SOLVING MINE DRAINAGE PROBLEMS AT SOUDAN STATE PARK – ONE STEP FORWARD, TWO STEPS BACK[1]

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Abstract. Soudan State Park contains Minnesota's first iron mine and offers tours through parts of the old underground mine workings. The mine began in 1884 as an open pit before switching to an underground operation in 1892. U.S. Steel operated the mine from the 1920's until it closed in 1962.

The average mine dewatering discharge is around 60 gallons per minute and contains copper and cobalt in excess of the permit standards of 0.020 mg/L copper and 0.005 mg/L cobalt. Annual average concentrations have varied from 0.083 to 0.5 mg/L copper and 0.006 to 0.026 mg/L cobalt. Despite at least 60 years of discharge, all the copper and cobalt are removed in about a 5-acre portion of a downstream wetland. Copper concentrations in the peat ranged from around 100 to 3380 mg/kg, and cobalt from 20 to 260 mg/kg. Both metals are strongly bound to the peat; less than 0.5% was removed in laboratory extraction tests

About 94% of the total copper and 44% of the total cobalt come from one area in the mine. In 1998, DNR proposed to treat this water in an organic substrate/ limestone bed. Remaining low levels of metals in the mine discharge would be removed within the 5 acres of the wetland that already had elevated concentrations. To compensate for the use of the wetland, an equivalent area of wetlands would be restored in a state park in the southern part of the state. This proposal was approved in 1999 and the wetland mitigation was completed.

Despite having approval, land ownership issues and some internal reluctance about using a natural wetland stalled construction. In 2002, the Department signed a compliance agreement and installed an ion exchange unit to remove the majority of metals from the largest source. As soon as the unit was installed, a white precipitate appeared in the inflow water and plugged the unit. In 2006, the Department was fined and signed a stipulation agreement. The current proposal is to construct a wetland at the park to treat the entire mine flow. The estimated cost for this proposal is about 4-5 times the original treatment plan developed in 1998.

Additional Key Words: wetland treatment, copper, cobalt

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Introduction

Soudan State Park provides an opportunity for one of the most unique park experiences anywhere in the United States. The park contains Minnesota's first iron mine and offers tours through parts of the old mine workings. The mine began in 1884 as an open pit but switched to an underground operation in 1892. U.S. Steel operated the mine from the 1920's until 1962, when it closed. In 1965 the mine and surrounding land were donated to the State of Minnesota and is currently operated by the Department of Natural Resources, Division of Parks and Recreation (Fig. 1).

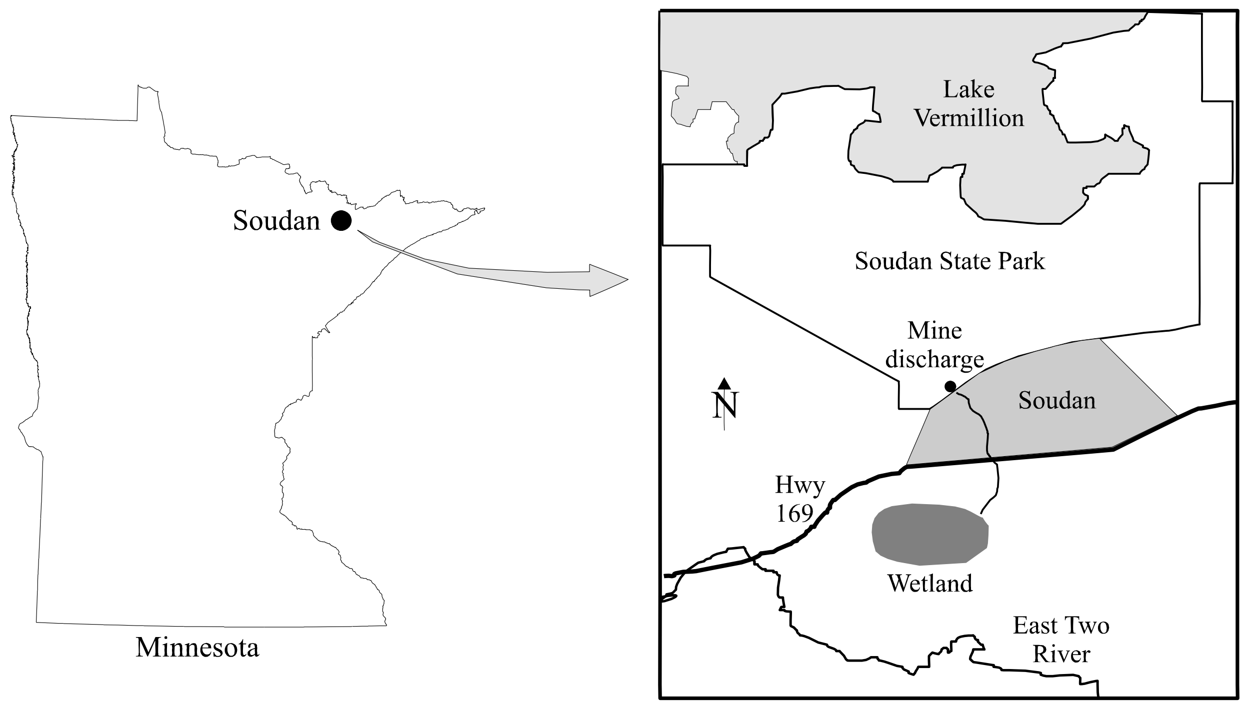


Figure 1. Soudan State Park.

