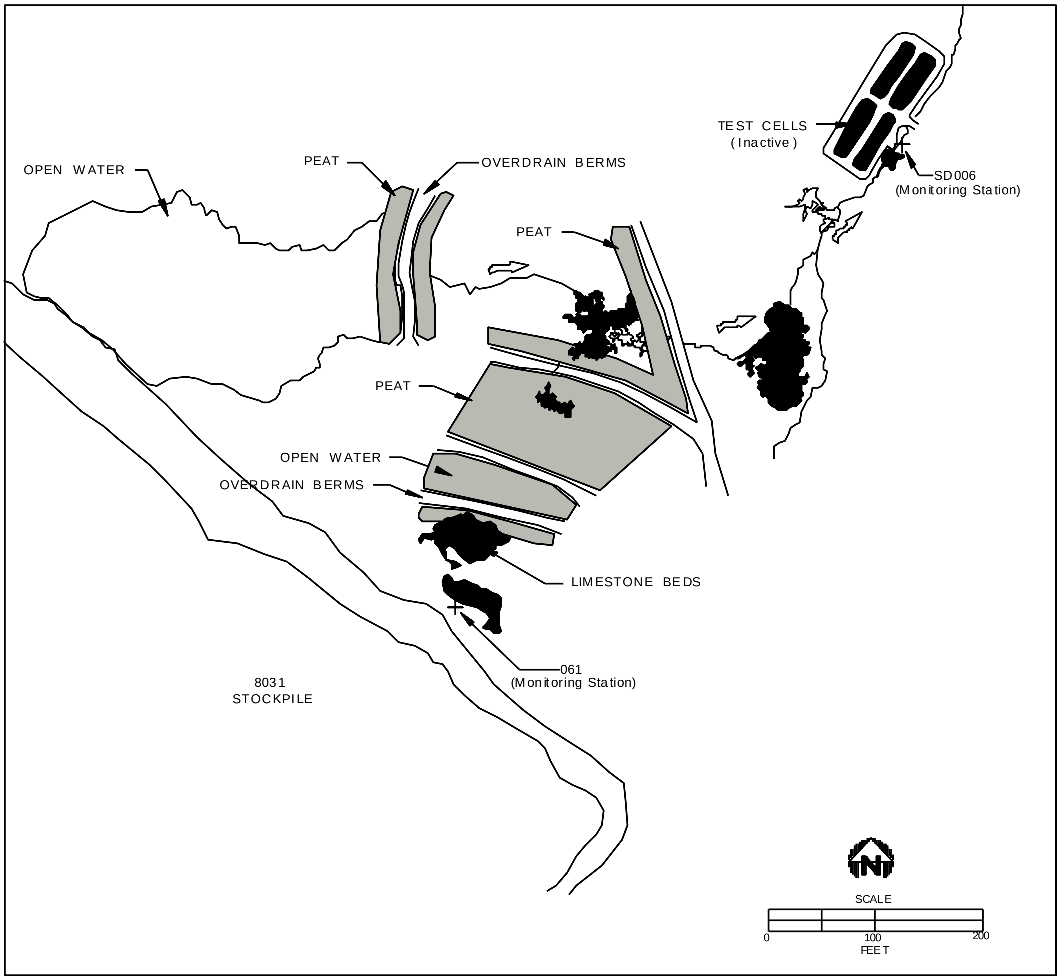

Figure 3. W2D/3D Wetland

<u>W1D system</u>

The majority of the flow to this system originates from the base of the 8018 stockpile, although additional seepage from the 8031 stockpile also drains to this area (Fig. 4). Annual average flow from the stockpile, from 1986-94, ranged from 75 - 150 L/min, with peak flows exceeding 750 L/min. Water quality samples were generally colleted twice per month during the period of flow (generally March - December). From 1992-94, the average flow to the wetland was 125 L/min and had an average pH of 7.1, 3.94 mg/L nickel, 0.07 mg/L copper, 0.05 mg/L zinc and 0.03 mg/L cobalt (Table 1).

The original W1D treatment system, constructed in the spring of 1992, covered 7000 m^2 and contained a series of 9 berms. In 1993 and 1994, changes were made to the system to disperse flow, minimize channeling and improve contact between the drainage and the substrate. In 1995, the system was expanded by 10,000 m^2, and included an alternating series of overflow and underflow berms. Prior to construction of these berms, the original organic soils were removed; the berms were then built on the mineral soil base and compacted to minimize any future settling.

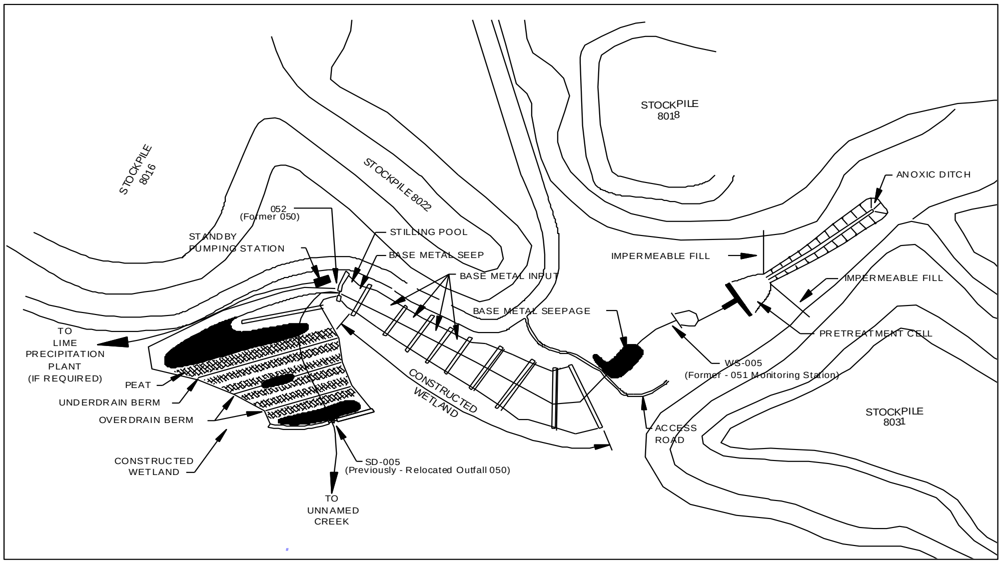

Figure 4. W1D Wetland.

