Dispersion of tailings from the Stirling Zn-Pb-Cu mine site, Cape Breton Island, Nova Scotia

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The Stirling Zn-Pb-Cu mine, located at Stirling in Richmond County, Cape Breton Island, was active between 1935 and 1938, and 1952 and 1956, when one million tons of ore were produced grading 6.21% Zn, 1.48% Pb, and 0.73% Cu. During the first period, 180 000 t of tailings were discharged directly into Strachans Brook, whereas in the 1950s the tailings, totalling 800 000 t, were impounded. Since that time there has been ongoing erosion and downstream dispersion of tailings. The purpose of this study was to quantify this dispersion, to determine the effectiveness of neutralization of acid generation in the tailings, and to evaluate levels of downstream contamination.

Downstream sediments in Strachans Brook have mean metal enrichments of 70x Zn, Pb and Cu, 35x Cd, As, and Ag, 20x Au, and 10x Mn, compared to upstream sediments. Close physical and geochemical similarities between tailings and downstream sediments indicate a severe level of downstream contamination.

Runoff from the tailings is pH-neutral, strongly enriched in sulphate, Ca, Mg, Fe, Mn, Zn and Cu, and slightly enriched in Cd, As, Sb, Se, Co, Ni, V, and Cr. However, downstream water is less acidic than upstream water and is slightly enriched only in Ca, Mg, Mn, and Zn. Dispersion of metals in solution is minimized due to effective neutralization by dolomite of acid generation within the tailings, and its impact on the downstream environment is reduced by upstream dilution of the effluent from the tailings.

La mine de Zn-Pb-Cu Stirling située à Stirling comté de Richmond, dans l'île du Cap-Breton, a été en activité entre 1935 et 1938 puis entre 1952 et 1956. On y a produit un million de tonnes de minerai d'une teneur de 6,21 % de Zn, 1,48 % de Pb et 0,73 % de Cu. Au cours de la première période, 180 000 t de résidus ont été rejetées directement dans le ruisseau Strachans, alors que dans les années cinquante, on a accumulé une quantité totale de 800 000 t de résidus dans un bassin prévu à cette fin. On a depuis lors assisté à une érosion permanente et à une dispersion en aval des résidus. Cette étude visait à quantifier cette dispersion, à déterminer l'efficacité de la neutralisation de l'effluent acide produit dans les résidus et à évaluer les niveaux de contamination en aval.

Les sédiments en aval du ruisseau Strachans présentent, comparativement aux sédiments d'amont, des enrichissements moyens en métaux de 70 fois supérieurs dans le cas du Zn, du Pb et du Cu, de 35 fois supérieurs dans le cas du Cd, de l'As et de l'Ag, de 20 fois supérieurs dans le cas de l'Au et équivalant au décuple dans le cas du Mn. Les similarités géochimiques et géophysiques étroites entre les résidus et les sédiments d'aval révèlent un degré prononcé de contamination en aval.

Le ruissellement des résidus affiche un pH neutre fortement enrichi en sulfate, Ca, Mg, Fe, Mn, Zn et Cu, en même temps que légèrement enrichi en Cd, As, Sb, Se, Co, Ni, V et Cr. L'eau d'aval est toutefois moins acide que l'eau d'amont et elle est légèrement enrichie en Ca, Mg, Mn et Zn seulement. La dispersion des métaux en solution est réduite en raison de la neutralisation efficace de l'acide produit parmi les résidus par la dolomie et son incidence sur l'environnement en aval est atténuée par la dilution d'amont de l'effluent des résidus.

Traduit par la rédaction

INTRODUCTION

The Stirling base metal deposit (also known as the Mindamar Mine) is located in Richmond County, southeastern Cape Breton Island (Fig. 1). Mineralization was discovered in Strachans Brook in the 1890s. Acquired by British Metals Corporation in 1927, the first successful mining operations began in 1935 and continued until 1938. During this time, 196 000 t of ore were mined, averaging 9.55% Zn, 2.28% Pb, and 0.94% Cu. Almost 17 000 t of Zn, Pb, and Cu were recovered using a flotation process that was approximately 60% efficient. The remaining 180 000 t of waste and unrecovered metals were discharged directly into Strachans Brook, as no regulations governing waste disposal were then in place (Roscoe, 1985). Mindamar Metals Corporation re-opened the mine between 1952 and 1956, and produced 863 000 t of ore averaging 5.54% Zn, 1.30% Pb, and 0.69% Cu. During this time, the mine wastes were impounded in a tailings pond as required by regulations. Production then ceased due to a significant decrease in ore grades. Subsequent detailed sampling of the tailings (to determine their gold content for Seabright Resources) showed that they totalled about 800 000 t with an average grade of 1.23% Zn, 0.38% Pb, 0.17% Cu, 17.53 g t^{-1} Ag, and 0.51 g t^{-1} Au (Jacques, Whitford and Associates Limited, 1985).

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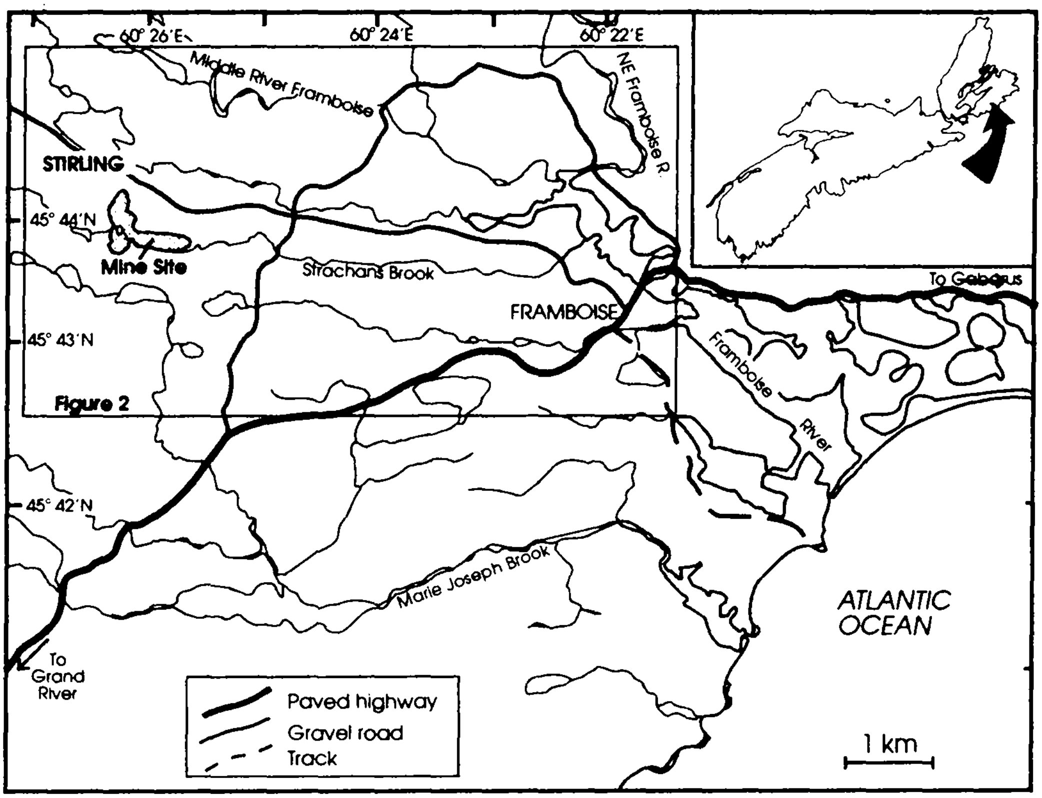


Fig. 1. Location of the Stirling mine site, Richmond County, Cape Breton Island, Nova Scotia.

