PILOT SCALE CONSTRUCTED WETLAND FOR THE REMOVAL OF NICKEL FROM TAILINGS DRAINAGE, SOUTHERN NORWAY

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ABSTRACT

The Storgangen Mine was in operation between 1916 and 1965 and is situated near the village of Hauge i Dalane in Rogaland county, southern Norway. The mine produced ilmenite concentrate, during which approximately 8 million tons of tailings were generated. The coarse tailings fraction, which contained minor amounts of nickel sulfides, was released in the Sandbekk impoundment. Present seepage from the Sandbekk tailings impoundment has a neutral pH, but with slightly elevated concentrations of dissolved nickel. In June 1998 a pilot scale wetland was constructed to test the removal of nickel from the tailings drainage water. The wetland consisted of 3 subsurface flow anaerobic treatment cells, 1 surface flow aerobic treatment cell, an aeration cascade and a rock filter cell. The average flow into the constructed wetland was 35 l/min with an estimated retention time of approximately 10 hours. From three weeks after construction and throughout the remaining summer and fall, approximately 98% of the nickel was removed from the water. During the winter months nickel removal was reduced to between 35 and 71%, and during the spring nickel removal increased to between 64 and 99%. The highest removal of nickel occurred in the anaerobic cell which had the lowest Eh conditions. The nickel removal occurred due to the precipitation of sulfide particles which were filtered from the water by organic material. Excellent removal of other trace metals was also found, with removals of up to 96% aluminum, 98% copper, 98% cadmium, 99% zinc, and 64% chromium. The use of constructed wetlands appears to be a promising method to remove nickel and other metals from water draining from the Sandbekk tailings impoundment.

INTRODUCTION

The Storgangen Mine was in operation between 1916 and 1965 by Titania A/S near the village of Hauge i Dalane in Rogaland county, southern Norway (Figure 1). The mine produced ilmenite concentrate from a large layered ilmenite norite dike within the Egersund anorthosite complex. During this period approximately 8 million tons of tailings were generated, of which the coarse fraction was hauled by aerial tramline to the Sandbekk impoundment. Revegetation efforts have been conducted during the past 10 years to reduce dust transport from the area.

The tailings impoundment is located between 90 to 150 m above sea level in a steep mountainous area with deciduous and conifer forest. The site is 5 km from the North Sea and the average precipitation of the area is around 1940 mm/year with an average yearly temperature around 6ºC.

Each year approximately 750,000 m^3 of water seeps from the tailings drain into two small tributaries and from a wooden pipe installed during operations to drain the tailings. The three tailings water seepages drain directly into the Sandbekk River which flows into the Sokno River and eventually into the North Sea near the village of Sokndalsstrand (Figure 1).