In 1995, the 8018 and 8031 stockpiles were reclaimed. A 30 mil LDPE liner was placed on the 8018 stockpile while the 8031 was covered with local soil and revegetated. Flow and concentrations decreased after reclamation. For 1999-2004, input flow was around 40 L/min, and average metals concentrations ranged from about 0.02 for copper and zinc to 0.76 for nickel (Table 1).

Seep X system

The Seep X system was built in 1995 and included a series of overflow and underflow berms with a dividing berm down the center of the wetland (Fig. 5). The berms were constructed with local soil and were built in a similar manner to those used in the expanded W1D system.

The top of each berm was covered with approximately 5 cm riprap and pipes were used to collect and route water over and through the overflow berm. The underflow berms had about a 30 cm thick layer of coarse limestone at the base to allow water movement under the berm. About a 15-30 cm mixture of peat and peat screenings was placed along all the berms and the .wetland was seeded with cattails

Flow to the wetland comes from a seep from the 8013 stockpile, which for 1999 - 2004 had an average flow of about 100 L/min, with a pH of 7.4, 1.82 mg/L nickel, 0.37 mg/L copper and 0.58 mg/L zinc (Table 1).

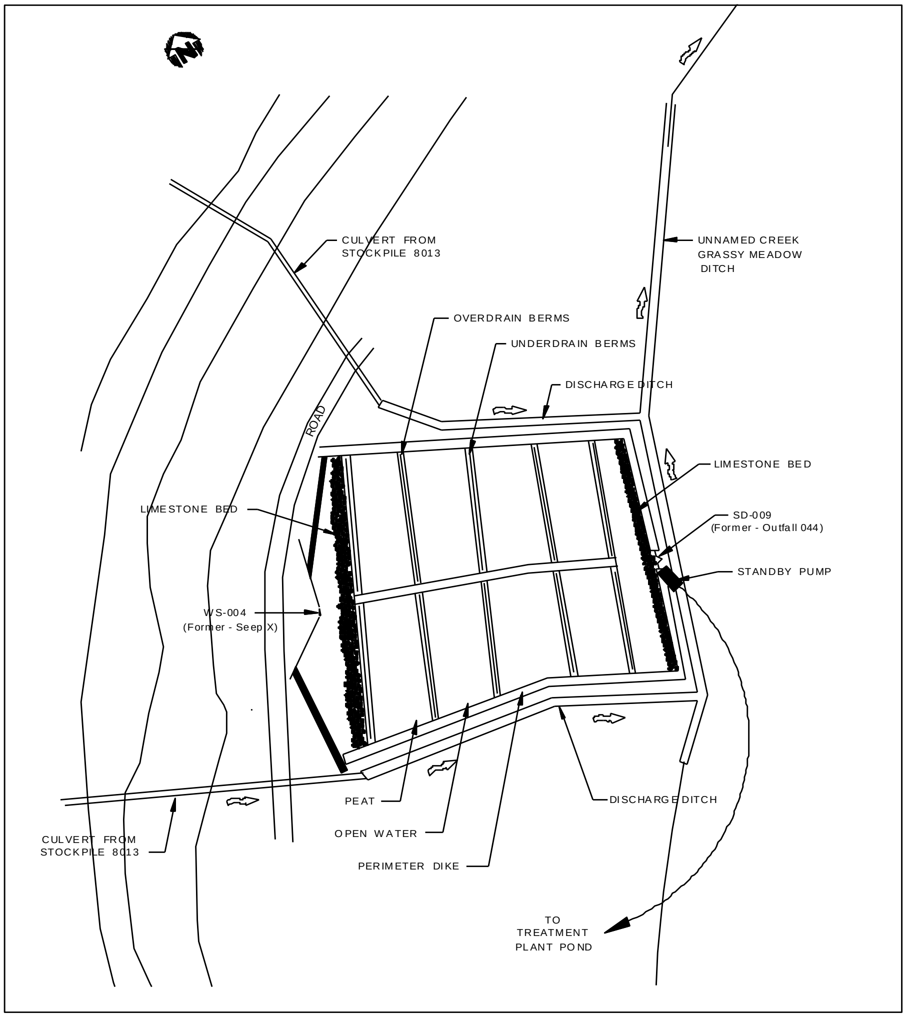

Figure 5. Seep X Wetland.

Seep 1 system

The Seep 1 system was also constructed in 1995 and was built similar to the Seep X wetland. The wetland is about 2500 m^2 and contains 2 underflow and 1 overflow berms (Fig. 6). Input to this system originates as a combination of small seepages and diffuse flow from the 8013 stockpile. A pretreatment system containing peat and limestone was built at the toe of the stockpile in 1992. The pretreatment system increased average pH from 5.4 to over 7 while nickel and copper concentrations decreased 50-70% respectively (Eger et al 2000) Average input metal concentration to the wetland for 1999 - 2004 ranged from 0.043 mg/L for copper to 3.27 mg/L for nickel (Table 1).