Stirling is classified as a volcanogenic massive sulfide (VMS) deposit (Poole, 1974; Miller, 1979). With a total tonnage of about 1 Mt, it is considered to be relatively small when compared to other Canadian deposits of this Zn-Pb-Cu sub-type, which have an average size of 5.6 Mt grading 3.60% Zn, 1.46% Pb, 1.23% Cu, 79 g t^{-1} Ag, and 2.0 g t^{-1} Au (Franklin, 1996). The Stirling ore deposit is made up of a group of irregularly shaped lenses of sulfides in a quartz-carbonate-talc envelope. Sulfide mineralogy of the ore which was processed included pyrite, sphalerite, galena, chalcopyrite, and tennantite, and gangue mineralogy included dolomite, siderite, talc, magnesite, chlorite, quartz, and feldspar (Miller, 1979).

Oxidation of pyrite within tailings derived from the processing of VMS ores can result in low-pH pore waters that contain high concentrations of sulfate, iron, and other base/heavy metals, unless carbonate minerals are present in sufficient quantities to neutralize acid generation (Blowes and Ptacek, 1994). It was hypothesized that carbonate minerals associated with the ore at Stirling probably significantly reduced the effects of acid generation, and one purpose of this study was to determine the effectiveness of such buffering in inhibiting dispersion of base/heavy metals in solution from the mine site.

SITE DESCRIPTION

In the area around Stirling, topographic relief is less than 30 m and is characterized by prominent east-west till ridges and scattered drumlins (Grant, 1972) which are separated by swampy low-gradient streams with numerous still-waters and small lakes (Fig. 2). The Stirling mine site, which can be reached via well-kept gravel roads, is marked by a comparatively small area of ground disturbance of about 0.06 km^2 (not including the tailings impoundment). Strachans Brook flows through the middle of the site, which is marked by a flooded glory hole and a small open pit, and by various concrete foundations (Fig. 3). The concentrator was located south of the brook and some ore and concentrate still remain in concrete bins in the foundations of the complex. The main shaft is located just north of the glory hole but has been sealed off.

Tailings impoundment

The tailings impoundment occupies a 600 m by 200 m rectangular area (0.12 km^2) adjacent to Strachans Brook on the east side of the mine site (Figs. 2, 3). The average thickness of the tailings has been determined to be about 4 m (Jacques, Whitford and Associates Limited, 1985) and numerous dead trees still stand within it. During periods of moderate to high rainfall, surface water flows from north to south across the tailings and then laterally towards the east, via a network of shallow erosion channels, where it accumulates on top of the tailings impoundment. A gabion fence has been constructed at the eastern end of the impoundment to act as an overflow/spillway to focus discharge into Strachans Brook during periods of excess precipitation. This structure prevents the water from overflowing and further eroding the retaining berm along the southern margin of the impoundment. However, it is evident from the accumulation of dune-like deposits along the edge of Strachans Brook that tailings sediment is wind blown

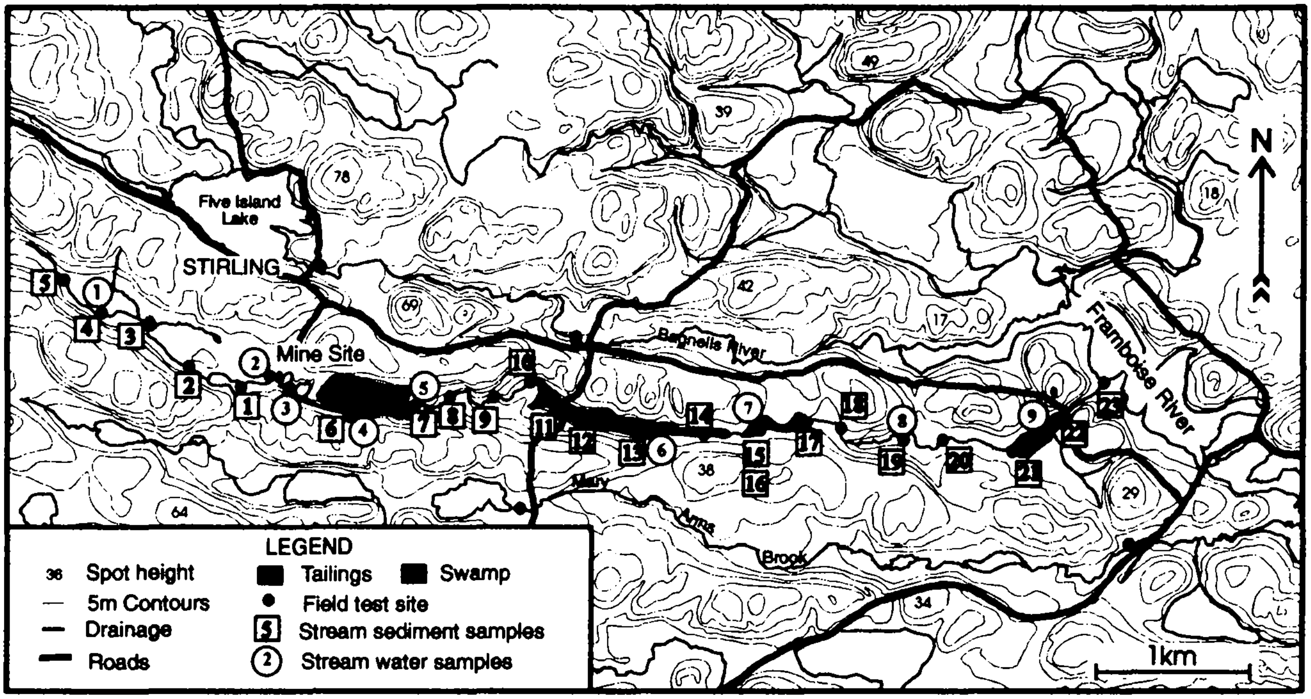


Fig. 2. Topographic map of the Stirling area showing sample locations along Strachans Brook.