In 1990, as part of the permit application process, water samples were collected from the mine discharge. These samples contained elevated concentrations of Cu. Limited sampling in 1993 confirmed the existence of elevated Cu, and in 1994 a more thorough sampling of the mine outflow was established. Total Cu concentrations in 1994 ranged from 0.11 to 0.98 mg/L. Cobalt concentrations were also elevated in some of these samples and ranged from <0.01 to 0.040 mg/L. All other parameters were within acceptable limits for discharge. In 1996 the Minnesota Pollution Control Agency (MPCA) issued a NPDES permit to the park that required a plan to mitigate the elevated metal levels in the discharge.

In March of 1996 a study was initiated to:

1. Identify the major sources of Cu and Co in the mine.
2. Determine the seasonal variation in flow and water quality.

3. Determine potential treatment approaches to achieve discharge limits.
4. Examine the concentrations in the waters that receive the mine discharge.

Water quality and flow monitoring sites were established both within and outside the mine. Field and laboratory studies were designed to determine the feasibility of using passive treatment systems to remove metals from the discharge. Two wetland cells began operation in August 1996, and laboratory column experiments using limestone and organic substrates began in the winter of 1997.

Background

Open pit mining began in 1884 and continued until 1892, when safety issues dictated that under-ground mining methods were needed to continue to mine the steeply dipping ore body. Over 15.5 million long tons of high-grade iron ore were removed from the mine during its production lifetime. The mine is about 2400 feet deep and contains 18 levels.

The iron ore was a massive exceptionally hard bluish-gray hematite, containing over 60% Fe that sold at a premium price. The waste was primarily jasper, although some greenstone material was also encountered in the mine. The ore body also contained small quantities of quartz, chlorite, apatite, and locally pyrite, chalcopyrite, and other copper minerals. Chalcopyrite and associated pyrite tend to be found around the perimeter of the hematite ore bodies and are moderately common in portions of the western part of the mine (Klinger, 1960). Native copper, although sparse, occurs primarily as a coating on joint surfaces in the ore.

Mine water has been discharged ever since the mine began. Although it is not known exactly when the discharge was moved to the present location, some of the old miners recall that the discharge was flowing through town in the 1940s. Water enters the mine through a series of open pits and fractures, with some flow occurring on all levels of the mine (Fig. 2). Water flows along small ditches on the side of the mine drifts and is collected in a sump on each level. Pumps are located on three levels to lift the water out of the mine (Maki,1996).