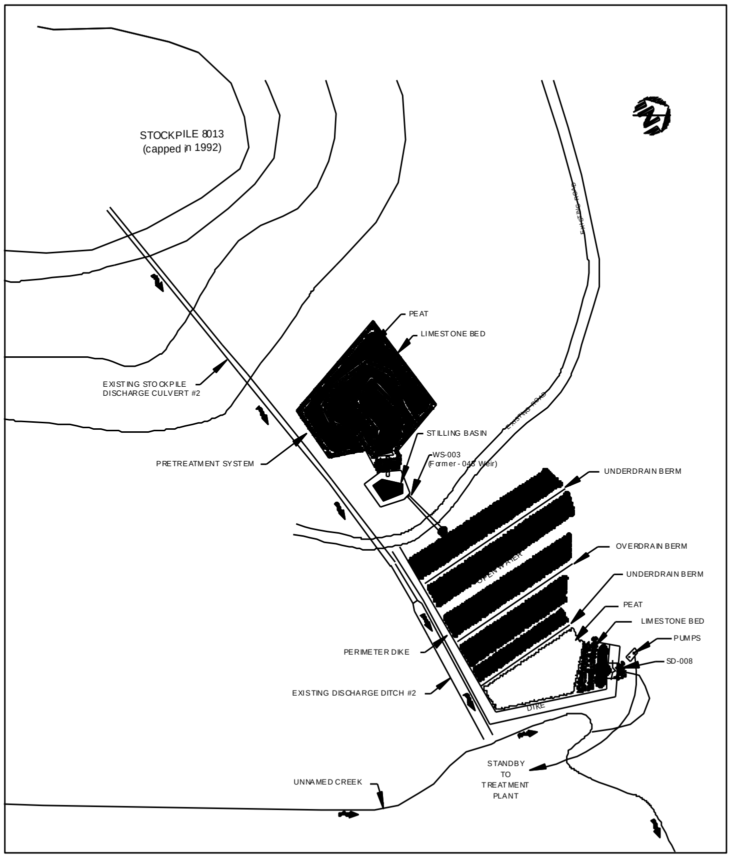

Figure 6. Seep 1 Wetland.

EM 8

This was the newest system and was built in 1997. The wetland covers 16,000 m^2 and does not include any under or overflow berms (Fig. 7). Berms were built to provide access to the wetland so that peat could be placed with a backhoe. Water enters the wetland in a pool area and leaves the pool via three adjustable weirs. Openings were placed in the berms to encourage flow dispersion through the wetland and some of the openings contain stop-log control devices so that water level and flow can be adjusted. For 1999-2004, the input to the wetland had an average pH of 7.4 and metal concentrations ranged from 0.026 mg/L copper to 2.08 mg/L nickel (Table 1).

Methods

Flow

In general, continuous level recorders were installed at the inflow and outflow of each system and were operated from May through October. Each site contains a V notch weir and flows are estimated using a standard weir equation. During the rest of the year, the site was checked twice per month and spot readings of water level were collected.

Water Quality

Samples are collected at most sites twice/month and analyzed for pH, trace metals, (copper, nickel, cobalt and zinc) sulfate and calcium and magnesium. Samples were analyzed by NETS laboratories in Virginia, Minnesota.

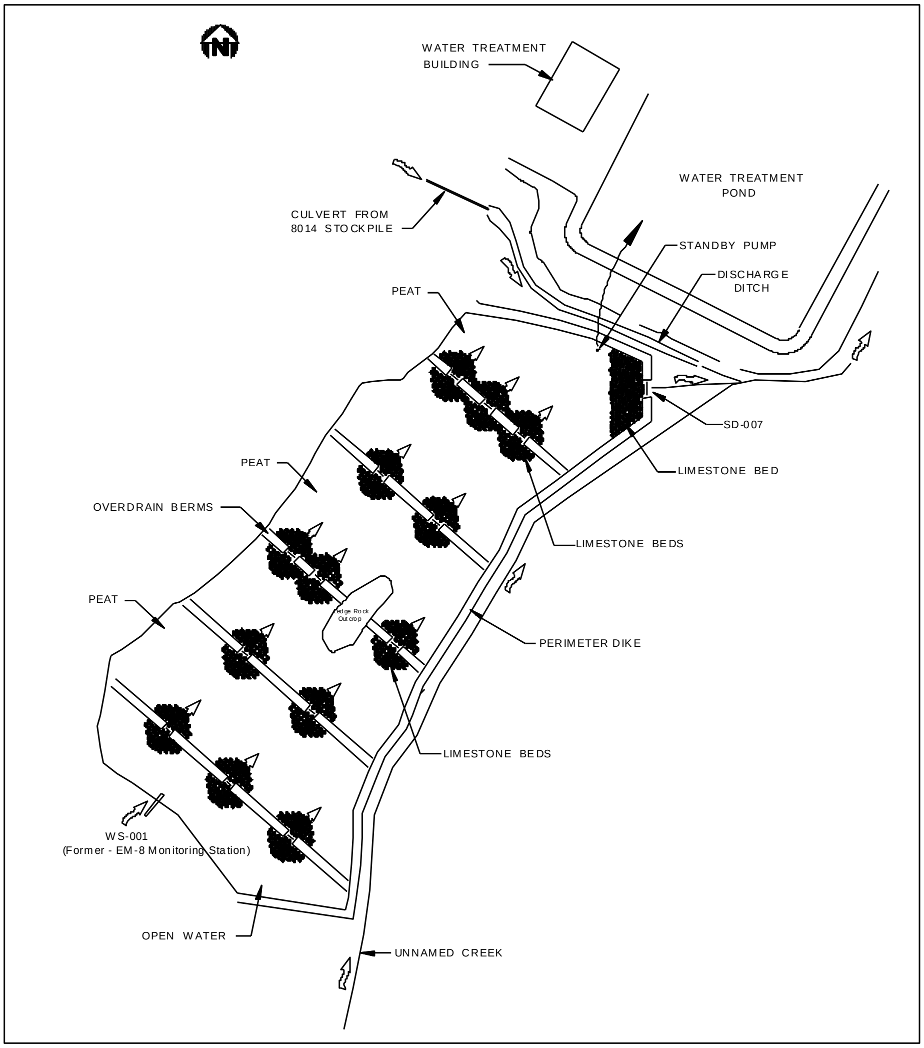

Figure 7. EM8 wetland treatment system.

Results

Although all systems removed metals, the degree of removal varied widely between systems and with time. Metal removal ranged from about 30% for nickel at Em8 to over 90% at W2D/3D (Table 1).

