Contaminant sources and sinks: Summary of R& D 1985 to 2002, South Bay

Background :

The South Bay Waste Management Area (SBWMA) is located in Northern Ontario, approximately 85 km north east of Ear Falls (51^o 08N, 92^o 40E). A zinc and copper mine was operated on the site from 1970 to 1981. The mine, the site of the former mill, a waste rock pile and the tailings are all located on a peninsula within the watershed of Confederation Lake, an important fishing lake with hunting lodges in the English River drainage basin. In fact, the former mine site is virtually surrounded by a chain of tributary lakes which feed Confederation – Boomerang Lake (1M m^3) to the south which flows directly into Confederation, and Mud Lake (0.07M m^3) and Lena Lake (0.7Mm^3)to the north and northwest which flow to Confederation by way of Armanda Lake (1 M m^3). Boomerang Lake was contaminated during the life of the mine, and Mud Lake was contaminated in 1994 by a groundwater plume moving from the tailings. Both have been designated as part of the SBWMA and have been utilized in the clean-up effort. .

Decommissioning activities, undertaken immediately after the closure of the mine, consisted of burying the portal and sealing the shaft, raises and caps. All buildings were destroyed - except for the concrete foundations that were left in place - and the contaminated building materials buried except for those materials subsequently used in the restoration. The tailings were covered in gravel to a depth of one foot and re-vegetated. These efforts had no effect on the generation of acidity and contaminants. A 1986 environmental study noted that acidic plumes were leaving the site and recommended that they be treated by the occasional liming of Boomerang Lake, a proposal that was not accepted. In 1986, Boojum Research Limited was invited to assess the potential applications of ecological engineering at the SBWMA and the site has thus become a demonstration site of this decommissioning approach.

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The SBWMA contains two distinct contaminant-generating areas; the Mine/Mill Site and the tailings basin. Measures taken at the SBWMA have substantially reduced the mobilization of contaminants on the site, and redirected all contaminants into two major contaminant sinks, Boomerang Lake and Mud Lake. Mass balances are presented below for the contaminants mobilized on-site and captured by the sinks. The noted retention of tons of contaminants provides a measure of the effectiveness of the effort to date.

1. Contaminant Source 1: Mine/Mill Site

The Mine/Mill Site covers 50 hectares. When the mine was developed, about 11.9 hectares of this was built up with acid-generating waste rock, used as construction fill; this had been further contaminated by Cu and Zn concentrates. The central mine compound also contains a small acid-generating waste rock pile. A bedrock outcrop subdivides the Mine/Mill Site into a Western Drainage Basin, an area of 12.7 hectares surrounding the Backfill Raise, originally draining towards Confederation Lake and an

Eastern Drainage Basin, an area of about 24.3 hectares draining into Boomerang. Drainage from the central building site flowed into both basins.

The varied sources of contamination in the Eastern Drainage Basin are summarized in Table 1. Since the onset of mining operations in 1971 surface run-off from the basin - contaminated by its passage through the waste rock fill and residual ore concentrates – flowed into Mill Pond and from there, by way of a steep valley into Boomerang Lake. This was identified as the major source of contamination to Boomerang. Three retention structures (gravel/ mud reinforced beaver dams) were constructed in the valley (Dave's Dam, Upper and Lower Dam) to slow the passage of the water so that some metal removal could occur. As well, fertilizer, organic material and natural phosphate rock (NPR) were added to Mill Pond to stimulate biotic activity and enhance biological polishing. By 1991 this had somewhat reduced the metal load; Cu by 0.2 t/y, Fe by 0.5 t/y, S by 4 t/y Zn by 2 t/y and acidity by 2.9 t/y.

Table 1: Mill Pond Outflow and Lower Dam Load (t/y)

MILL POND OUTFLOW	Cu	Fe	S	Zn	Acidity
	Annual Flow (m^3/y) 31,536				
No treatment 1987-91 (365 days flow)	0.59	1.09	17.34	8.55	19.1
After NPR and fertilizer 1992-98 (365 days flow)	0.38	0.61	13.33	6.61	16.2
After siphoning to drain pond 1999 (185 days flow)	0.46	0.46	9.22	3.78	10.1
After blasting 2000-02 (185 days flow)	0.15	0.94	8.09	4.83	11.7
Cumulative load in sediment (1987-1998), t/y	0.07	0.24	0.11	0.15	na
LOWER DAM	Annual Flow (m^3/y) 33,990				
No treatment 1987-91 (365 days flow)	0.04	0.36	2.78	1.03	4.88
After NPR and fertilizer 1992-98 (365 days flow)	0.04	0.33	5.20	2.14	5.68
After siphoning to drain pond 1999 (185 days flow)	0.05	0.02	6.29	3.06	6.60
After blasting 2000-02 (185 days flow)	0.04	0.06	3.75	2.20	4.87
Cumulative load in sediment (1987-1998), t/y	0.02	0.17	0.02	0.03	na

Total air-dried sediment weight in the Mill Pond area (2200 m^3): 287 ton.