Methods

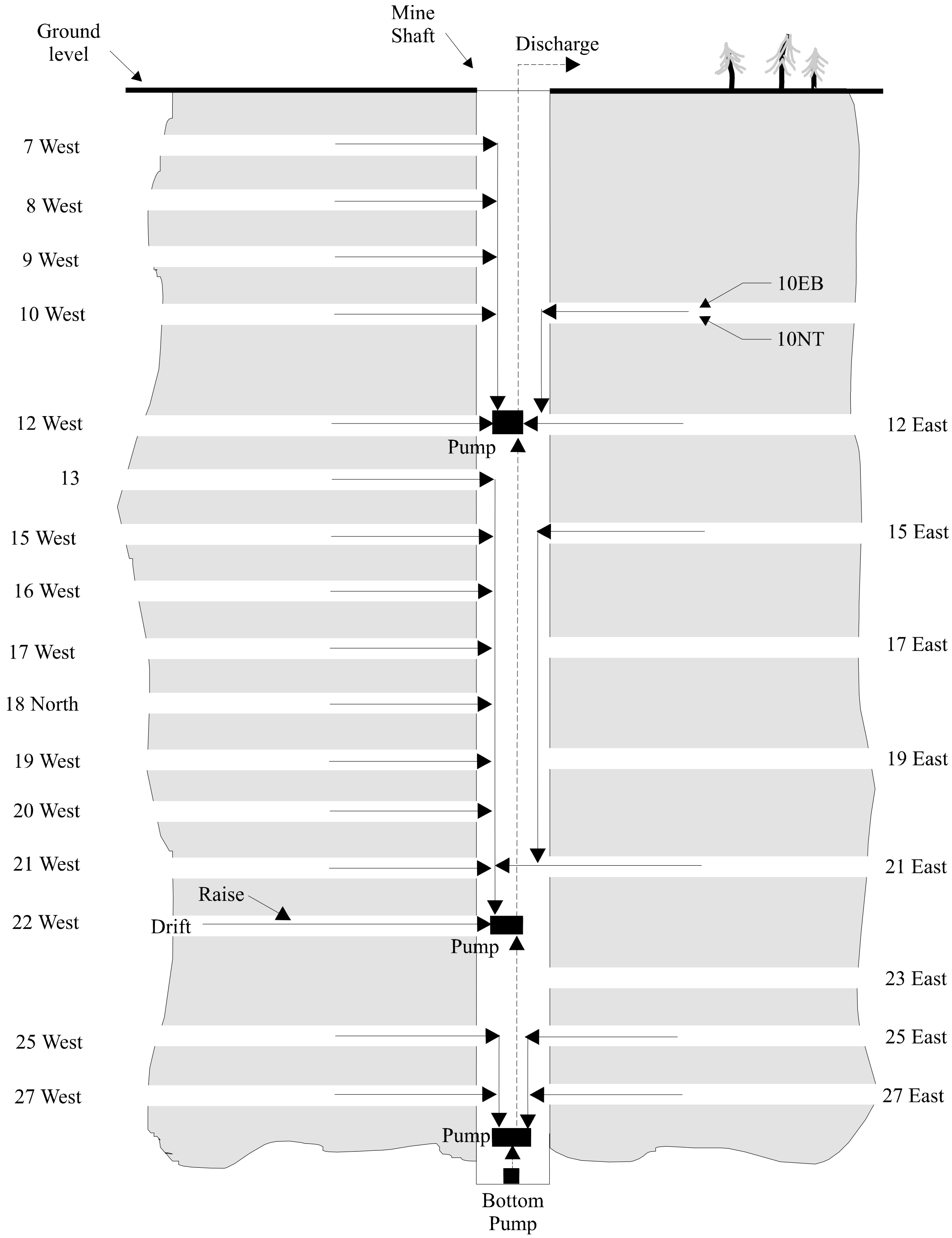
In-mine Sampling

Water quality and flow monitoring stations were developed at each level within the mine (Fig. 2). Water samples were collected about once per week during the high flow period of spring melt, and decreased to about once per month during low and base flow periods. Routine analyses included pH, specific conductance, and total Cu and total Co. Occasionally samples were analyzed for other trace metals, filtered Cu and Co, major cations and anions.

Mine Discharge

Samples were collected twice a month at the discharge outlet (P010) and analyzed for pH, specific conductivity, Cu, Co and total suspended solids (quarterly for Fe, Al and Mn).

Figure 2. Flow and sample sites in Soudan Mine.



Downstream Sampling

Site selection. The mine water discharges to a small ditch which flows through town, passes under the highway and flows through a wetland prior to discharging to the receiving stream (East Two Rivers) (Fig. 3). A network of sampling sites was established to evaluate the impact of the discharge on the downstream receiving waters. Samples were initially collected upstream of the highway (site Highway 169) and as the water left the wetland at the railroad crossing (site RRX).

In 1998, three surface water sites were established within the wetland (sites W37, W11, W33; Fig. 3). The monitoring sites were placed in areas of the wetland where flow had channelized so that a representative samples could be collected. Surface water and shallow groundwater were also collected from within the wetland at two sites (sites 3, 4, Fig. 3).