W2D/3D

The W2D/3D system has been in compliance with permit requirements since it was constructed in 1992 (Table 1, Fig. 8). Although, the constructed portion of the wetland treatment system is about 4,200 m^2, there is an additional 12,500 m^2 of natural wetland before the final effluent sample is collected. As a result, the total area available for treatment is on the order of 17,000 m^2 . In 1995, the flat portions of the 8031 stockpile were covered with local soil and vegetation was established. Although no direct measurements of input flow or water quality are possible, a flow reduction of 40% would be expected from the reclamation activities but there would be no change in water quality (Eger and Lapakko, 1981; Eger et al, 1990a, 1990b).

Limited data collected prior to construction of the treatment wetland indicated that the metal concentrations were already reduced to acceptable levels in the natural wetland. The construction of the wetland treatment system with the addition of new substrate increased the efficiency and lifetime. Using a mass accumulation model, the original lifetime of the entire wetland was estimated to be over 100 years. By revegetating the stockpile and reducing the total flow, the estimated lifetime of the system has doubled. Using a model developed for the W1D wetland, this wetland should generate enough metal removal sites each year to balance about ½ of the estimated annual metal load to the wetland and as a result the lifetime can be calculated to be on the order of 400 years (Eger et al, 2002).

W1D

For the period 1992-94, the average annual flow rate was 125 L/min. The average pH of the drainage was 7.1 with 4 mg/L nickel. After the stockpile was capped in 1995 flow and metal concentrations began to decrease. The average flow and concentration for 1999-2004 were almost 70% less than pre-capping values (1992-94; Table 1).

As the input flow and concentrations have decreased, the outfall concentrations have also decreased. Nickel concentrations at the outfall of the original wetland have been generally less than the initial effluent standard of 0.213 mg/L (Fig. 9).

Since the wetland was built to treat the volume and quality of drainage flow from the stockpile prior to reclamation, the decrease in flow and concentration has dramatically increased the projected lifetime of the system. Currently there appears to be an approximate balance between the annual production of new removal sites and the annual input of nickel, which suggests that the wetland should be capable of treating the drainage in perpetuity (Eger et al, 2002)

Seep X

Seep X originates from the 8013 stockpile that was reclaimed in 1991. Since the wetland was constructed in 1995, the flow into the wetland has averaged about 100 L/min. The average pH and metal concentrations in 1999-2004 were about 20% higher than the input in 1995-97 and metal concentrations in the outfall increased by 40- 80 % (Table 1).

Seep 1

This seep also originates from the 8013 stockpile and although the flow was low (20-27 L/min), this seep contained the highest metal concentrations at the mine.

Average concentrations were substantially higher in 1999-2004 then in 1995-1997. Nickel increased by about 25% while copper concentrations doubled. Despite the large increase in copper concentrations, outfall copper concentrations decreased but nickel removal decreased from about 66% in 1995-1997 to 50% in 1999-2004.

Em8

Em8 has the largest flow of any of the seeps. The average flow measured between1995-1997, after the 8011 stockpile was reclaimed, was 400 L/min. Nickel removal was only about 33%, the lowest efficiency of any of the wetland systems.

Table 1. Wetland Treatment Summary, LTV Dunka Mine.

Site	Time	Size m^2	Flow	Design Factors - Input					Performance Factors - Output				
				Metal Concentrations (mg/L)					Metal Concentrations (mg/L)				
			L/min	pH	Ni	Cu	Co	Zn	pH	Ni	Cu	Co	Zn
W2D/ 3D	1992 to 1994	4200	75*	7.0	1.9	0.05	0.02	0.05	7.0	0 .08	0.004	0.002	0.008
	1996-98		45	7.0	1.9	0.05	0.02	0.05	7.0	0.06	<0.001		<0.001
	1999 to 2004[a]		45	7.0	1.9	0.05	0.02	0.05	7.4	0.036	0.002		0.006
W1D	1992 to 1994	7000	125	7.07	3.98	0.068	0.036	0.052	7.18	0.36	0.008	0.008	0.013
	1996-98		57	7.3	0.74	0.03	0.009	0.021	7.48	0.19	0.003	0.001	0.006
	1999 to 2004		38	7.26	0.76	0.020		0.019	7.34	0.10	0.002	<0.001	0.006
Expanded	1996 to 1999	17,000	57	7.3	0.74	0.03	0.009	0.0216	7.38	0.18	0.005	0.001	0.011
	1999 to 2004		38	7.26	0.76	0.020		0.019	7.37	0.099	0.002		0.011
Seep 1	1995 to 1997	2500	20	6.94	5.39	0.15	0.13	0.65	7.23	1.85	0.05	0.04	0.29
	1999 to 2004		27	7.28	6.64	0.325		0.928	7.34	3.27	0.043		0.385
Seep X	1995 to 1997	10,000	100	7.03	1.50	0.33	0.08	0.48	7.13	0.61	0.08	0.02	0.21
	1999 to 2004		103	7.38	1.82	0.37		0.58	7.35	1.09	0.11		0.37
EM8	1999 to 2004	16,000	400[c]	7.41	2.08	0.026		0.052	7.30	1.40	0.009		0.032
Water Quality Standards[b]													
Current permit (Acute toxicity)									6.5-8.5	Final Acute Value ≤.1			
Chronic toxicity									6.5-8.5	0.508	0.023	0.050	0.343

[a] estimated values

[b] based on a hardness of 400 mg/L $CaCO_3$ (MN Rules 7050)