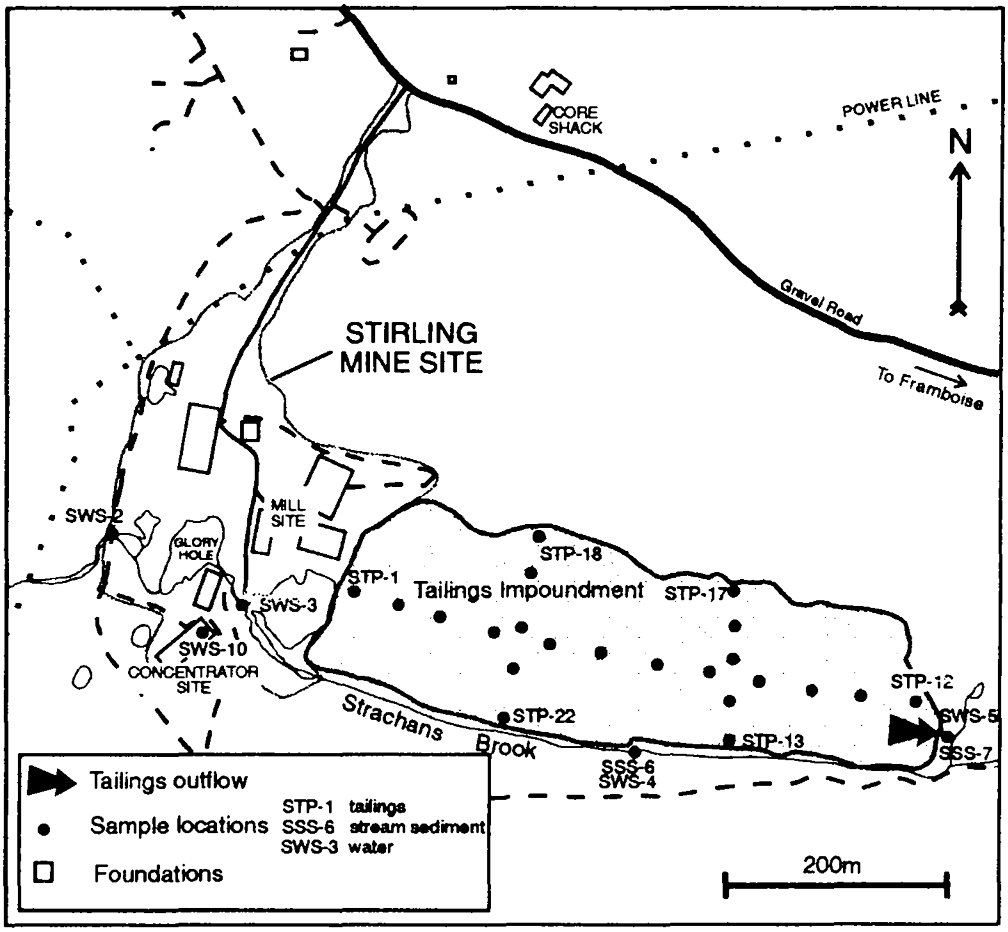


Fig. 3. Detailed map of the Stirling mine site showing mine features, tailings impoundment, and sample locations.

over the berm under dry conditions into a position where it may be washed downstream during subsequent periods of moderate to high precipitation.

Two distinctly different types of interstratified sediment fill the impoundment: orange pyritic sandy silt, and blue-grey pyritic silty mud, deposited in alternating layers generally 1 to 15 cm thick. The orange color associated with the coarser sediment is caused by iron oxyhydroxide coatings which are presumed to have precipitated as a result of oxidation within these more permeable layers. Grain size analyses of bulk samples give median (50th percentile) values close to 0.05 mm (Jacques, Whitford and Associates Limited, 1985).

Extensive erosional features are observed within the tailings impoundment but it is difficult to quantify the losses caused by erosion. Old vegetative debris, mainly tree roots and stumps, holds sediment in place, preventing erosion and contributing to the development of erosional relief in these areas. A crude, but conservative estimate of the amount of erosion (based on erosional channels with an average relief of 0.5 m affecting 50% of the impoundment area) indicates that ca. 16 000 t of tailings sediment may have been released by erosion into Strachans Brook since mine closure in 1956.

Strachans Brook

Strachans Brook flows for 8 km, essentially from west to east, before joining the estuary of the Framboise River, 4 km from the coast (Figs. 1, 2). The width and depth of this brook vary significantly and several gradient changes occur along its length between areas of outcrop (or near-outcrop) and swampy areas. These changes account for large variation in flow rate, which overall is relatively slow (0.51 ± 0.20 m s^{-1}), and also affect the turbulence in the brook influencing to some extent the amount of dissolved oxygen in the water (12.30 - 13.80 mg l^{-1}).

Sediments in the brook upstream from the mine site are dark grey to black, organic-rich sandy-silty material, reflecting the sluggish still-waters that are dominant in the upstream section. Downstream from the mine site, stream sediments are predominantly blue-grey to grey-brown mud forming (i) channel and over-bank deposits in the low-gradient swampy reaches, and (ii) thin veneers and patches in medium-gradient cobbled reaches. Other more localized sediments include dark grey organic-rich silt and reddish till washed in from adjacent ridges. The erosive ability of Strachans Brook is not very high due to the slow flow of the brook; however, the low-gradient swampy reaches are characterized by incised channels which are believed to have developed as a result of progressive over-bank deposition. Reconnaissance drill-sampling of these over-bank deposits, in the first swampy area 1 to 2 km downstream from the tailings impoundment (Fig. 2), indicated that they are tailings-derived sediment about 0.6 m thick, with metal grades very similar to those of the tailings impoundment itself (Jacques, Whitford and Associates Limited, 1985). Test pits excavated as part of the present study showed that they consist of distinctive, inter-stratified pyritic orange sandy silt and blue-grey mud layers similar to those found in the tailings impoundment. It is estimated from the area of over-bank deposition along this 1 km reach of the brook that up to 100 000 t of these sediments may have accumulated here.

Comparison of aerial photographs (although variable in scale and definition) taken between 1939 and 1993 indicates that there have been only minor morphological changes in the brook since routine large-scale discharge of tailings ceased in 1938. Over time, the low-gradient reaches of the brook appear to have expanded, accompanied by change in vegetation from trees to swamp grasses, presumably in response to continuing over-bank sedimentation. However, such deposition is assumed to have declined more recently as the channel became increasingly deepened.

Current influx of tailings into Strachans Brook is interpreted to be episodic, during periods of relatively high precipitation when the sediment is either flushed through the brook into the Framboise River estuary where a small deltaic fan has accumulated at the mouth of the brook, or deposited as a thin veneer of overbank sediment under higher flood conditions.

Given its apparent state of near morphological equilibrium, Strachans Brook can be categorized as a passive fluvial dispersal system (Miller, 1997).

METHODS

Sampling for this study was done in the late spring of 1997 at a time when water levels were relatively stable, although some patches of old snow still remained in the thickest woods. Budget constraints did not permit analysis of water samples collected at other times of the year in order to monitor seasonal variations in water chemistry, so the results presented here represent only the situation at the end of the spring run-off.