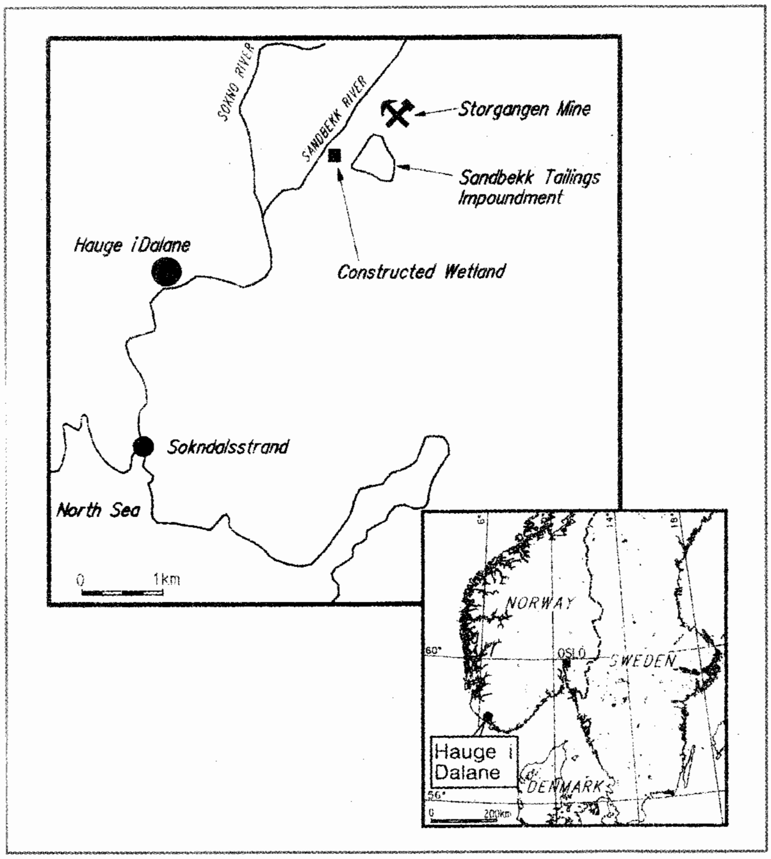

Figure 1. General map of Southern Scandinavia and location of Huge i Dalane.

The waters draining from the tailings impoundment are neutral with respect to pH values and showed a variation between 6.0 and 7.6 during 1998. However, the dissolved nickel concentrations are slightly elevated, which varied between 0.95 and 5.21 mg/l in 1998. The higher nickel concentrations are seemly correlated to heavy precipitation events that were preceded by extended dry periods. The Sokno River is well known for recreational salmon fishing, and no effects have been found on the aquatic life due to the release of nickel from the Sandbekk impoundment.

However, the Titania A/S Company took the initiative to investigate cost-effective methods to reduce the amount of nickel being released from the tailings impoundment. In June 1998 a pilot scale wetland was constructed to investigate the use of this technology to remove dissolved nickel.

Bog ores, which were mined in parts of Norway since the Iron Age, provide an example of how metal concentration occurs in a natural wetland. The use of artificial wetlands has been widely applied in recent years to treat metal-bearing acidic mine drainage (see Eger and Lapakko, 1989; Machemer et al., 1990; Robb & Robinson, 1995; Gusek, 1995, Skousen et al., 1997; Younger, 1997). Removal of metals in wetlands is the result of several mechanisms including uptake into plants, sorption to organic material, precipitation and filtration of oxyhydroxides, or precipitation and filtration of sulfides.

Wetlands are generally composed of two environments, a shallow aerobic zone and a deeper anaerobic zone. The anaerobic zone is oxygen-poor and typically contains sulfate-reducing bacteria. The sulfate reduction mechanisms in the anaerobic zone can be utilized to remove certain metals, such as nickel. In the anaerobic zone alkalinity is increased and sulfur reduced with the following general reaction:

$$SO_4^{-2} + 2\,CH_2O \Rightarrow HS^- + 2\,HCO_3^- + H^+ \quad (1)$$

Under these conditions, dissolved nickel combines with the sulfide ion and nickel sulfide precipitates by the following reaction:

$$Ni^{+2} + HS^- \Rightarrow NiS + H^+ \quad (2)$$

The sulfides precipitate as gray/black particles and settle or are filtered out from the water by the organic material. The sulfides will remain stable within the wetland as long as saturated and/or anaerobic conditions are maintained, such that they do not oxidize.

WETLAND DEMONSTRATION PROJECT

Construction

In June 1998 a pilot scale wetland was constructed to test the removal of nickel from the tailings drainage water at Sandbekk. Water for treatment was redirected to a constant head tank from the wooden pipe that drained water directly from the tailings impoundment. The wetland consisted of 3 subsurface flow anaerobic treatment cells, 1 surface flow aerobic treatment cell, an aeration cascade, and a rock filter cell (Figure 2). Because the seepage water from the tailings had a neutral pH, no limestone was used in the construction.

The anaerobic cells (cells A, B & C) were constructed as individual 1 x 1.5 x 10 meter lined basins. The substrate in each tank was constructed with gravel, wood chips, rotten grass hay, and covered with peat bog soils. To introduce sulfate-reducing bacteria, these basins were inoculated with a mixture of cow/sheep manure before filling. The cells were connec-