[c] 1995-1997 flow

[d] based on site specific testing

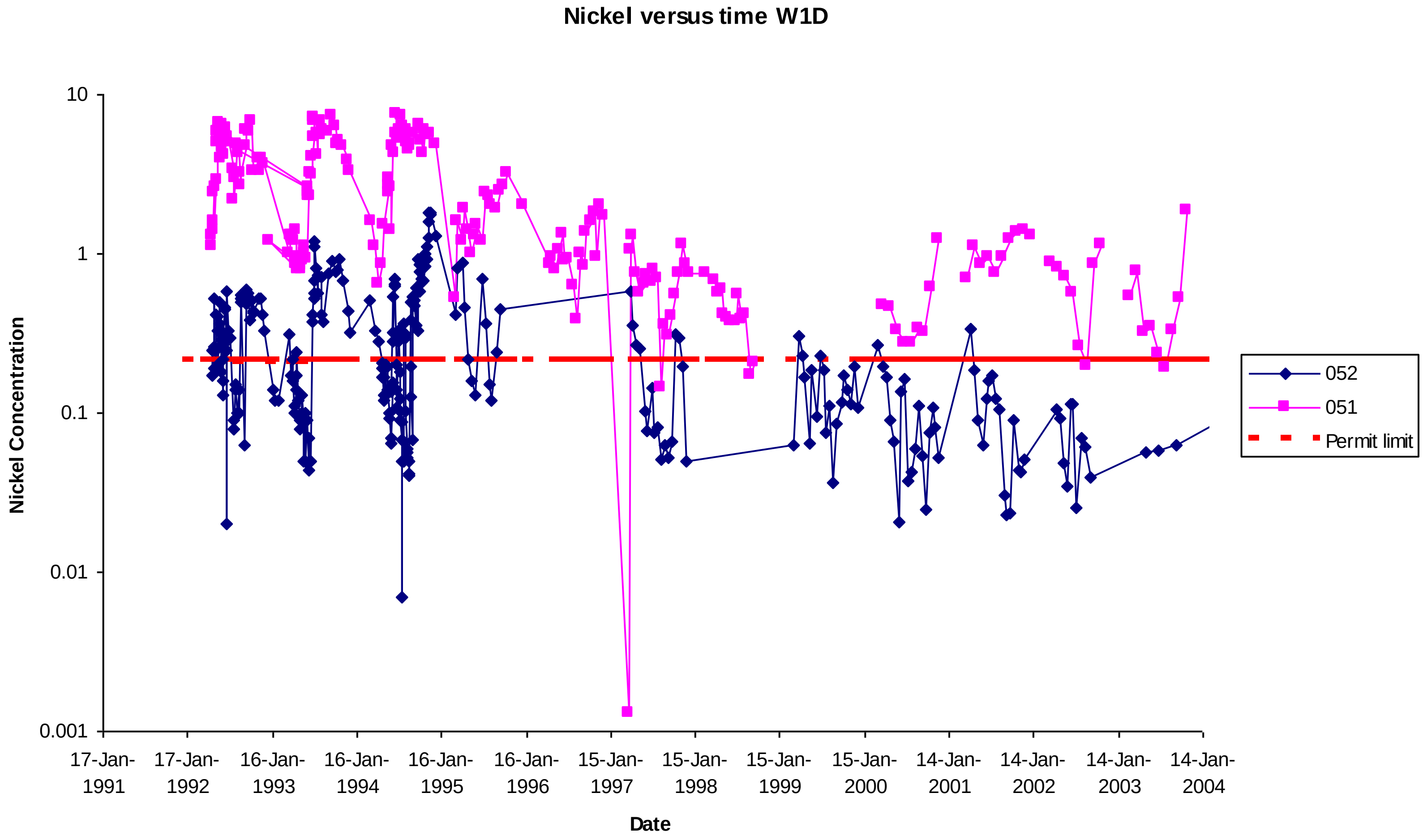

Figure 8. Nickel vs. time, W1D input (051) and outfall (050) of original wetland treatment system 2002).