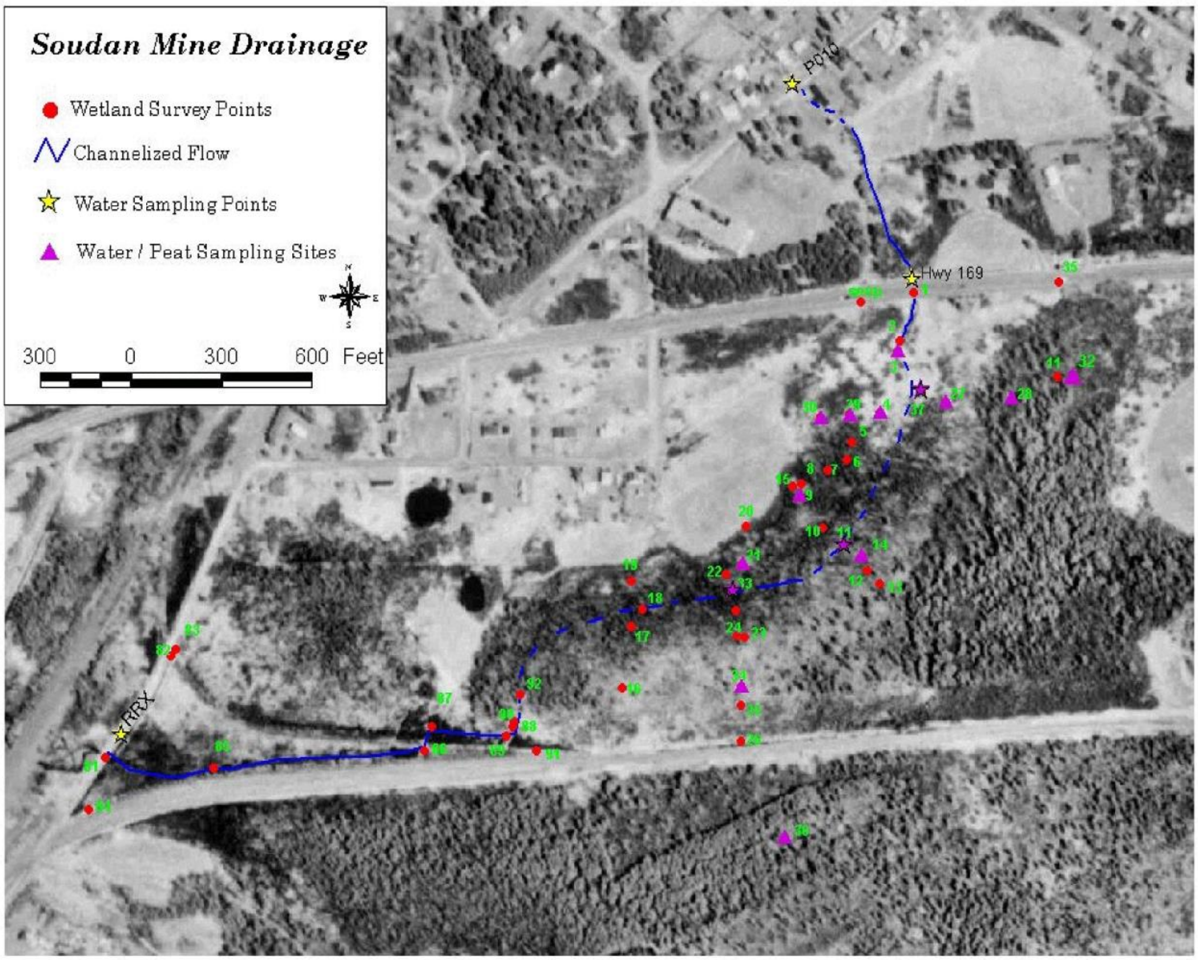


Figure 3. Location of downstream sample sites, Soudan Mine.

Substrate samples. In 1998, peat samples were collected from sites in the wetland. Samples were collected with a Macauley peat sampler, typically at 0-20 cm and 20-50 cm depths. Samples were dried, blended, sieved to -80 mesh, and totally digested with a mixture of HC1 and HNO_3

using a microwave procedure. Samples were analyzed for copper and cobalt by the Department of Agriculture using atomic absorption spectrophotometry.

Water samples. Samples were collected monthly (May through October) from three surface sites within the wetland (W37, W11 and W33), a site prior to the wetland (Hwy 169) and at a site near the outlet of the wetland (RRX). Samples were also collected from two more surface sites along with well samples (3 and 4) on three dates during the summer. A grab sample of flowing water (when possible) was collected at the surface sites. Well were purged prior to sample collection.

Results

In-Mine Sampling

Flow. Flow varied both among and within sites. Most of the flow came from the upper levels of the mine (level 12 and above) which were most influenced by rainfall and snowmelt. The highest flows were recorded during spring melt in April and May. Level 12 produced most of the water, ranging from around 12 gpm in the winter to 100 gpm in May 1996.

Flows generally decreased in the deeper levels of the mine and tended to be relatively stable, and were on the order of a few gallons per minute. Flows at all levels were lowest during the winter months. A more complete discussion of flow in the mine is presented in a hydrology report prepared by Maki (1996).

pH. With the exception of water from 4 sites, the pH in the mine was circumneutral, generally ranging from 6.5 to 7.5. The mean pH of the mine outflow ranged from 6.7 in 1996 to 7.6 in 1999 and 2000 (Table 1).

Copper. The highest copper concentrations were measured at site near the top of the mine (site 10NT). The average total Cu concentration from February 1997 through August 1997 was 16.5 mg/L and the maximum Cu concentration of 31.5 mg/L occurred during spring high flow. Filtered Cu values at 10NT were essentially the same as the total values.

Elevated Cu values were also found at three additional sites deeper in the mine (13, 21W and 27W) (Fig. 4). Total Cu concentrations were almost two orders of magnitude lower than 10NT, and generally ranged from 0.2 to 0.3 mg/L.

Copper concentrations in the discharge (site P010) were highest in 1997, and averaged 0.5 mg/L, or 25 times the current standard. Concentrations were markedly lower in 1998 to 2000 and ranged from 0.083 to 0.090 mg/L, or about four times the standard (Table 1).

Cobalt. Cobalt concentrations in the mine discharge are about an order of magnitude less than Cu values. Sites with elevated Cu tend to have elevated Co. The maximum cobalt concentration was 0.4 mg/L at 10NT, and most cobalt values were between 0.2 and 0.3 mg/L (Fig. 5). There was essentially no difference between total and filtered values.

Table 1. Water quality of Soudan mine discharge (permit site P010), 1993-94, 1996-2000.

Year	Average Values						Number of Samples
	pH	Specific Conductance Φmho/cm	Copper (mg/L)	Copper Limit[2] (mg/L)	Cobalt (mg/L)	Cobalt Limit[2] (mg/L)	
1993	7.6[1]	2350[1]	0.361	0.020	Not Measured	0.005	1-8
1994	7.4	2280	0.358	0.020	0.022	0.005	13-14
1995	no samples collected						
1996	6.7	1570	0.466	0.020	0.019	0.005	23-24
1997	6.9	1530	0.502	0.020	0.026	0.005	23-26
1998	7.4	2390	0.090	0.020	0.019	0.005	24-25
1999	7.6	1860	0.083	0.020	0.006	0.005	24
2000	7.6	1720	0.084	0.020	0.008	0.005	22

[1]One sample [2]Discharge limits established by Minnesota Pollution Control Agency