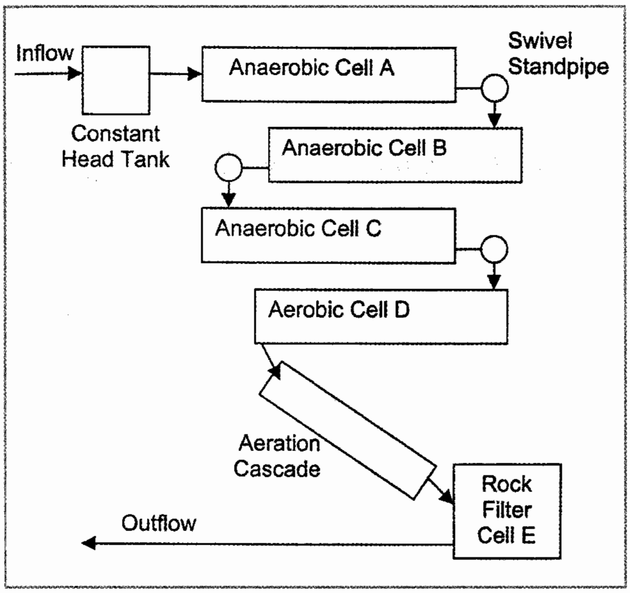

Figure 2. Schematic diagram of constructed wetland system (Not to scale).

ted so that water flowed by gravity through the entire length of each cell before flowing to the aerobic cell. An adjustable swivel standpipe controlled the water level within each cell. The water levels were adjusted to be directly below the peat bog layer to avoid short circuiting of water flow in the basins.

The aerobic cell (Cell D) was constructed as a 1 x 1.5 x 10 meter basin with a thin substrate of coarse sawdust and peat bog soils. Natural wetland vegetation was harvested from a local wetland and replanted within the substrate. An adjustable swivel drain controlled a water level of about 25 cm deep in the cell.

Oxyhydroxide precipitation was observed at the outflow of the aerobic cell after four months of operation. An aeration cascade and rock filter (Cell E) was thereafter constructed below the aerobic cell in an attempt to effectively remove these precipitates. The aeration cascade was constructed having a 2 meter fall over a 10 meter distance. The cascade was constructed in a shallow lined trench that was filled with large stones and gravel. The rock filter cell was constructed as a 4 x 4 x 0.5 meter basin filled with anorthosite gravel. The rock filter was intended to remove solid precipitates.

The water flow through the constructed wetland varied from 25 to 40 l/min. Based on the water volumes during initial wetland filling and a flow of 35 l/min, the estimated maximum retention time for the water in the anaerobic cells was 8.5 hours, followed by 3.5 hours retention time in the aerobic cell and 1 hour in the rock filter cell.

Methods

Monitoring wells were placed near the middle of each cell, in addition to the standpipes in the anaerobic cells that could be used for monitoring. The pH, Eh, TDS, temperature and sulfate concentrations were occasionally monitored at these sites in addition to sites near the outflows from the aeration cascade and rock filter.

Biweekly water samples were collected from the standpipes at each of the anaerobic cells, and the outflow from both the aerobic cell and the rock filter. Titania A/S analyzed the pH and dissolved nickel concentrations (ICP) in these samples. Periodic water samples were collected for conducting more complete water chemistry analysis. Sludge gathered from the standpipe drains and within the aerobic pond was occasionally collected for XRF analysis at Titania A/S.

Results and Discussion

The following summarizes the results shown in Table 1. Data from the first three weeks after construction showed only 40% removal of nickel (Table 1). During this same period the pH values were generally reduced after each cell.

After three weeks anaerobic conditions were apparently achieved in some of the cells, noticeable by a H_2S odor resulting the reduction of sulfate, and the increased removal of nickel. Results from nickel analyses, four weeks after construction (05.08.98), showed that 97% of the nickel was removed, mostly within Cell C. The measurements also showed that pH was slightly decreased in the anaerobic cells.