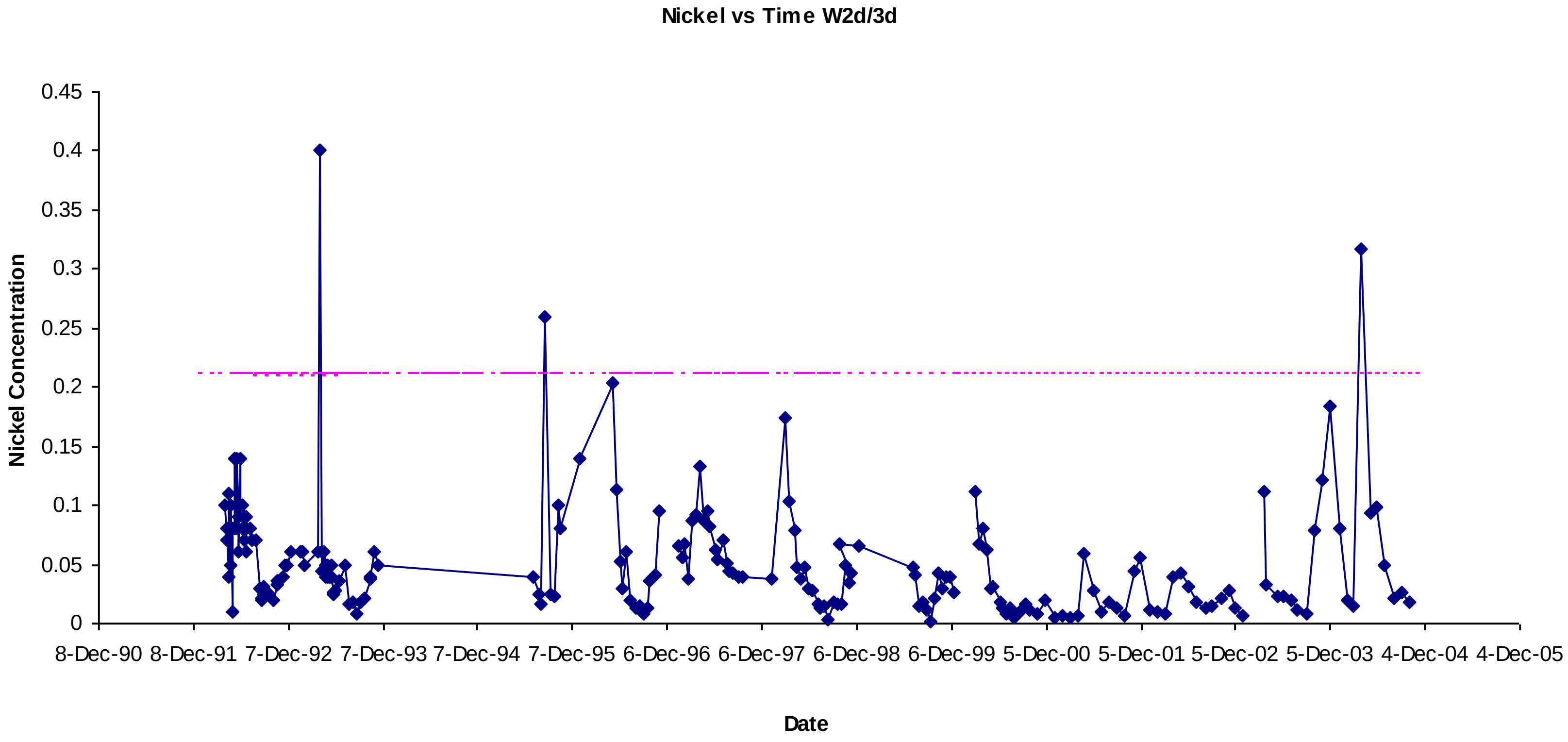

Figure 9. Nickel versus time, outfall of W2D/3D system, with original permit limit

Discussion

Although all the wetland treatment systems removed metals, removal varied substantially between systems and among metals. While the removal efficiency is important, the critical issue at this site was compliance with regulatory standards. Since the water quality issues at the Dunka were not anticipated when the mine was built, standards have been modified over time and the current standards would probably not be applicable to new mining operations in the state

Water Quality Standards

In Minnesota, all effluents must be non-toxic. Therefore at a minimum, metals concentrations must be below the Final Acute Values (FAV) (MN rules Chapter 7050). Since metal toxicity decreases as hardness increases, permissible metal concentrations generally increase with hardness up to a maximum allowable hardness of 400 mg/L as $CaCO_{3.}$

For the metals at Dunka, the final acute values range from 126 ug/L for copper to 9136 ug/L for nickel (Table 2). Due to limited toxicity data on cobalt, no provision for hardness is included in the rules. LTV conducted a site specific bioassay study which demonstrated that cobalt toxicity decreased as hardness increased (LTV).

Originally, permit standards for the mine were based on chronic toxicity values, which were up to an order of magnitude lower than acute values (Table 2). When the company went bankrupt several years after the mine had closed, it sought a variance for several of the discharges.

The new permit based standards on FAV, but also included biological monitoring in the receiving stream to insure that the higher concentrations were not producing any adverse impacts on the aquatic system.

Since the seeps at Dunka contain a mixture of metals, the current permit assumed that the toxicity of the effluent would be equal to the sum of the toxicities from the individual metals. Therefore in order to insure that the effluent was non-toxic, the permit requires that

$$\sum \frac{\text{Concentration of metal}}{\text{Final acute value}} \leq 1$$

Performance for the wetland systems has varied substantially; effluent from the W2D/3D and W1D systems met the original chronic standards while effluent from the Seep 1 and Seep X systems could not even consistently meet the acute toxicity values (Fig. 10, and 11) Performance was particularly poor during winter and early spring. Maximum FAV occurred at Seep 1 during a high flow period in July 1999 when the pretreatment area could not neutralize the acidic drainage. The pH into the wetland reached a minimum of 5, and the maximum values for copper and nickel were on the order of 2 and 14 mg/L respectively.

Table 2. Minnesota Water Quality Standards. Concentration in ug/L, hardness in mg/L $CaCO_3$.

Trace Metal	Standard	Hardness, 50	Hardness,100	Hardness 200	Hardness 400
Copper	CS	6.4	9.8	15	23
	MS	9.2	18	34	63
	FAV	18	35	68	126
Nickel	CS	88	158	283	508
	MS	789	1418	2549	4568
	FAV	1578	2836	5098	9136
Zinc	CS	59	106	191	343
	MS	65	117	211	3784
	FAV	130	234	421	7567
Cobalt*	CS	2.8	2.8	2.8	2.8
	MS	436	436	436	436
	FAV	872	872	872	872

Standards: CS = Chronic Standard; MS = Maximum Standard; FAV = Final Acute Value

All values in ug/L

The chronic standard (CS) is defined as "the highest water concentration of a toxicant to which organisms can be exposed indefinitely without causing chronic toxicity". This is considered the ambient in stream water quality standard, which must be met on an average basis.

The maximum standard (MS) is defined as "the highest concentration of a toxicant in water to which aquatic organisms can be exposed for a brief time with zero to slight mortality. The MS equals the FAV divided by two." This is considered the ambient in stream concentration that cannot be exceeded on any given day

The Final Acute Value (FAV) is defined as "an estimate of the concentration of a pollutant corresponding to the cumulative probability of 0.05 in the distribution of all the acute toxicity values for the genera or species from the acceptable acute toxicity tests conducted on a pollutant". By rule, any wastewater discharge must not exceed these standards at end-of-pipe at any time.

*LTV conducted site specific testing and demonstrated that cobalt toxicity was a function of hardness. The cobalt chronic value for the Dunka Mine was increased to 50 ug/L.

Additional variances were granted for the Seep 1 and Seep X systems for spring flow and the company instituted a contingency plan to avoid water quality violations. If the concentrations in the outfall exceed the variance levels, water is collected and pumped to the beginning of the W1D system. Although this has been effective, it is a costly and cumbersome procedure.

Part of the explanation for the difference in performance appears to be the size of the treatment systems. Before the systems were built, pilot tests were conducted to determine the ability of wetlands to treat the stockpile drainage and to develop criteria to design full scale systems (Eger et al, 1989, 1991, 1993, 1994, 1996). Based on these tests the average areal removal rate for nickel was about 40 mg nickel/m^2 day. Using this value and the estimated nickel loading to the wetland, the area required to treat each seep was calculated. Area ranged from about 0.4 hectare (4100 m^2) for Seep 1 to about 3.2 hectares (32,200 m^2) for Em8 (Table 3).

In general, adequate treatment was achieved when the size of the wetland exceeded the calculated area. Originally the W1D system was not effective in meeting the original permit requirements but performance improved after the system was expanded (Eger et al 1996). After the stockpile was reclaimed, the original part of the system met the criteria and currently meets the original water quality standard.