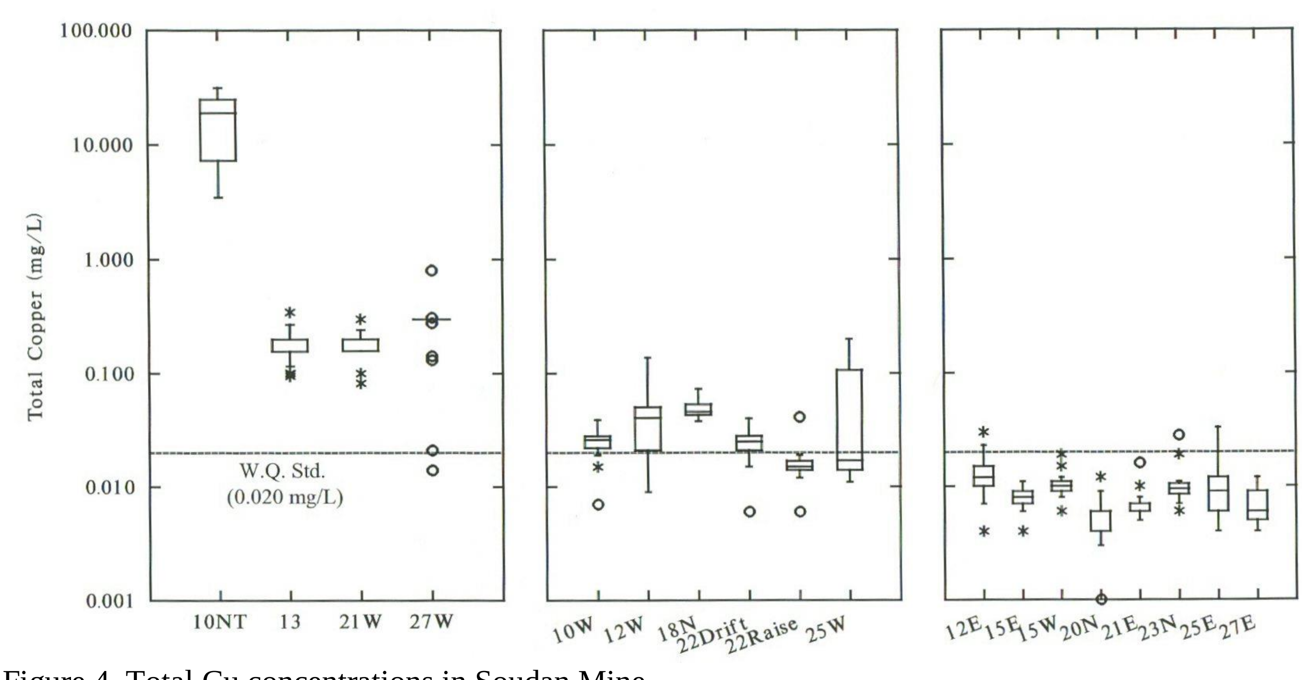


Figure 4. Total Cu concentrations in Soudan Mine

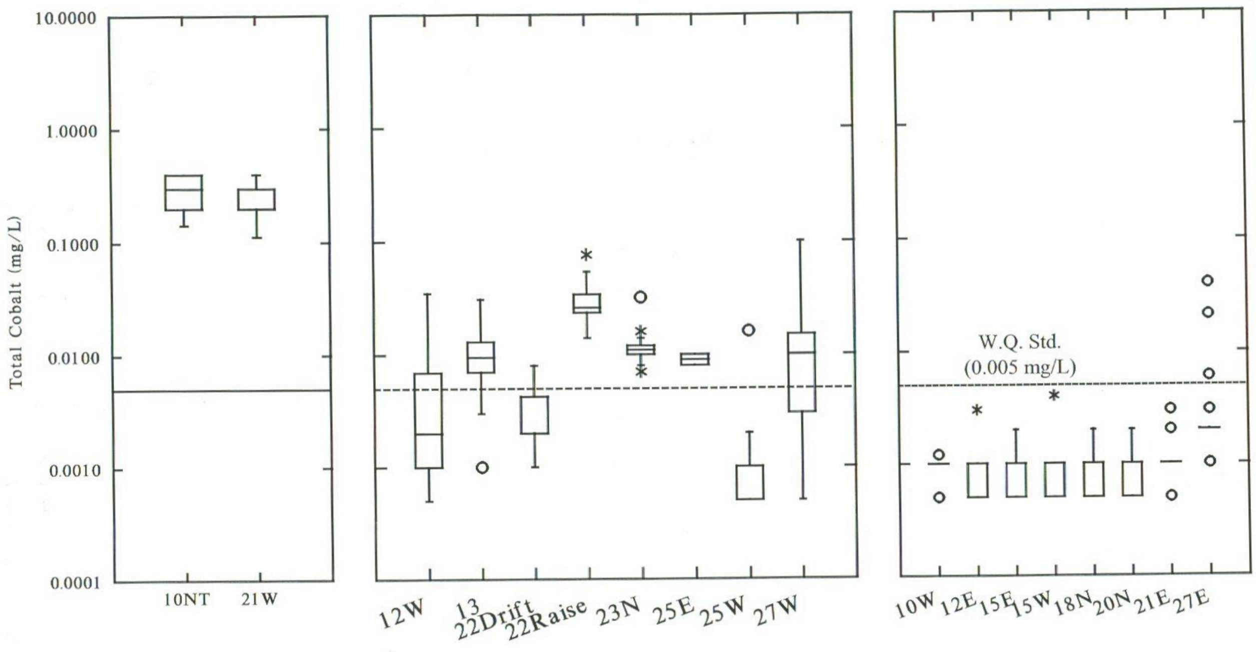


Figure 5. Total Co concentrations in Soudan Mine

The maximum Co concentrations in the discharge occurred in 1997 when the average was 0.026 mg/L. The lowest values were measured in 1999 and 2000 when Co averaged 0.006 and 0.008 mg/L, respectively (Table 1).