Date	Untreated water mg Ni/l *(pH)*	Outflow Cell A mg Ni/l *(pH)*	Outflow Cell B mg Ni/l *(pH)*	Outflow Cell C mg Ni/l *(pH)*	Outflow Cell D mg Ni/l *(pH)*	Outflow Cell E mg Ni/l *(pH)*	Total Ni removed mg Ni/l *(% removed)*
08.07.98	4.04 *(7.5)*	3.76 *(7.1)*	3.11 *(6.8)*	2.54 *(6.7)*	2.27 *(6.6)*		1.77 *(44%)*
22.07.98	2.74 *(7.2)*	2.65 *(6.7)*	2.42 *(6.5)*	1.84 *(6.5)*	1.68 *(6.6)*		1.06 *(39%)*
05.08.98	2.01 *(7.1)*	1.73 *(6.8)*	1.54 *(6.6)*	0.06 *(6.7)*	0.06 *(6.9)*		1.95 *(97%)*
19.08.98	1.75 *(7.2)*	1.68 *(6.5)*	1.35 *(6.6)*	0.07 *(6.8)*	0.06 *(6.8)*		1.69 *(97%)*
2.09.98	2.42 *(7.3)*	2.14 *(6.6)*	1.63 *(6.6)*	0.03 *(6.8)*	0.03 *(6.9)*		2.39 *(99%)*
16.09.98	2.10 *(6.9)*	1.91 *(6.5)*	1.62 *(6.6)*	0.05 *(6.8)*	0.03 *(6.8)*		2.07 *(99%)*
30.09.98	2.84 *(7.2)*	2.44 *(6.6)*	1.95 *(6.6)*	0.06 *(6.8)*	0.05 *(6.8)*		2.78 *(98%)*
14.10.98	2.92 *(7.0)*	1.46 *(6.6)*	0.06 *(6.8)*	0.02 *(7.1)*	0.04 *(7.5)*		2.88 *(99%)*
28.10.98	2.25 *(6.7)*	2.30 *(6.4)*	1.89 *(6.4)*	1.54 *(6.4)*	1.46 *(6.4)*		0.79 *(35%)*
11.11.98	2.74 *(7.1)*	2.57 *(6.6)*	1.62 *(6.5)*	0.90 *(6.5)*	0.85 *(6.6)*	0.80 *(6.9)*	1.94 *(71%)*
25.11.98	3.85 *(6.7)*	3.51 *(6.6)*	2.94 *(6.6)*	1.98 *(6.6)*	1.78 *(6.5)*	1.81 *(6.4)*	2.04 *(53%)*
09.12.98	4.72 *(6.9)*	4.39 *(6.6)*	4.28 *(6.5)*	3.22 *(6.5)*	3.07 *(6.7)*	2.68 *(6.8)*	2.04 *(43%)*
23.12.98	5.61 *(6.9)*	4.94 *(6.6)*	4.62 *(6.5)*	3.42 *(6.6)*	3.18 *(6.8)*	3.20 *(7.0)*	2.41 *(43%)*
6.01.99	3.08 *(6.8)*	3.03 *(6.7)*	2.54 *(6.5)*	1.74 *(6.6)*	1.71 *(6.9)*	1.74 *(6.9)*	1.34 *(44%)*
3.02.99	3.72 *(6.9)*	3.70 *(6.7)*	3.06 *(6.5)*	2.14 *(6.5)*	2.07 *(6.8)*	2.15 *(6.9)*	1.57 *(42%)*
17.02.99	3.90 *(7.2)*	3.99 *(6.7)*	3.27 *(6.5)*	1.76 *(6.5)*	1.71 *(6.8)*	1.73 *(6.9)*	2.17 *(56%)*
25.02.99	3.50 *(7.2)*	3.40 *(6.8)*	2.38 *(6.8)*	0.84 *(6.6)*	0.81 *(6.9)*	0.85 *(6.9)*	2.65 *(76%)*
3.03.99	3.18 *(7.2)*	3.03 *(6.8)*	2.30 *(6.6)*	0.90 *(6.5)*	0.81 *(6.9)*	0.81 *(7.0)*	2.37 *(75%)*
17.03.99	2.86 *(7.0)*	2.83 *(6.7)*	2.24 *(6.6)*	1.04 *(6.6)*	1.02 *(6.9)*	1.03 *(6.9)*	1.83 *(64%)*
30.03.99	3.07 *(7.2)*	3.00 *(6.9)*	2.20 *(6.7)*	0.74 *(6.6)*	0.69 *(6.9)*	0.71 *(7.0)*	2.36 *(77%)*
14.04.99	3.33 (7.1)	3.14 (6.7)	2.10 (6.6)	0.67 (6.5)	0.67 (6.9)	0.68 (7.0)	2.65 *(80%)*
27.04.99	3.97 (7.0)	3.91 (6.6)	2.42 (6.5)	0.46 (6.5)	0.44 (6.9)	0.44 (6.8)	3.53 (88%)
12.05.99	4.68 (7.2)	4.45 (7.0)	2.72 (6.8)	0.36 (6.8)	0.30 (7.0)	0.32 (7.0)	4.38 (93%)
14.05.99	4.66 (6.8)	4.24 (6.5)	1.60 (6.5)	0.07 (6.5)	0.10 (6.7)	0.13 (6.9)	4.53 (97%)
26.05.99	4.39 (7.0)	4.09 (6.8)	1.41 (6.6)	<0.01 (6.6)	<0.01 (7.0)	0.01 (6.9)	4.38 (99%)