Area of Upper Dam is 300m(length) x 50m(width) x 0.1m(depth)+(75m x30m x0.1m)=1725m^3

Area of Lower Dam is 100m(length) x 25m(width) x 0.1m(depth)+(75m x30m x0.1m)=475m^3

The three dams in the steep valley covered 0.17 hectares with shallow water. In 1998, sediment cores were collected from these wetlands to a depth of 30 cm of which 20 cm consisted of living and dead vegetation and 10 cm of sediment. The retention of contaminants was calculated for the period 1987 to 1998 and divided by eleven (representing the number of years since the construction of the dams) to allow comparison to the annual contaminant loads leaving Mill Pond in the water. In the upper part of the valley 11 % of the annual load of Cu, 22 % Fe, 0.5 % S and 1.7% of Zn had been retained. In the lower valley, where contact with adsorption surfaces was somewhat better, about 50 % of the Cu and Fe was retained. Only about 1 per cent of both S and Z were retained (Table 1). This low retention reflects clearly, that retention structures without ecological engineering measures do not retain contaminants effectively.

In the Western Drainage Basin a longstanding source of contaminants was a seep emerging from the BRC to form a highly acidic pool. The decommissioned mine was allowed to flood naturally so that by l996 the BRC seepage had increased substantially with a commensorate increase in the size of the acidic pool. As well, new flows began to emerge from the buried portal and its raise. All these seepages then flowed towards Confederation Lake. Some of the new seeps were not large but they contained high concentrations of metals; particularly of copper (79 mg/l), iron (380 mg/l), sulphur (1770 mg/l) and zinc (1440 mg/l). Given the existing drainage pattern, a single seep had the potential to deliver, for example, 3.6 t of zinc per year to Confederation Lake.

An investigation of the hydrological conditions of the mine site was undertaken. Nine piezometers, which had been in place since 1987, and continually monitored for chemistry and water level, indicated that Mill Pond, which fluctuated with the seasons, was pushing water across the boundary of the two drainage basins. The pond was initially siphoned to test the hydrological response to draining. Results were positive with a reduction of contaminants leaving by way of Mill Pond outflow; Cu from 0.59 to 0.46 t/yr , iron 1.1 to 0.46 t/yr, S from 17.3 to 9.2 t/yr , Zn from 8.5 to 3.8 t/yr and acidity from 19.1 to 10 t/yr. Consequently, in 2001, an exit was blasted into bedrock, which permanently lowered the pond by two metres. This eliminated some seepages and reduced the so-called Warehouse Seep (WHS), which emerged in the former building site, flowing from 0.4 L/s throughout the year previous to blasting to 0.02 L/s flowing for half a year (Table 1)

The investigation also revealed the presence of two distinct aquifers beneath the Mine/Mill Site. The first was shallow and drained into both the Eastern and Western Basin. It was characterized by identical levels of contamination in water from the mine shaft and from the BRC seepage (200 mg/l of zinc, 100 mg/l of Fe and 1900 mg/l of sulphur) and by almost identical values in an easterly flow towards Boomerang which was differentiated only by higher Cu values (22 mg/L as compared to 0.02 mg/l) probably due to windborne contamination from the copper concentrates. This shallow aquifer is driving the greatly reduced Warehouse Seep. A second, deeper aquifer reaching below Confederation Lake was considerably less contaminated (5 mg/l of zinc, 28 mg/L of Fe and 900 mg/l of sulphur).

The investigation also determined that water in the portal raise and the backfill raise was hydrologically connected and that it had created a hydraulic head which was driving the BRC seepage. The Backfill Raise Cap (BRC), a concrete structure, was excavated to a depth of 4 metres so that the system drained at elevation of 418.08 masl. A drainage ditch was then constructed to capture and reverse the flow of all surface seepage from Confederation to Boomerang Lake. The ditch was later deepened to an elevation of 411.9 masl, virtually the same elevation than Confederation Lake, so that the shallow aquifer was draining as much as possible towards Boomerang lake. Subsequently the water quality in Confederation Lake, as recorded by monitoring station C8 just off the Mine/Mill Site, showed considerable improvement. The reversal of the seepage was later confirmed by geophysical conductivity surveys.