Streams, ponds, and seepages were measured directly for pH, conductivity, dissolved oxygen, and temperature at each sampling location, using YSI Model 3560 and Model 55 water quality monitoring systems (Hulshof, 1998). Water samples (filtered to <0.5 μm and acidified to pH 2) were analyzed by inductively coupled plasma - mass spectrometry (ICP-MS) for 64 elements by Activation Laboratories Limited, Ancaster, Ontario. Equivalent samples (filtered but not acidified) were also analyzed using inductively coupled plasma - atomic emission spectroscopy (ICP-AES), ion electrode, and titration methods for their major cation-anion content by the Nova Scotia Department of Agriculture and Marketing laboratory in Truro, Nova Scotia.

All stream sediment and tailings samples were analyzed for Fe, Mn, Cu, Pb, Zn, Ag, Co, and Ni by atomic absorption spectroscopy (AAS) at Acadia University, and selected samples were analyzed for a package of 48 elements by a combination of inductively coupled plasma-emission spectroscopy (ICP) and induced neutron activation analysis (INAA) by Activation Laboratories Limited, Ancaster, Ontario. For AAS analysis, the -170 mesh fractions from tailings and sediment samples were treated with a 1:3 HNO_3 hot acid leach which was effective in getting the Cu, Pb, Zn, Ag, Co, and Ni into solution, but less effective for Fe and Mn, based on AAS results from USGS standards GXR-2, 5, 6, and from combined ICP and INAA results on duplicate samples (Hulshof, 1998).

Sediment geochemistry

Forty-eight samples of tailings and stream sediments were analyzed for Fe, Mn, Zn, Pb, Cu, Ag, Co, and Ni using AAS (Table 1a). Sixteen samples selected from these were analyzed also by a combination of ICP and INAA methods for a range of 46 elements (26 of which are presented in Table 1b).

Upstream sediments, which are assumed to be representative of background bedrock and till materials, show metal concentrations which are less than threshold values determined for the general Framboise-Stirling area (Rogers and MacDonald, 1984), and therefore are not geochemically anomalous (Table 2a). They are distinctive only in their very slightly elevated Ti, Co, Ni, Cr, and V concentrations (Table 1b) which may reflect the more mafic composition of bedrock to the west of Stirling (Macdonald and Barr, 1993).

Compared to other stream sediments in the general Framboise-Stirling area (Rogers and MacDonald, 1984), the downstream sediments are anomalous in Fe, Mn, Zn, Pb, Cu, and Ag by factors of 2x-32x (Table 2a). Compared to upstream sediments, they are highly enriched (3x-72x) in Fe, Mg, Ca, Mn, Zn, Pb, Cu, As, Sb, Cd, Ag, and Au, and are somewhat depleted in Al, Na, K, Ti, Co, Ni, Cr, and V (Tables 2a, 2b). They also have distinct correlation cluster patterns of these enriched and depleted elements which resemble those shown by the tailings (Fig. 4). One notable difference is that the ore-related elements in the downstream sediments show a closer correlation with manganese than they do in the tailings.

Mean results obtained by AAS for the tailings of 1.13% Zn, 0.34% Pb, 0.11% Cu, and 22 ppm Ag (Table 1a), and by combined ICP and INAA methods of 1.03% Zn, 0.32% Pb, 0.12% Cu, 17 ppm Ag, and 0.66 ppm Au (Table 1b) are very similar to the previously quoted average tailings grades from over 3000 samples (Jacques, Whitford and Associates Limited, 1985). Compared to the upstream sediments, they are highly enriched (8x-71x) in Fe, Ca, Mg, Mn, Zn, Pb, Cu, As, Sb, Cd, Ag, and Au (Table 2b), and depleted in Al, Na, K, Ti, P, Co, Ni, Cr, and V. Several elemental groupings or associations can be recognized statistically within these data from Pearson correlation cluster analysis: most notably (i) a strong clustering of the ore-related elements Zn-Pb-Cu-Ag-As-Sb, and (ii) a moderate clustering of predominantly carbonate-related elements Ca-Mg-Mn-Ti (Fig. 4a).

The tailings and downstream sediments are very similar in their overall metal concentrations (Table 1b, Fig. 5a). However, the downstream sediment samples show distinctly more variance than do the tailings samples, presumably due to the various mixing and differentiation processes occurring within the drainage system. These processes include (i) mixing with upstream sediment and locally washed-in soil and till, (ii) response of metals in solution to changes in pH; e.g., from mixing of acidic upstream water with essentially neutralized tailings runoff, or from further downstream influx of acidic meteoric water, (iii) adsorption of metals by Fe-Mn (oxy)hydroxides, and (iv) the effects of temporal changes in tailings management and in the metal grades lost; e.g., 0.38% Cu lost directly to the downstream environment from 1935 to 1938, and 0.22% Cu lost to the tailings impoundment from 1952 to 1956 (Roscoe, 1985).

In Nova Scotia, no provincial guidelines state the maximum amount of metals and other contaminants permitted to be released into the environment; therefore, in order to assess the situation in Strachans Brook, the sediment quality guidelines from Ontario are used (Persaud *et al.*, 1993). These guidelines define a lowest level and a severe level effect of metal contamination. The lowest level is the concentration at which the sediments are considered to be marginally polluted, and to have the potential to affect some sensitive water uses; it indicates a level of sediment contamination that can be tolerated by the majority of benthic organisms. The severe level marks concentrations at or above which sediments are considered to be grossly polluted; above this level there can be a significant disturbance of the sediment dwelling community, and such concentrations would be detrimental to the majority of benthic species. In the case of the downstream sediments in Strachans Brook, the concentrations of Fe, Mn,

Table 1a. Summary of geochemical data for all stream sediment and tailings samples (analyses by AAS, values in ppm).

	Upstream Sediments n = 5		Downstream Sediments n = 18		Tailings n = 25	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Element						
Fe	11390	± 7420	51830	± 18090	144600	± 41950
Mn	735	553	8110	831	7530	1299
Zn	162	29	13460	2766	11250	3489
Pb	62	18	4519	1194	3428	959
Cu	35	8	2274	1088	1073	166
Ag	2	0	22	4	22	2
Co	10	5	12	2	14	2
Ni	13	2	15	3	15	3

Table 1b. Summary of geochemical data* for selected samples of stream sediment and tailings samples (analyses by combination of ICP and INAA, all values in ppm except for Au in ppb).