Mass loads. Flow data were combined with metal concentrations to determine the total Cu and Co mass released at each site in the mine. Average monthly concentrations were multiplied by the average monthly flow to give a monthly mass value. About 94% of the total Cu load and 44% of the total Co load comes from a single site near the upper levels of the mine (site 10NT, Table 2).

Table 2. Major Copper and Cobalt Loads within Soudan Mine

Mine Level	Copper Load, kg	Cobalt Load, kg
10NT	138.4	2.1
13	2.0	0.14
18	1.4e	0.03
21W	0.8	1.5e
12W	0.7	0.06
27W	0.5	0.02e
All other sites	3.5	0.75
Total	147.3	4.6

e = estimated Mass loads computed for period of study (April 1996 through August 1997)

Downstream Sampling Sites

Water quality. Initial data collected during 1996 and 1997 indicated that natural wetland removed virtually all of the Cu and Co from the discharge as metal concentrations were reduced to background levels at the discharge end of the wetland. (RRX; Eger and Wagner, 1998). Additional monitoring sites were established within the wetland to determine at what point Cu and Co met water quality limits (Cu = 0.020 mg/L, Co = 0.005 mg/L). In order to compare the difference in concentrations between the sites, only dates when all sites were sampled were included in the analysis, thereby restricting the analyses to the period April 1999 through October 2000.

Specific conductance at all the wetland sites was in the same general range as that measured at the mine discharge and at the input to the wetland with a median value of around 1100 µmho/cm. Conductance decreased to around 600 Φmho/cm as water left the wetland (site RRX; Fig. 6).

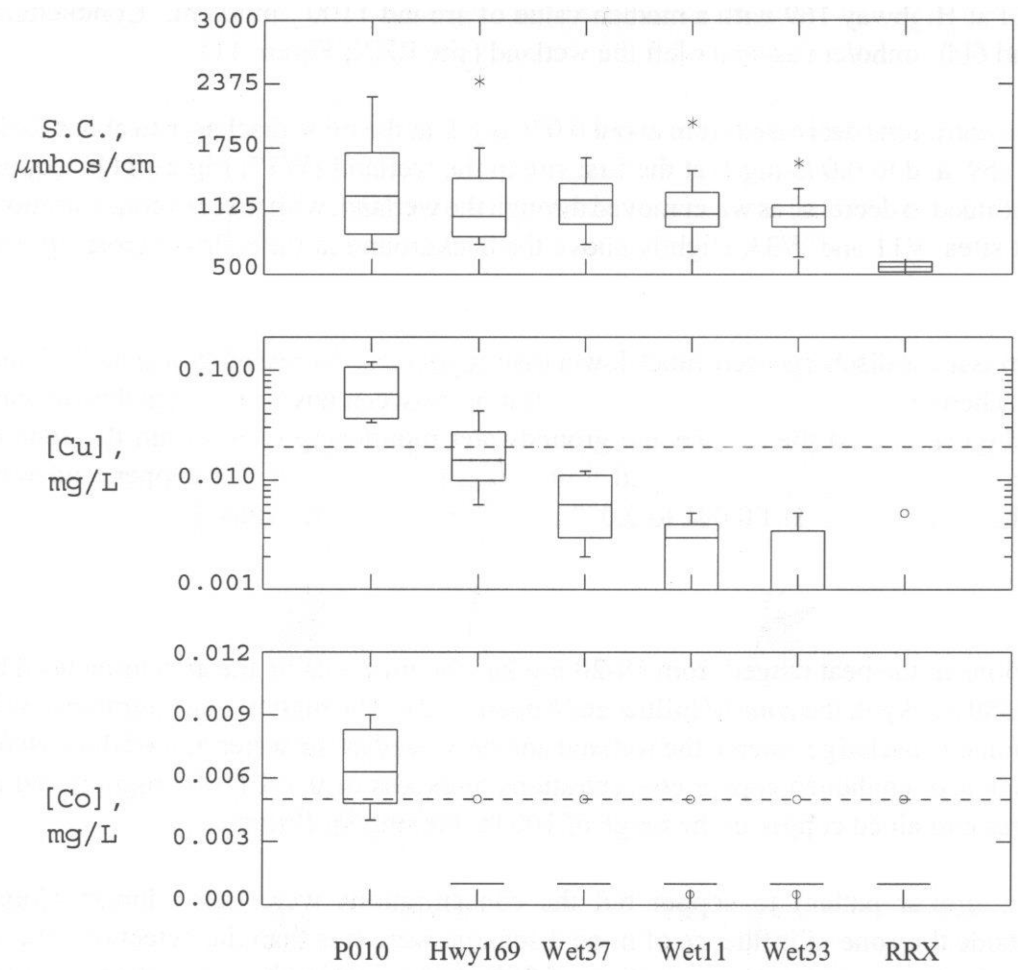


Figure 6. Comparison of concentrations at mine discharge and at downstream monitoring sites, April 1999 to October 2000.

Median Cu concentrations decreased from about 0.070 mg/L at the mine discharge to about 0.015 mg/L at the input to the wetland, and to 0.006 mg/L at the first site in the wetland (W37; Fig. 6). Copper concentrations continued to decrease as water moved through the wetland, with median concentrations of #0.003 mg/L at sites W11 and W33, slightly above the background at the railroad crossing (site RRX).