One of the most common reasons for the failure of wetland treatment systems, is that the systems were too small (ITRC, 2003). Wetlands can be effective but in general sufficient land must be available. Insufficient area was available at both Seep 1 and Em8 and the current systems are only about ½ of the calculated size.

Although the size of the Seep X wetland appears to be adequate for nickel removal, the effective treatment size is substantially smaller than the total size of the system. This system contains a series of soil berms that reduces the effective treatment area by about 20 %. Field observations revealed that the flow is not equally divided between the two cells, and that the northern portion of the wetland receives about 3 times as much water as the southern section.

Water is routed through the overflow berms by a series of pipes, which further tends to concentrate flow and lessen contact with the substrate. In addition, the limestone drains were not

effective in transmitting flow through underflow berms. The hydraulic gradient in the system is only about 1% and the permeability of the peat mixture is at best on the order of 10^{-3} cm/sec. Under these conditions, the drains could only transmit a few percent of the flow. Visual observation confirmed that a large volume of water was moving over the top of the underflow berms. Seep X also flows during most of the winter and channelization increases dramatically as areas with little water movement freeze. Metal removal decreases too less than 10% during the winter and the FAV of outfall is essentially the same as the input (Figure 10). Channelization has also been observed in the Seep 1 system and despite the inclusion of level maintenance structures in Em8, flow has not been evenly distributed partially due to a lack of maintenance and adjustment of the level control structures.

In 2004 substantial renovation was preformed on the Seep 1 and Seep X systems. The goal was to provide better flow distribution and increase the contact of the drainage with the peat substrate. Berms, which had subsided, were raised by adding limestone to the surface and additional peat was added to some of the open water areas to increase the amount of reactive surface area. Maintenance work on the EM 8 system is scheduled to occur during the summer of 2005. The performance of these systems will be monitored to determine the success of the renovation.

In contrast, maintenance requirements for the W2D/3D and the W1D expanded system have been minimal. The systems were built with sufficient area to treat the original flow and water quality and reclamation activities have further reduced the input load, so that both systems are estimated to be have lifetimes well in excess of 100 years. Based on a model that calculates the addition of new removal sites, it appears that for the W1D system, there are enough new removal sites generated each year to remove the annual nickel load from the stockpile. As a result, the wetland can theoretically remove nickel in perpetuity.