	Upstream Sediments n = 5**	Downstream Sediments n = 6		Tailings n = 9	
	Composite	Mean	S.D.	Mean	S.D.
Element					
Al	32700	20380	± 9185	10790	± 2271
Fe	17100	55930	38290	148400	57400
Mg	4800	74530	16100	81360	5991
Ca	10100	71030	17370	83260	7220
Na	6400	1500	1563	1800	252
K	6400	3200	2343	1514	488
Ti	2000	292	163	171	49
P	730	237	68	177	13
Ba	430	3167	811	6643	739
Mn	750	7191	1966	7817	698
Zn	146	10440	2826	10300	3930
Pb	47	3328	1118	3216	824
Cu	26	1820	773	1227	149
Ag	0.5	21	7	17	3
Cd	1	33	13	31	13
As	5	180	42	187	26
Sb	3	81	22	76	15
Se	<3	5	2	9	2
Mo	8	16	3	17	1
Bi	<5	17	6	17	7
Hg	<1	3	1	3	2
Co	12	5	2	4	0.5
Ni	14	10	3	7	2
V	49	32	11	18	3
Cr	55	26	11	21	3
Au (ppb)	29	580	225	662	150

*Not included are results for 22 other trace elements, including Rb, Sr, Zr, REE, etc.
**The upstream values are for a composite sample made up of 5 individual samples.
< indicates values below detection limits.

Zn, Pb, Cu, As, and Hg are at, or above the severe level according to the guidelines (Fig. 5b). Potentially, the overall impact of such contamination could include the elimination of species, simplification of the food chain, and thus significant reduction of ecological stability (Gray, 1997). Evaluation of any such impact in the Stirling area would require further, biologically focussed research.

WATER GEOCHEMISTRY

Water samples were collected from 8 locations along Strachans Brook (Fig. 2). In addition, one sample was collected from the tailings pond, and one from leachate from ore concentrate left in ore bins in the mill foundation. These samples were analyzed by ICP-MS for a wide range of elements, 26 of which are presented here (Table 3). Major cation-anion analyses for water quality were also done on 6 samples using ICP-AES, ion electrode and titration methods (Hulshof, 1998).

Surface water in the tailings impoundment (compared to upstream water) is highly enriched (67x-478x) in Ca, Mg, Mn, and Zn, and slightly to moderately enriched (2x-25x) in Fe, Cu, Pb, Cd, As, and Sb (Fig. 6). In comparison, the leachate from the ore bins (which is volumetrically insignificant) is very highly enriched in the main ore elements Zn, Pb, and Cu, and is also highly enriched in Ca, Mg, Mn, As, Cd, Sb, and Ag.

Downstream water (compared to upstream water) shows slightly elevated concentrations of Ca, Mg, Mn, Zn, V, and Cr, no significant change in Pb, and decreased concentrations of Cu, Ni, and Co. The fact that Cu and Pb are not found in very

Table 2a. Mean metal enhancement factors for upstream, downstream, and tailings sediments, compared to calculated threshold values for regional stream sediments.*

	Fe	Mn	Zn	Pb	Cu	Ag
Threshold (ppm)	30100	4240	388	106	65	0.7
Upstream	0.6x	0.2x	0.4x	0.5x	0.4x	0.8x
Tailings	4x	1.8x	27x	30x	19x	25x
Downstream	2x	1.7x	27x	32x	28x	32x

* threshold values (= means + 2 S.D.) from Rogers and MacDonald (1984).

Table 2b. Mean metal enhancement factors for downstream sediments, and tailings sediments, compared to upstream sediments.

	Ca	Mg	Fe	Mn	Zn	Pb	Cu	Cd	As	Sb	Ag	Au
Upstream (ppm)	10100	4800	17100	750	146	47	26	1	5	3	0.5	0.29
Tailings	8x	17x	8x	10x	71x	69x	47x	28x	39x	28x	34x	23x
Downstream	7x	16x	3x	10x	72x	71x	70x	30x	38x	30x	42x	20x

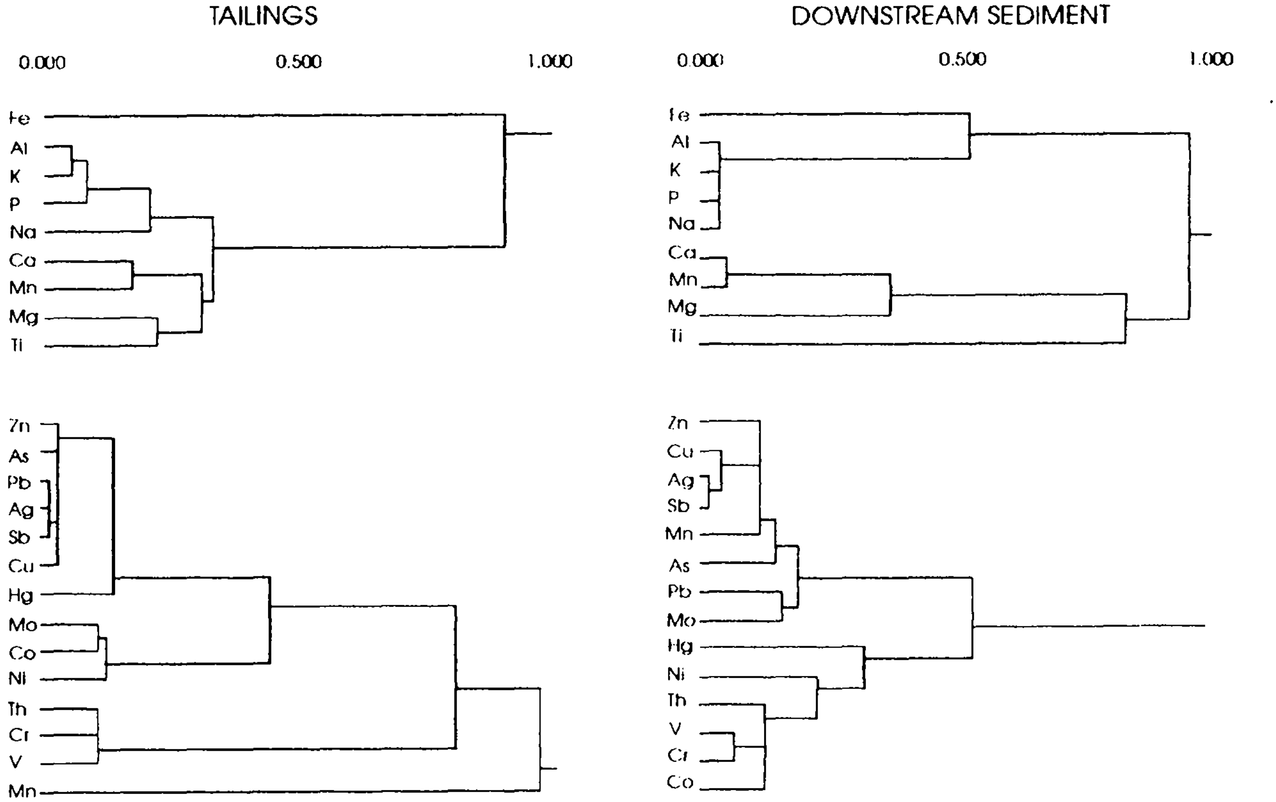
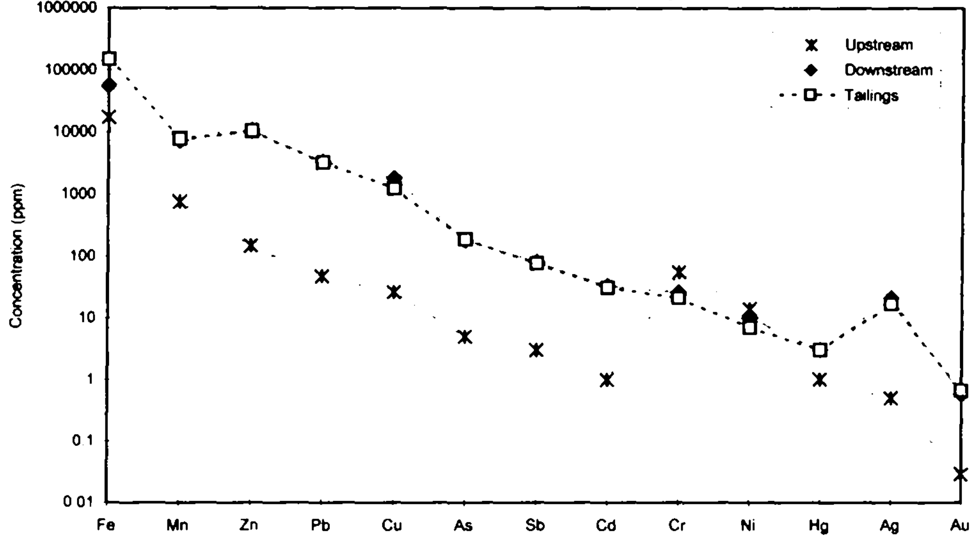