On completion of these measures, the flow of effluent from Backfill Raise Cap (BRC) remained relatively constant in both volume (0.1 - 0.3 l/s) and level of contamination, providing further confirmation that the source was the deeper aquifer which contained the mine workings. This was notably distinct from the seasonal variation of the flow generated by the shallow aquifer still evident in the flow of the Warehouse Seep. Since these remaining seepages, both deep and shallow, are long term, treatment options are being investigated. Metallic magnesium scrap has been immersed in both seeps on a test basis. This work is ongoing and is expected to provide a treatment strategy..

A combination of hydrological and chemical treatment measures have substantially reduced the generation of most contaminants in the seeps in the Western Drainage Basin (Table 2). Fe and total acidity in the deeper aquifer emerging at BRC are unchanged but copper, sulphur and zinc loads have been reduced slightly. In the Warehouse Seep all elemental loadings have been reduced; Cu from 0.24 to .01 t/yr, Fe from 0.7 to 0 .1 t/yr, S from 6.1 to 1.0 t/yr, Zn from 4.4 to 0 .7 t/yr and acidity from 11 to 1.7 t/yr. A monitoring station at the outflow of the Backfill Raise Ditch, where these seeps merge with seeps from previous tailings spills, showed an overall reduction in Cu from 0.2 to 0.1 t/yr, Fe from 2.3 to 0.6 t/yr, S from 26 to 7 t/yr, Zn from 12 to 3 t/yr and acidity 36 to 17 t/yr. And, well, of course, much contamination has been avoided by the elimination of seepages and ground water discharges into Confederation Lake which could not be quantified.

Subsequent remediation measures, undertaken in 2001 and 2002, on the Mine/Mill Site included applications of wood ash, fertilizer and seeds to encourage the growth of moss on rock surfaces and vegetation on the metal-laden peat from the former pond. These measures have already produced a reduction in Cu (0.38 to 0.15 t/yr) and Zn (6.6 to 4,8 t/yr) although the effect on other contaminants is not yet apparent (Table 1).

Table 2: South Bay Mine/Mill Site Contaminant Loads

	Flow (m^3/y)	LOADS (t/y)				
		Cu	Fe	S	Zn	Acidity
BACKFILL RAISE						
Pre - Mill Pond Draining	6,200	0.0002	0.5	3.9	1.4	3.8
Pre - Mg Metal	5,500	0.003	0.3	3.3	1.4	3.6
Present - with Mg Metal	5,200	0.0001	0.4	3.1	0.9	4.5
WAREHOUSE SEEP						
Pre - Mill Pond Draining	5,200	0.24	0.7	6.1	4.4	11.0
Pre - Mg Metal	1,500	0.02	0.2	1.7	1.1	3.0
Present - with Mg Metal	900	0.01	0.1	1.0	0.7	1.7
BACKFILL RAISE DITCH						
Pre - Mill Pond Draining	36,800	0.2	2.3	26	12	36
Pre - Mg Metal	15,800	0.1	0.8	11	5	15
Present - with Mg Metal	15,800	0.1	0.6	7	3	17

Contaminant Source 2: Tailings and Kalin Canyon below the gravel pit

The second major source of contamination in the SBWMA is the 23-hectare tailings deposit containing 0.785 Mt of acid-generating materials (41 % pyrite 4 % phyrrotite). The five-hectare remnant of the decant pond is 0.5 metre deep and is bordered by an acid-generating tailings beach. The major movement of contaminants out of the basin is by groundwater, either into Boomerang Lake directly and by way of a diversion ditch constructed in 1991 or northeast to Mud Lake via a subterranean bedrock valley (Kalin Canyon). Surface contaminants originating in the waterlogged shore of the pond were reduced by the installation of an organic, partially-submerged ARUM (Acid Reduction Using Microbiology) beach. The volume of AMD emerging from the beach cannot be adequately measured, but a month after the completion of the beach the pH had increased from 3.1 to 5.0 while Zn declined from a high of 19 mg/L to 8.8 mg/L and Fe from 79 mg/L to 2.4 mg/L. These values remained low until as recently as 2001 when some phosphate rock was applied.

An understanding of the chemistry and flow of ground water out of the tailings was obtained by the continuous monitoring of piezometers installed in 1986 and through a groundwater model, constructed in 1998. The model quantified four layers of ground water, each approximately 4 metres in depth and each of them moving, at varied volumes and speeds, to the south and northeast. Generally, the four layers carry fewer contaminants towards Boomerang than into Kalin Canyon. Moreover, there are fewer contaminants in Layer 1 and 2, than in the deeper Layers 3 and 4. When first exposed to oxygen, the pH of the groundwater in all layers is generally 5 or 6 but within 24 to 48 hours drops to about 3.5. A further drop in pH to below 2 has been noted when samples are stored for weeks or years.