Table 1. Nickel concentrations and pH. Measured from the constructed wetland cells.

Results from the first monitoring round (05.10.98) are shown in Table 2. The results confirmed that anaerobic conditions had indeed been achieved in cells B and C, but that Cell A not yet achieved anaerobic conditions. Sulfate was reduced in each anaerobic cell indicating that reduction to HS^- was occurring (see equation 1). The slight pH reduction in the anaerobic cells also showed that H^+ was generated (see equation 1).

Short circuiting was determined to be a problem in Cell B during October, which showed anaerobic conditions yet little nickel removal (Table 1 & 2). The drainage system from Cell B was therefore uncovered and repaired so that a lower water level could be maintained. The subsequent analysis after this reparation (14.10.98) showed a significant increase in nickel removal.

	Date	Flow (l/min)	pH	Eh (mV)	T (°C)	SO_4 (mg/l)	TDS (mg/l)
Inflow	5.10.98	35	6.9	370	10.8	340	290
Cell A well			6.6	100	9.3	--	290
Cell B well			6.4	-80	10.2	--	270
Cell C well			6.5	-40	8.7	--	280
Outflow D			6.5	30	9.8	220	310
Inflow	23.02.99	33	6.6	390	4.9	250	270
Cell A well			6.5	340	3.3	--	260
Cell B well			6.2	260	4.3	220	230
Cell C well			6.2	100	3.9	210	240
Outflow D			6.1	110	3.9	--	260
Outflow E			6.5	340	3.6	200	260
Inflow	12.05.99	24	6.5	370	7.9	420	330
Cell A well			6.1	350	7.4	--	330
Cell B well			6.5	300	7.5	--	330
Cell C well			5.6	0	7.4	--	330
Outflow D			6.2	0	7.6	--	330
Outflow E			6.6	320	7.4	400	330
Inflow	14.05.99	10	6.8	410	8.1	410	330
Cell A well			6.4	370	8.4	--	340
Cell B well			6.5	-20	8.1	--	330
Cell C well			6.4	-20	8.1	--	330
Outflow D			6.5	-20	8.1	--	330
Outflow E			6.9	320	6.8	340	320

Table 2. Results of control measurements.

During winter the percentage of nickel removal was dramatically reduced to between 35 and 71%, although the total amount of nickel removed remained fairly similar to previous and subsequent analyses (Figure 3). This may have been the result of either higher nickel concentrations entering the wetland combined with lower water temperatures, or a lack of nutrients for the sulfate-reducing bacteria. To determine the effect of nutrients on the wetland 40 kg of sugar and 5 liters methanol were added to the anaerobic cells (23.02.99). Results from Cell C showed a strong increase of nickel removal following this "feeding".

Occasionally, more complete metal analyses of the untreated and treated water were conducted (Table 3). Aside from excellent removal of nickel, these results showed removal of aluminum (50 to 96%), copper (91 to 98%), zinc (73 to 99%), cadmium (85 to 98%) and chromium (47 to 64%) in the wetland cells. During the latest sampling, the best removal of nickel occurred with the lowest water flow (10L/min), however, at a higher water flow (24L/min) the removal of the other metals was more efficient. Results showed that removal of iron, manganese or lead was not achieved.