Cobalt concentrations in the discharge were much lower than Cu and decreased to near background as the water entered the wetland. There was little difference in concentration between any of the sites in the wetland (Fig. 6). At the surface and groundwater monitoring sites within the zone of elevated Cu, concentrations generally ranged from 0.002 to 0.028 mg/L for Cu, and were usually less than the detection limit of 0.001 to 0.002 mg/L for Co.

Peat. Copper concentrations in the peat ranged from 10-20 mg/kg (for sites outside the area influenced by the discharge) to 3380 mg/kg in the zone of influence. The highest concentrations were measured at the point the discharge entered the wetland and decreased as the water moved through the wetland. About one acre contained Cu concentrations in excess of 0.1% (1000 mg/kg) and an additional four acres contained Cu in the range of 100 to1000 mg/kg (Fig. 7).

Cobalt followed a similar pattern to Cu but the concentrations were much lower. Cobalt concentrations outside the zone of influence of mine discharge were less than the detection limit of 10 mg/kg, and reached a maximum concentration of 260 mg/kg within the area affected by the discharge.

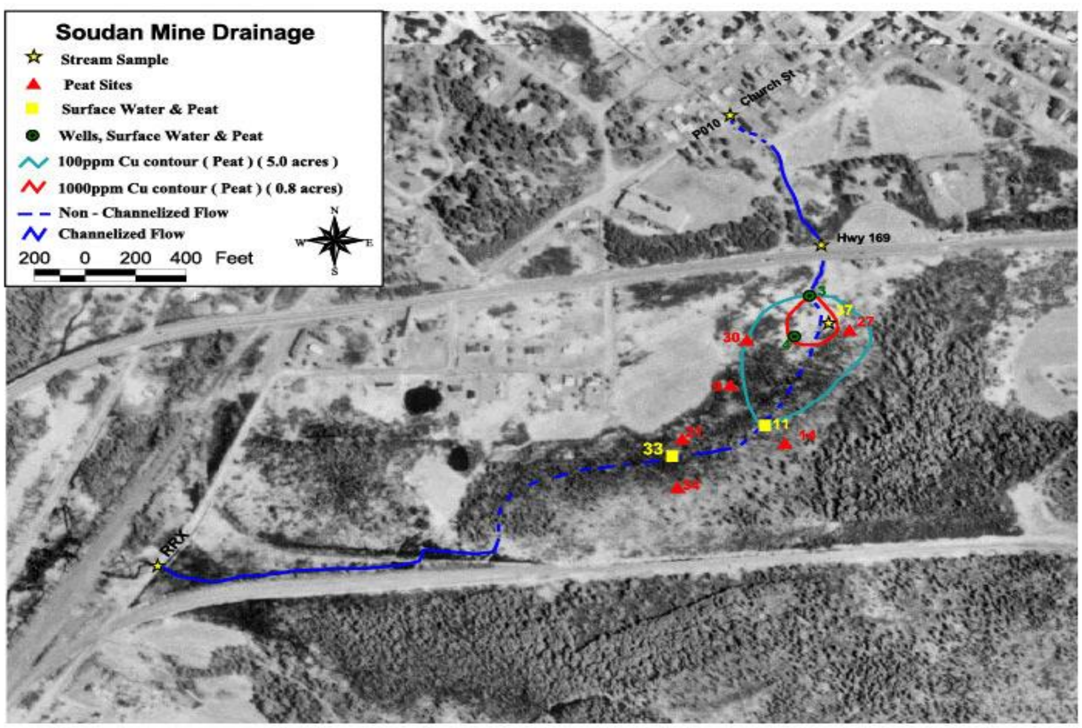


Figure 7. Copper concentrations in wetland downstream of mine.

Discussion

Impacts on Downstream Waters

Despite more than 60 years of discharge to the wetland, both Cu and Co were completely removed in the wetland and there was no impact on the East Two Rivers. The ability of wetlands to remove and accumulate Cu has been documented in both natural wetlands and in wetlands treating mine drainage. In a natural wetland in Canada, Cu concentrations reached up to 10% by weight, while concentrations of several tenths of a percent have been observed in both natural and mining impacted wetlands in Minnesota (Boyle, 1977; Eger et al., 1980; Eger and Lapakko, 1988). The maximum concentration measured in the Soudan wetland was 0.3%. Peat samples from well site 3 and well site 4 (Fig. 4) were extracted to determine how strongly the Cu and Co were bound to the peat. A synthetic precipitation leaching procedure (SPLP; SW-846-1312 method) using a weak acid solution was used. Less than 0.5% of the Cu or Co was removed from the samples, which demonstrated that both metals were strongly bound to the peat and were unlikely to be removed and become a future metal source.

There are at least an additional 15 acres of wetland downstream of the zone with elevated values, so the wetland could continue to remove metals for a very long time. If some of the Cu was removed from the discharge, the rate of generation of new removal sites within the impacted area could equal the amount of Cu entering the wetland. If this occurred the wetland would be self sustaining and would provide long term treatment (Eger et al., 2001).

Natural Wetland Treatment

The downstream wetland effectively removes both Cu and Co from the mine discharge, reducing the concentration of the metals to background levels by the time the water leaves the wetland (site RRX). Although there is no historical data on the quality of the mine discharge prior to the 1990s, mining on the 10th level began in the 1920's. The wetland could have been removing metals for up to 80 years and could continue to treat the discharge for many years.