Table 3: Load Reduction from Tailings to Kalin Canyon and Boomerang Lake from 1996 to 2002

	Layer	Flow	Fe	S	Zn	Acidity
		m^3/y	t/y	t/y	t/y	t/y
Kalin Canyon	1	391	2.20	1.30	0.04	1.75
	2	3,485	19.6	11.1	0.44	21.5
	3	5,507	28.6	14.9	6.2	-19.3
	4	11,173	4.58	1.84	1.03	4.70
Boomerang Lake (South of Tailining including Diversion Ditch)	1	189	1.06	0.63	0.02	0.85
	2	3,615	2.96	1.27	-0.07	1.68
	3	1,453	7.56	3.92	1.63	-5.08
	4	11,875	19.1	12.8	0.86	29.2

In 1999, natural phosphate rock (NPR) phosphate was applied to the tailings on an experimental basis to precipitate contaminants within the tailings; the NPR also stimulated the growth on the tailings of indigenous vegetation. In addition, since 2000, the tailings have been drained each year, removing about 15,000 m^3 annually of accumulated atmospheric precipitation. Geochemical reactions within and below the tailings have not yet been fully analysed so the effect of these measures cannot be precisely assessed; nonetheless it seems safe to assume that they have been beneficial. Table 3 presents the reduction in contaminant loads for each layer in from 1996 and 2002. Most notably, in the flow towards Kalin Canyon, Fe is reduced by 28.6t/yr in Layer 3 and 4.5 t/yr in Layer 4; S by 14.9 t/yr in Layer 3 and 1. 8 t/yr in Layer 4; Zn by 6.2 t/yr in Layer 3 and 1 t/yr in Layer 4. Acidity increased in Layer 3 by 19 t/yr but decreased in Layer 4 by 4.7 t/yr .

The passage of the ground water to Mud Lake through Kalin Canyon, a bedrock valley underneath the gravel pit is complex. Here Layer 1, 2 and 3 are fast moving and flow generally towards Confederation Lake and are essentially clean (\ Fe 3.6 mg/l to 12.7 mg/l, S from 13.5 mg/l to 68.6 mg/l and Zn from 0.4 mg/l to 6.1 mg/l.) In stark contrast however, Layer 4, directly above the bedrock, contains elevated levels of Fe (412 mg/l to 2272 mg/l), S (1282 mg/l to 2743 mg/l and Zn (57.3 mg/l to 152.5 mg/l). Layer 4, and its burden of contaminants, surface through 5 to 8 metres of sediment in Mud Lake at a rate of 1L/sec.

3. Contaminant sink #1: Mud Lake

Mud Lake is a shallow lake (0.5 m to 1 m depth) mostly surrounded by an extensive, floating muskeg shore, excepting for one well-defined outlet over bedrock. The lake receives fresh run-off from a large drainage basin to the northeast, resulting in three annual exchanges of water in the open lake; total dilution of the lake's outflow is about 10 times. The lake freezes in the winter reducing the effluent to a trickle. The contaminated groundwater plume arrived at the lake in 1994.

In 2000, eight sediment cores were collected from Mud Lake to a depth of 30 cm in 10 cm sections and analyzed for Fe, S and Zn. They confirmed that the contaminants had accumulated only on the surface of the sediment; moreover the special distribution of the contamination was clearly related to the proximity to the discharge area of the plume. Contaminants in the sediment pore water were also measured. Together these measurements provided the accumulation of contaminants in the open water covered sediments; 15 to 496 t of Fe, 35 t to 94 t of S and 0.1 t to 26 t of Zn(Table 4).

Subtracting the contaminants in the lake outflow from those in the ground water discharge into the lake, over six years, should yield the minimum and maximum values remaining in the lake sediments; Fe from 78 to 104 tonnes, S from 88 to 459 tonnes and Zn from 12 to -13 (Table 4). These numbers more or less agree with the ranges of elemental mass estimated for sediments and pore water. The localized discharge of the contaminants, the fast turn over rate, the natural sediment retention capacity and the strong control of iron oxidation induced by the application of phosphate, make accounting for the contaminant fate difficult.

Up to 1996, for 2 winters, the pH of the lake water recovered from a summer low of 3 to a high of 5 in the winter, as a result of the natural acid-reducing capacity of the sediments; after 1996 this was exhausted and the pH fell to below 2.5, the level at which oxidized iron does no longer precipitate into sediments as iron hydroxide, removing some zinc in the process. Sixty tonnes of phosphate rock were added to the lake sediments in 1996; this prevented the iron already in the sediment from oxidizing, fertilized the sediments and maintained the pH of the lake at about 3 until 2001 when it began to fall again. An application of wood ash to correct this was proposed, based on field and laboratory tests, but has never been approved. As noted above, measures have been taken to induce the precipitation of iron in the tailings which will eventually reduce the loadings. As well, field trials are underway of a technique to treat the ground water plume in situ.