Fig. 4. Pearson correlation cluster diagrams for selected samples of (a) tailings (n = 9) analyzed by a combination of ICP and INAA methods (Table 1b) and (b) downstream sediment (n = 6).

(a) Stream Sediments vs. Tailings



(b) Level of Contamination in Sediment

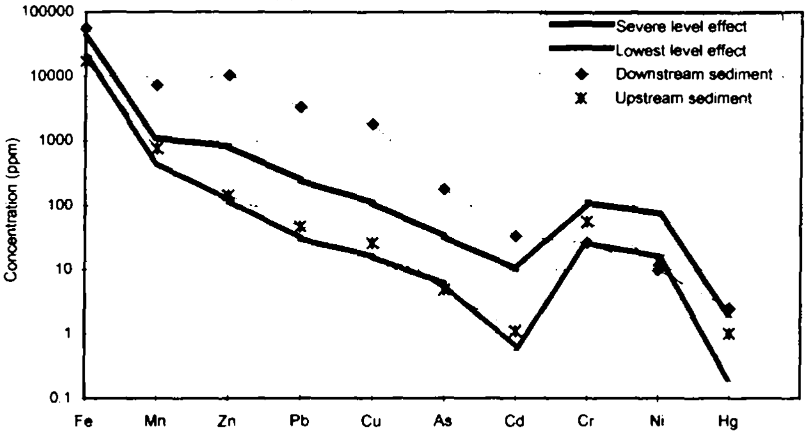


Fig. 5. Geochemical comparison of (a) upstream and downstream sediments with tailings, and (b) upstream and downstream sediments with Ontario Ministry of the Environment guidelines for contamination levels in sediments (Persaud *et al.*, 1993).

significantly increased concentrations in the tailings impoundment and downstream waters, despite their relatively high concentrations in associated sediments, presumably results from their decreased solubility in near-neutral pH solutions (Brookins, 1988). Manganese, Zn, As, Sb, Cd, Se, V, and Cr are present in increased concentrations in both the tailings impoundment and downstream waters, but their concentrations are generally significantly lower downstream. This difference is probably due in large part to dilution by upstream water, but also may result partly from precipitation and adsorption processes (given the strong correlation between Mn and associated elements in downstream sediment (Fig. 4b).

The visibly high concentration of pyrite in the tailings, together with the abundance of flocculated orange iron oxyhydroxide on the surface of the tailings and within subsurface silt layers, suggest that oxidative dissolution of pyrite is occurring and releasing hydrogen ions. However, it appears that acid is being neutralized by carbonate mineral dissolution, because the tailings water contains very high Ca and Mg, high sulphate, and has pH of ~7.0. Acidity is likely neutralized by the dissolution of dolomite, a reaction which requires 2 moles of carbonate to neutralize the acidity generated by 1 mole of pyrite:

$$4FeS_2 + 15O_2 + 6H_2O + 4CaMg(CO_3)_2 = 4Fe(OH)_3 + 8SO_4^{2-} + 4Ca^{2+} + 4Mg^{2+} + 8CO_2$$

The contrast in pH between ~5.6 upstream and ~6.6 downstream suggests that Strachans Brook is being buffered by influx of pH-neutral water from the tailings impoundment. However,

Table 3. Summary of geochemical data* for water samples (analyses by ICP-MS, all values in ppb).

	Upstream n = 2		Mine Site n = 2		Ore Leachate n = 1	Tailings Outflow n = 1	Downstream n = 4	
	SWS-1	SWS-2	SWS-3	SWS-4	SWS-10	SWS-5	SWS-6,7,8,9	
Element							Mean	S.D.
Ca	1922	2032	3102	2433	78110	128200	5813	± 337
Mg	638	731	903	760	10660	104400	2072	151
Na	3404	3235	3564	3298	3154	11070	2948	268
K	1289	532	745	699	1245	1423	647	171
Si	667	678	613	645	5675	1294	800	44
Al	134	172	116	137	1491	107	80	22
Fe	161	137	213	163	419	759	249	238
Mn	18	33	35	25	1197	4528	46	22
Ti	0.7	0.7	1.1	0.9	30	53	2.1	0.2
V	0.3	0.5	0.5	0.4	1.1	1.4	1.6	0.4
Cr	1.2	1.5	1.2	1.2	4.2	3.4	4.8	0.7
Co	0.13	0.11	0.12	0.09	4.62	1.96	0.08	0.03
Ni	5.2	1.6	1.8	2.4	5.6	14.4	1.7	0.6
Cu	34	8	23	12	8234	74	21	8
Zn	44	14	87	35	57520	21050	126	47
Pb	5	3	4	3	1403	121	8	3
As	0.23	0.22	0.35	0.21	3.34	4.99	0.64	0.08
Se	<0.2	<0.2	<0.2	<0.2	2.3	1.8	0.6	0.4
Mo	0.08	<0.05	0.05	0.12	<0.05	0.65	0.07	0.02
Cd	3	2	48	1	206	24	5	3
Sb	0.21	0.04	0.18	0.16	2.27	3.84	0.46	0.08
Ba	4	6	6	5	10	21	19	3
Tl	<0.005	<0.005	<0.005	<0.005	0.832	1.09	0.028	0.029
Bi	<0.005	<0.005	<0.005	<0.005	<0.005	0.125	0.005	0
Th	0.007	<0.002	0.003	0.021	0.042	0.053	0.003	0.002
U	0.022	0.015	0.012	0.022	0.114	0.060	0.019	0.008