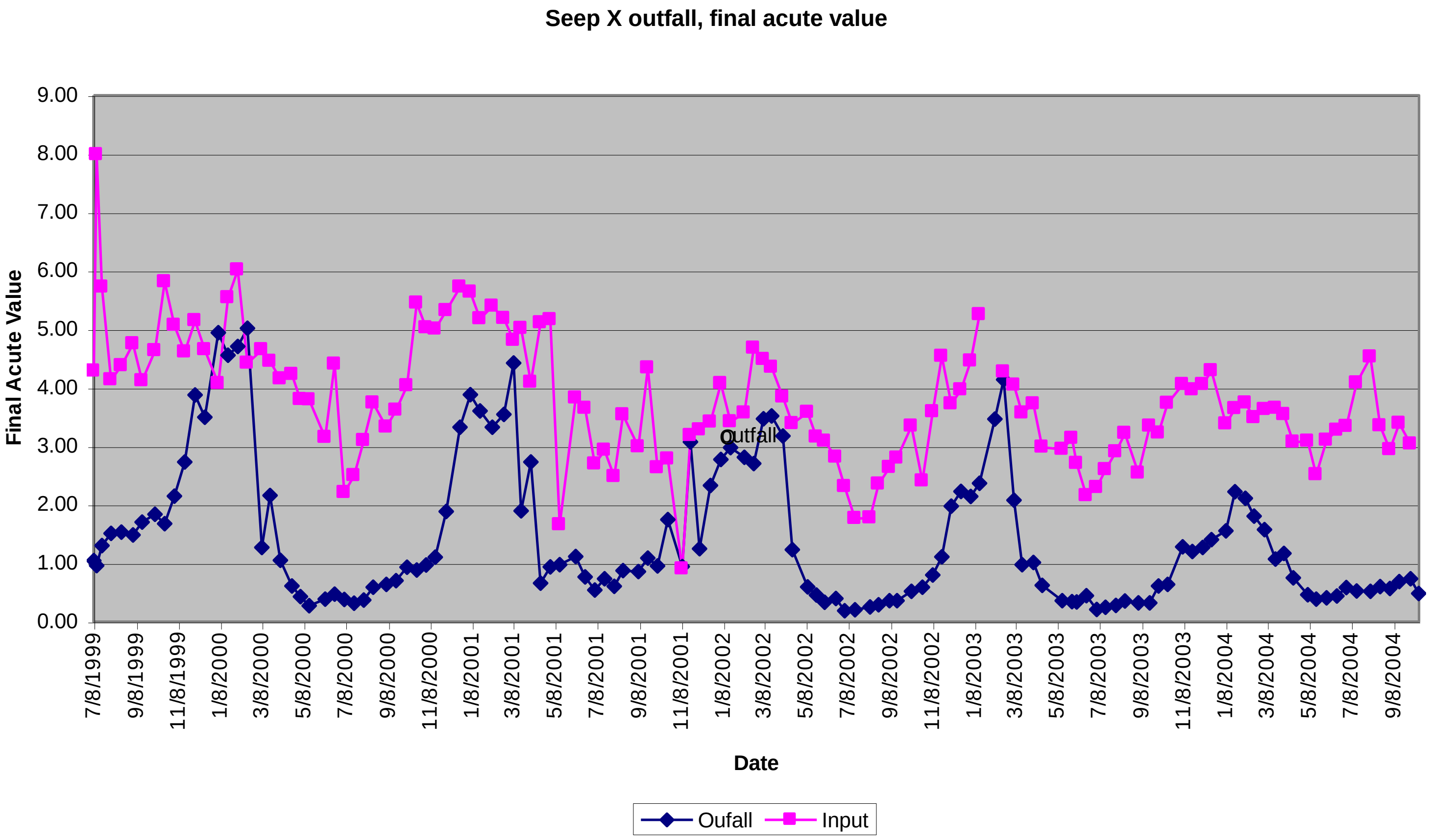

Figure 10. Final acute values, inflow and outfall, Seep X wetland

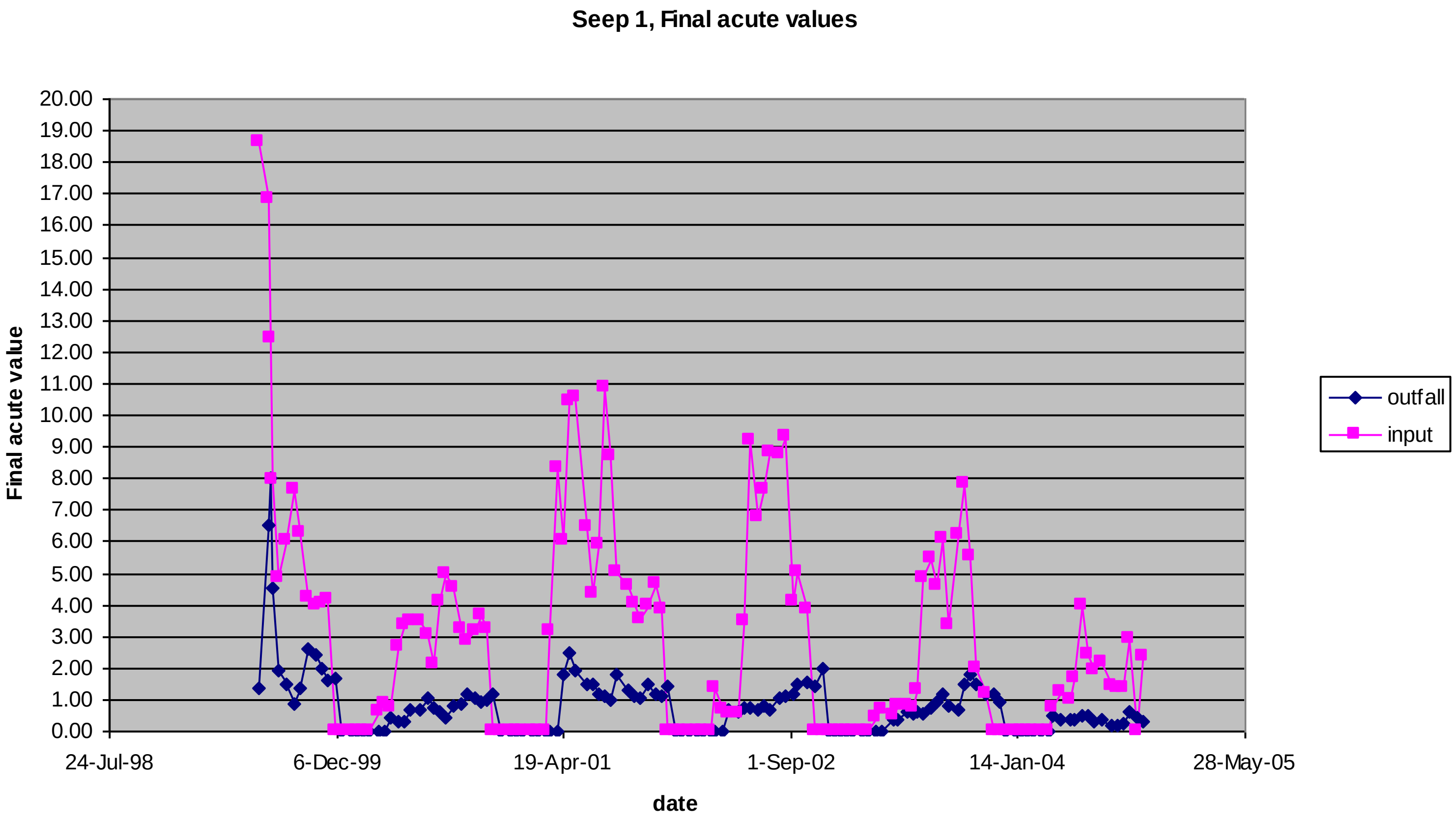

Figure 11. Final acute values, inflow and outfall, Seep 1 wetland

Table 3. Wetland sizing

	Input			Area m^2		
Seep	Average Flow L/min	Average Concentration mg/L	Daily load mg/day x 10^3	Calculated*	As Built	Expanded
<u>W2D/3D</u>						
Original	75	2	216	5,000	4200[a]	
After Reclamation	45 est[b]	2	130	3,000		
W1D	150	4	864	23,000	7000	17,000[c]
Original After Reclamation	40	0.8		1,200		
Seep 1	20	5.4	156	4100	2500	
Seep X	100	1.5	216	5000	10,000	
Em8[e]	400	2.1	1210	32,200	16,000	

*Area required. Based on an areal removal rate for nickel of 40 mg/m^2 day, which is average from test cells.

[a] This is the size of the constructed portion. There is about an additional 2 ,000 m^2 of natural wetland before the discharge monitoring point (SD-006).

[b] The 8031 was covered with 2 feet of local soil and revegetated. After successful reclamation flow is reduced by about 40% (based on field data from test stockpiles and HELP model).

[c] wetland was expanded in 1995.

[d] stockpile was capped with a 30 mill LDPE liner. Average May-October flow was reduced to 38 L/min, and average nickel concentration decreased to 0.8 mg/L.

[e] flow data from 1997. Data from 2001-2003; average flow 1140, which is higher than pre-reclamation flow data being checked.

For Seep 1, Seep X, the systems were built after the stockpile was capped in the fall of 1991, so there were no changes due to reclamation activity.

Note: Average flow is based on May-October records when continuous flow records are available.

Conclusion

Wetland treatment systems removed metals from all seeps at the Dunka Mine but efficiency varied substantially among systems. The key factor in wetland success was designing a system large enough to treat the incoming metal load. The construction of soil berms reduced the effective treatment area and berms with under drains could only transmit a small portion of the overall flow.

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