Table 4: Mud Lake Mass Balance (based on 2000 results)

	Fe		**S**		**Zn**	
	Min	Max	Min	Max	Min	Max
Sediment (0.3 m depth) total mass (t)	15	474	30	75	0.1	22
Sediment Pore Water(0.3 m depth) total mass (t)	0.7	21	5	19	0.001	4
Total mass in 0.3 m * 78,000 m^2 (open water) (t)	15.4	496	35	94	0.1	26
Annual Load **IN** Mud Lake (t/y) (0.8 L/s for 365 d)	18.3	47	27	169	1.980	4
Sum of 6 years (1994-2000) (t)	110	279	162	1014	11.88	22
Annual Load **OUT** (t/y) (14 L/s for 185 d)	1	34	12	92	0.044	5.9
Sum of 6 years (1994-2000) (t)	6	201	74	555	0.26	35
SEDIMENT REMOVAl (IN - OUT)	104	78	88	459	12	-13
In Lake per year, 3 times turnover	22		50		2.8	

Contaminant Sink #2: Boomerang Lake

Boomerang Lake, with a volume of 1M m^3 and is located in a drainage area of about 131 hectare. It has always been the primary recipient of contaminants from the Mine/Mill Site and the tailings. The lake is 4 to 5 metres deep and turns over on a 3-year cycle. ARUM and biological polishing have been promoted in the lake generally and especially in the outflow channel

Although the lake was studied from the outset of the project in 1986, the first large scale application of a remediation measure was in 1995 with the addition of 130 tonnes of NPR to the sediment, and more than 20,000 brush cuttings to serve as anchorage for agents of biological polishing. Annual loadings to the lake since the closure of the mine have varied due to restoration activities on the Mine/Mill Site as noted (Table 5).

Table 5: Boomerang Lake Total Contaminant Loads and Sediment Sink

	Cu			Fe			S			Zn		
Boomerang Lake Load in total tons												
	in	out	retain	in	out	retain	in	out	retain	in	out	retain
No Treatment (1987-1994)	2.6	0.7	1.9	355	9	345	461	239	221	101	22	79
Phosphate and Brush (1995-1999)	1.1	0.5	0.6	416	9	407	466	228	238	98	41	57
Magnesium (2000-2003)	0.8	0.6	0.2	314	11	303	339	244	95	88	47	41
Sediment Sink in total tons												
Sediment (1998)			2			468			na			51

Core samples taken to a depth of 30 cm in 1998 have yielded insight into the accumulations before and after the start of treatment. The mass accumulated in the sediment was 2 t copper, 468 t of iron and 51 t of zinc. These accord well with the differences between the total load entering from the Mine/Mill Site and the tailings. For each period where ecological engineering measures have been implemented, their gross effect has been estimated by using the total inputs to the lake (clean and contaminanted) and subtracting the output from the lake (300,000 m^3 x measured concentration) for these years. Between 1987 and 1994 these differences resulted in a retention of 1.9 t of copper, 345 t of iron and 79 t of zinc, quite well agreeing with the sediment concentrations. . Because of restoration activities, noted previously, the load to Boomernag increased during the period 1995 – 1999, but the applications of phosphate and brush enhanced the polishing capacity of the lake so that about 0.6 t of Cu , 407 t of Fe, 238 t of S and 57 t of Zn were estimated to be retained in the sediment. Since that time, the sediments have not been quantified. However the pH of the lake is currently falling, which inevitably will reduce its retention capacity. A field experiment, in which six tonnes of magnesium scrap were suspended in the lake to determine its effect on pH was completed in 2003. The results suggest that a further addition of 16 tonnes would raise the pH to 4.5. This has been recommended. .

Conclusion

Project mass balances indicate that a large quantity of contaminants have been retained on site, even though many of the ecologically engineered strategies being developed there have not yet been fully implemented. The development of such strategies proceeds slowly, to allow time for careful R&D. But, clearly, the measures introduced at the site, fully or in part, have been effective. It is essential that they be closely monitored; or that, if they are in the final stages of their field trials, that they be put in place. If the current treatment scenario for the SBWMA is abandoned, the systems already established might well be de-stabilized. More fundamentally, any failure to apply and build on the hard-won knowledge gained at the SBWMA would be tragic.

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