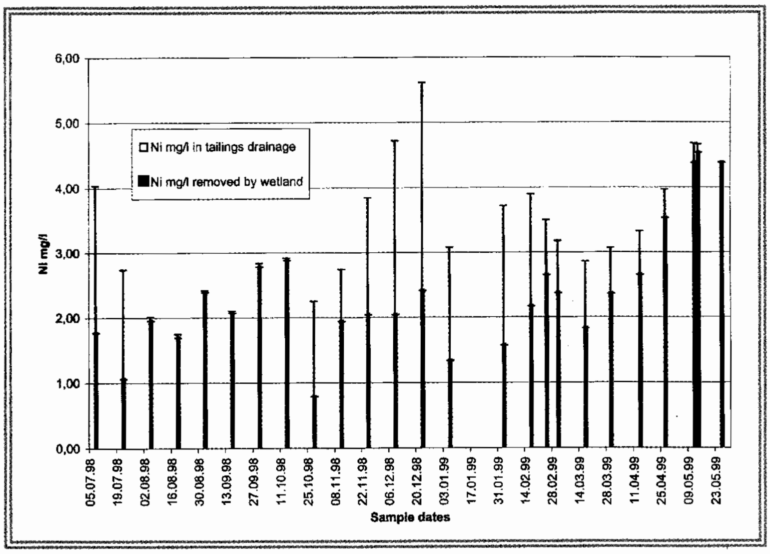

Figure 3. Concentrations of nickel in the tailing drainage and removed in the wetland.

In the fall of 1998 black sludge was observed in the standpipe drains in cells B and C, and white precipitates were observed on gravels in cells C and D. White precipitates were also observed in the aeration cascade shortly after construction. The black sludge from Cell B and white precipitation from Cell D were collected and analyzed in October 1998 (Table 4). The black sludge taken from Cell C contained 13 % nickel, 8% iron, 2.6% cobalt and 1.5% zinc which were likely present as sulfides, among other main elements such as silica, calcium, magnesium and aluminum. Volatile loss during analyses is presumed to be both sulfur and organic carbon. The white precipitates contained silica, iron, magnesium, titanium, aluminum and calcium, although the content of nickel, cobalt and zinc were low.

Sample Location:		Inflow	Outflow Cell D	Inflow	Outflow Cell E	Outflow Cell E
Date:		07.10.98	07.10.98	12.05.99	12.05.99	15.05.99
Water flow	l/min	35	35	24	24	10
Al	µg/l	23	11	92	4.0	4.8
Cr	µg/l	<0.2	<0.2	0.058	0.021	0.031
Mn	µg/l	12	23	25	21	25
Fe	µg/l	230	620	11	16	39
Ni	µg/l	3000	44	3900	280	130
Cu	µg/l	87	7.6	130	2.9	8.2
Zn	µg/l	120	33	190	2.1	5.2
Cd	µg/l	0.61	0.09	0.53	0.013	0.051
Pb	µg/l	0.64	0.78	0.060	0.067	0.15

Table 3. Metal analyses of water flowing into and from constructed wetland.

CONCLUSIONS

Constructed wetlands have showed very good potential for removing nickel and other metals from water draining from the abandoned Sandbekk tailings impoundment. The total amount of nickel removed during the first year of the constructed wetland operating was approximately 40 kg which is around 70 % of the total nickel which entered the system. At this removal rate, only 5% of the available volume in the wetland would be filled with nickel sulfides after 100 years! The main challenges in constructing wetlands that will remove metals over extended periods of time include maintaining anaerobic conditions and avoiding plugging of the system.

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Sample Location:		Cell B	Cell D
Date:		07.10.98	07.10.98
TiO_2	%	3.2	9.7
P_2O_5	%	2.4	0.64
S	%	2.7	2.4
Cr_2O_3	%	0.007	0.028
Fe	%	7.9	18
SiO_2	%	29	38
V_2O_3	%	0.029	0.08
CaO	%	6.4	5.1
MgO	%	4.5	13
Al_2O_3	%	7.0	6.3
MnO	%	0.13	0.28
K_2O	%	0.65	0.22
Na_2O	%	1.8	1.1
Zn	%	1.5	0.053
Ni	%	13	0.081
Cu	%	0.074	0.023
Co	%	2.6	0.028
Sum	%	84.7	99.55

Table 4. XRF analyses og sludge and precipitation in constructed wetland cells.

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