Wetlands are considered waters of the state. In 1991, the Wetland Conservation Act was passed to protect wetlands from development impact. Although this act was aimed primarily at actions that drained or filled wetlands, impacts on water quality were also included. The Wetland Act requires that prior to allowing actions that would impact a wetland, the project must be analyzed to determine if the disturbance can be avoided and/or minimized. If there is no feasible alternative, the wetland area that is impacted must be replaced.

Any impacts to the vegetation and ecology in this wetland probably occurred years ago and were likely more related to the increased water flow and total dissolved solids than the relatively low concentrations of Cu and Co. During active mining, it is likely that the mine discharge also contained elevated concentrations of NO_3 that resulted from the use of NO_3 based blasting compounds. This increased nutrient supply would also have affected the wetland vegetation. Since the wetland has already been affected, continued use is unlikely to further degrade the wetland. To compensate for its use, the Division of Parks would restore 5.6 acres of wetland in southern Minnesota; where over 90% of the original wetlands have been lost.

Original Proposal

In 1998 DNR developed a proposal that would have removed over 90% of the Cu and over 40% of the Co by treating the major mass load (site 10NT) with an organic substrate/limestone bed. The five acre portion of the downstream wetland, which had been previously influenced by the mine drainage, would be used as a polishing area to remove any remaining metals. The use of the wetland would be compensated.

This proposal was developed after a variety of treatment options were evaluated. The following four factors were included as the basis for the evaluation:

1. Treatment effectiveness.
2. Overall cost.
3. Annual operating cost.
4. Maintenance.

The proposed treatment system would decrease the median concentrations in the discharge to around 0.030 mg/L for Cu and 0.008 mg/L for Co. The low level of residual metals in the discharge would be removed within the five acre portion of the wetland that already had elevated concentrations of Cu in the peat. This approach would minimize any future accumulation of metals in the wetland and provide a cost effective approach for treating the discharge and protecting the environment. This plan was approved by PCA in 1999. To compensate for the use of the downstream wetland, 5.6 acres of wetlands were restored in Camden State Park (Appendix 11). The overall cost of this proposal was estimated to be $150,000.

<u>The application of Murphy's Law</u>

When US Steel donated the mine to the state, it retained ownership of the wetland. As a result, the plan could not be permitted since DNR did not own or have an agreement to use and access the wetland. Although initial discussions with US Steel were promising, some DNR managers were reluctant to use a natural wetland for treatment. As a result the project stalled.

In 2002, the Department signed a compliance agreement and installed an ion exchange unit to remove the majority of metals from the largest source. However, as soon as the unit was installed, a white precipitate appeared in the inflow water and plugged the ion exchange units and made consistent treatment impossible. In 2006, the Department was fined and signed a stipulation agreement. The current proposal is to construct a wetland at the park to treat the entire mine flow. The estimated cost for this proposal is about 4-5 times the original treatment plan developed in 1998.

Conclusions

Despite decades of discharge from the Soudan Mine, there has been little impact on the environment. All of the copper and cobalt in the discharge have been removed in a five acre area of a downstream wetland, and with the exception of a small area of cattails where the discharge enters the wetland, there is no visual evidence of impact on the wetland. The metal contained within the peat substrate is tightly bound and is unlikely to be a source of future metals.

By treating only a part of the overall discharge, metal levels at the point of discharge would have been reduced substantially. The natural wetland downstream would have easily removed the residual metals and protected receiving waters. A series of unfortunate events have led to fines, bad public relations and a much more elaborate and expensive treatment system.

References

Boyle, R.W. 1977. Cupriferous Bogs in the Sackville Area, New Brunswick, Canada. J. Geoch. Expl. 8: 495-528. http://dx.doi.org/10.1016/0375-6742(77)90094-2.

Eger, P., Johnson, A., Wagner, J. 2001. Investigation of elevated copper and cobalt concentrations in Soudan mine drainage. Minnesota Department of Natural Resources, Division of Lands and Minerals. St. Paul, MN. 36 p. plus appendices

Eger, P., Lapakko, K. A., Otterson, P. 1980. Trace metal uptake by peat: Interaction of a white cedar bog and mining stockpile leachate. P. 542-547. In Proc. of the 6th International Peat Congress. Duluth, MN. Aug. 17-23, 1980.

Eger, P., Lapakko, K.A. 1988. Nickel and copper removal from mine drainage by a natural wetland. P. 301-309. In Proc. 1988 Mine Drainage and Surface Mine Reclamation Conference, April 19-21, 1988, Pittsburgh, PA. V. 1. Mine Water and Mine Waste. U.S.D.I. Bureau of Mines IC9183 https://doi.org/10.21000/JASMR88010301

Eger, P., Wagner, J. 2002. The use of wetlands to remove nickel from mine drainage – is perpetual treatment really possible? Proc. 19th Annual Meeting ASMR, Lexington, KY, June 9-13, 2002.
https://doi.org/10.21000/JASMR02010798

Klinger, F. 1960. Geology and Ore Deposits of the Soudan Mine, St. Louis County, MN. PhD Thesis, University of Wisconsin.

Maki, J. 1996. Hydrologic Investigation on the Soudan Mine. Minnesota Department of Natural Resources, Division of Waters.