*Not included are results for 42 other trace elements, including Rb, Sr, Zr, REE, etc.
< indicates values below detection limits.

estimates of the ratio of dolomite to pyrite (about 1.3:1 in the tailings vs. 3:1 in the downstream sediment) suggest that there may not be enough dolomite in the tailings to neutralize all future acid generation which could be caused by the oxidation of pyrite. Although other carbonates which are present, such as siderite and magnesite, may be potential contributors to neutralization, their concentrations are minor and their effectiveness is limited; as dolomite is consumed, the buffering capacity of the tailings system could become reduced over time, resulting in a progressive increase in acidity within water draining from the tailings (Sherlock *et al.*, 1995). The extent to which this might occur is difficult to predict due to the complexity of the neutralization processes which occur when dolomite becomes less effective (Blowes and Ptacek, 1994).

No tributaries enter Strachans Brook at or below the mine site; therefore, the main area where mixing occurs is below the outflow from the tailings impoundment. The dilution factor of tailings outflow by upstream water is about 35, based on relative discharge rates measured in late spring, and assumes no significant ground water discharge from the tailings into the drainage system. (No direct evidence of such discharge was observed and no piezometer study of groundwater within the tailings was undertaken as part of this study.) This mixing is reflected in an increase in pH from 5.60 to 6.74 as acidic upstream water mixes with neutral run-off from the tailings impoundment (Fig. 7). Conductivity and total dissolved solids (TDS) also increase slightly downstream after mixing with tailings water which has conductivity of 659 µmhos and TDS of 580 ppm (Hulshof, 1998). Small increases in Ca, Mg, and SO_4 can be detected progressively downstream from the tailings impoundment (Fig. 7), suggesting not just simple dilution but continuing minor enhancement, perhaps from overbank deposits. Surface run-off and seepage from some of these areas could contain elemental enrichment similar to water from the tailings impoundment. However, other complicating factors such as influx of groundwater from the glacial ridges

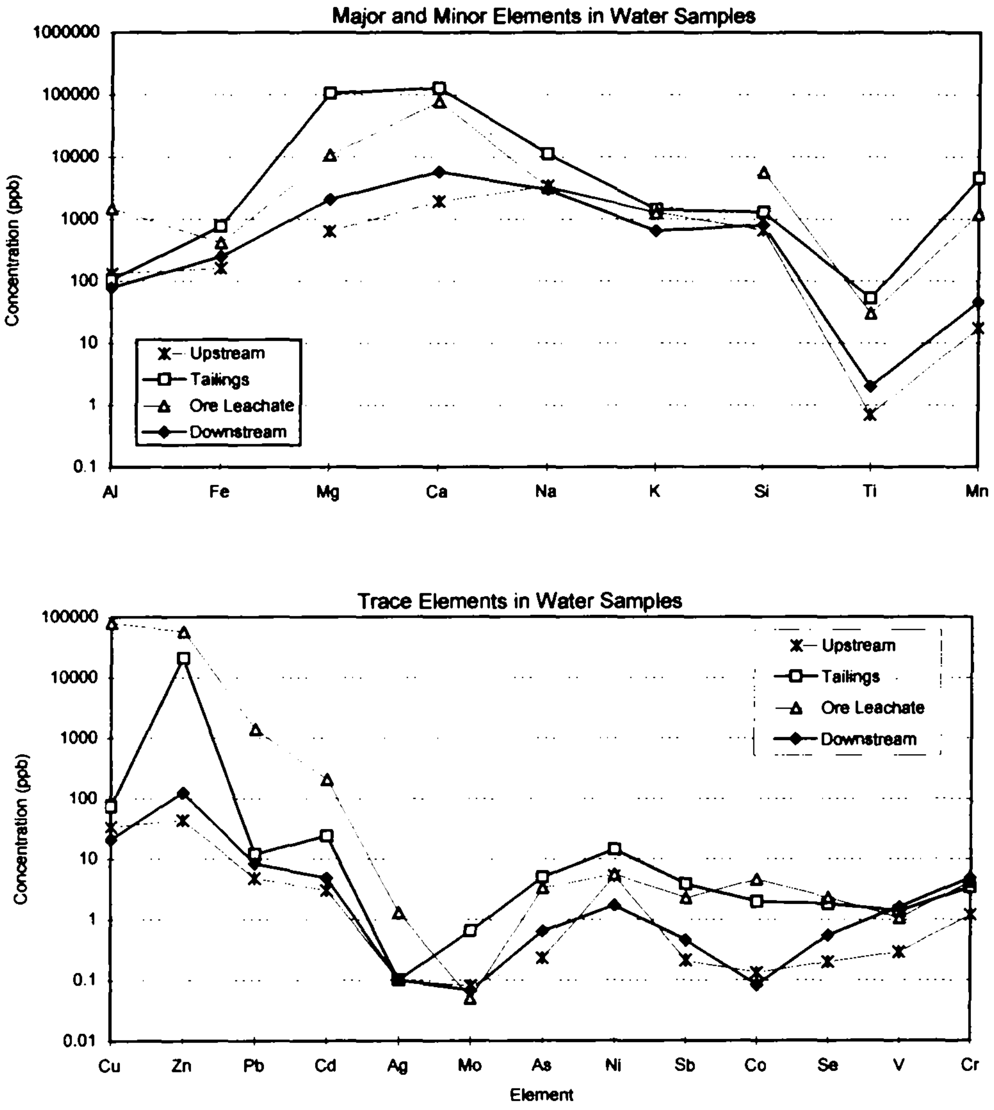


Fig. 6. Geochemical comparison of water samples (analyses by ICP-MS, data from Table 3).

north and south of the stream and variations in stream velocity and turbulence, could cause slight changes in the pH, conductivity, and concentration of ions in solution throughout the downstream reach of the brook (Hem, 1992).

Some measure of possible environmental impact on Strachans Brook by run-off from the tailings impoundment can be obtained by comparing various water quality parameters for the downstream against provincial guideline values. The sampled downstream water is within acceptable levels for alkalinity (<25 mg/l), and TDS (<1500 mg/l) as suggested by the Nova Scotia Department of Fisheries (Jason LeBlanc, personal communication, 1997). Levels of pH are also acceptable and are actually improved over upstream values. However, in the case of base/heavy metal concentrations no local provincial guideline values are available but using those defined by the Ontario Ministry of the Environment (Phyper and Ibbotson, 1990), Zn and Cu values are 4x higher than the limits of 30 ppb and 5 ppb set for these metals, respectively. But it should be noted that upstream water also exceeds this guideline limit for Cu, indicating that the elevated Cu values are most likely due to high natural background levels, not to contamination from the tailings. Hence, only Zn can be considered as a possible, tailings-derived metal contaminant in downstream water.

Although quality of outflow water from the tailings impoundment is poor in terms of its metal values, the pH is neutral, helping to minimize the amount of metals going into solution, and raising the pH level downstream. Had there been no carbonates present to neutralize H^+ produced by oxidation of pyrite, significantly higher concentrations of metals would have been expected and any detrimental effects on the downstream environment would have been much greater. As an example, the leachate from the concentrate bins shows concentrations of Zn, Cu and Pb which are much higher than those found in the tailings water (Table 3). These elevated metal concentrations reflect localized acid generation, corresponding with measured low pH (~4.5) conditions.

CONCLUSIONS

The purpose of this study was to assess the dispersion mechanisms involved in the transport of tailings into the downstream area of Strachans Brook from the Stirling mine site,

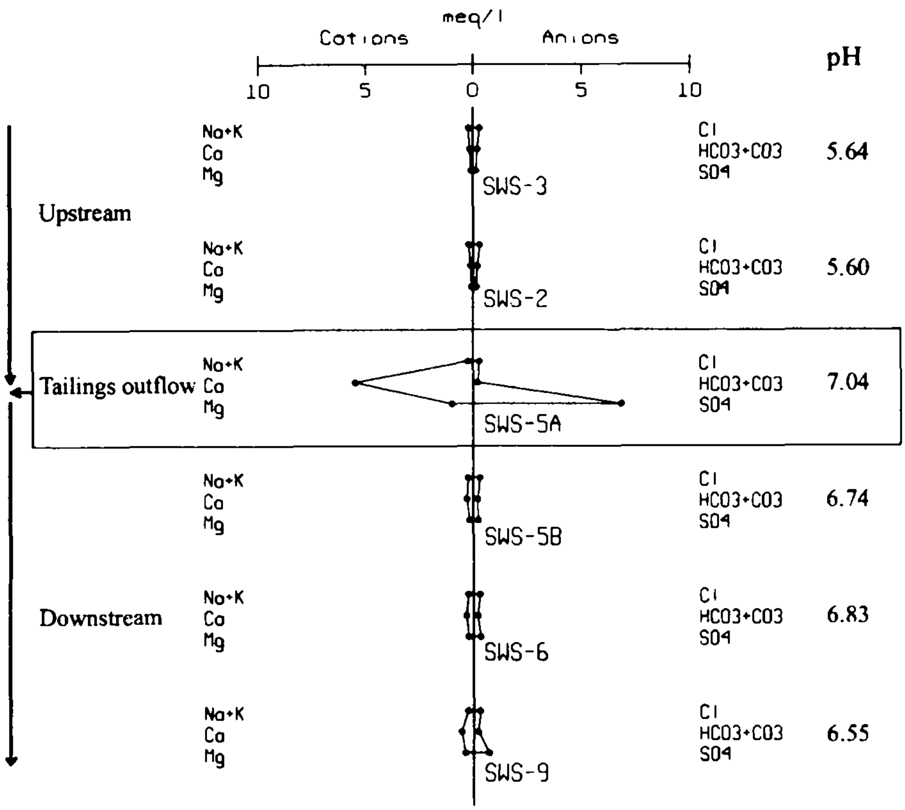


Fig. 7. "Stiff" water geochemistry diagram showing changes in major ion concentration and pH along Strachans Brook (data from Hulshof, 1998).

and to determine the impact that past mining activity may have had on the environment. The physical and geochemical character of the downstream and upstream sediments, compared to the tailings, shows that the downstream sediments closely resemble the tailings. The mean metal enrichment factors in the downstream sediments relative to the upstream sediments are approximately 70 for each of Zn, Pb, and Cu, 35 for Cd, As and Ag, 20 for Au, 10 for Mn, etc. These are very similar to the enrichments shown by the tailings, but there is greater variability downstream than in the tailings as a result of differentiation and mixing processes occurring within the drainage system.

The tailings, produced between 1935 and 1938, were discharged directly into Strachans Brook at a rate approximating 45 000 t yr^{1}. Sediment loading on this scale must have actively transformed channel morphology (but without pre-1935 air photography it is not possible to document this), and a considerable amount of tailings-derived material accumulated in downstream low-gradient reaches as over-bank deposits. Between 1952 and 1956, the tailings were impounded, but since mine closure, ongoing erosion and dispersion from the impoundment has occurred at a rate estimated to be in the order of 500 t yr^{1}. As the channel morphology of the brook appears to have remained relatively unchanged since then, it is assumed this sediment dispersal was essentially passive. At the present time, the main mechanism of tailings dispersion from the impoundment into Strachans Brook is by physical erosion and transport, involving both wind during dry interludes and overflow during flooding. It is hypothesized that the downstream transport of this sediment is periodic, at times of moderate to high precipitation and surface run-off, and that the sediment is deposited as (i) over-bank deposits in swampy reaches of the brook, and (ii) as flow-through deltaic and more dispersed sediments in the estuary of Framboise River. Over-bank deposition may in fact be decreasing over time as the channel becomes progressively deepened relative to its banks so that tailings are dispersed increasingly into the Framboise River. The downstream sediments are contaminated with ore-related elements to an extent which may impact negatively on benthic organisms (Persaud *et al.*, 1993) but this is an aspect which requires further study.

The downstream transport of metals in solution does not appear to be a major environmental concern as the geochemical character of downstream water is only slightly different than it is upstream. Results show that the upstream water is moderately acidic and naturally enriched in copper. After mixing with the tailings runoff which is neutral, strongly enriched in Ca, Mg, Fe, Mn, and Zn, and slightly enriched in Cu, Cd, As, Sb, Se, Co, Ni, Cr, and V, the downstream water is only slightly acidic, and only slightly enriched in Ca, Mg, Mn, and Zn. It is likely that neutralization by dolomite and dilution by upstream water have both played important roles in minimizing the effects of inputs from the tailings.

Further study would be required before it could be determined whether any remedial intervention is warranted in the Stirling area. Remediation and rehabilitation of mine sites is a costly and not always effective process, requiring as prerequisites (i.e., prior to designing any control measures) the quantification of metal concentrations and fluxes, of pH and redox patterns, and speciation of metals in the various sub-systems, and supporting biology-based impact assessments (Allan, 1997; Gray, 1997). Future studies in the area could assess (i) differences in aquatic biota between the downstream and the upstream environments compared to adjacent streams to determine whether there are any negative biological effects from tailings dispersion in Strachans Brook, (ii) the quality and quantity of groundwater within the tailings impoundment and within downstream overbank deposits, and (iii) the quality of the sediment and water in the estuary of the Framboise River to determine whether it has been adversely affected by the long term dispersal of tailings. The area should also be monitored in the future as the neutralizing capacity of the tailings and the sediments is not predictable in the long term due to the complexity of the neutralization of acid-producing reactions (Blowes and Ptacek, 1994).

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