Hydrochemical and stable isotope assessment of tailings pond leakage, Nickel Plate Mine, British Columbia

M.M. Ghomshei · D.M. Allen

Abstract An integrated hydrogeochemical and stable isotope study was undertaken to assess tailings pond leakage at the Nickel Plate Mine site in British Columbia, Canada. The approach used consisted of a hydrochemical mixing model for sulfate in conjunction with stable isotope data (18O and 2H) to estimate possible levels of contamination reaching surface waters from leakage through the dam and to determine the relative percentages of "seepage" that can be attributed to leakage through the dam and to natural groundwater flow beneath and around the dam. Results suggest that tailings pond waters are diluted by groundwaters by approximately 50% before their arrival in the collection swamps, and that the leakage from the tailings pond partially by-pass the collection (and pump-back) system at a rate of between 0.09 and 0.12 l/s. Stable isotope data indicate that tailings pond waters and swamp waters are enriched in the heavier isotopes as a result of evaporation, and thus, tend to plot along an evaporation line of slope 3.9 (D/18O). The isotope data indicate that seepage beneath the dam consists of approximately 50% real seepage and 50% meteoric waters (both surface water and groundwaters).

Key words Stable isotopes · Hydrochemistry · Acid rock drainage · Tailings pond leakage

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Background

The Nickel Plate gold mine is near the town of Hedley, British Columbia about 50 km west of Penticton (Fig. 1). Mining activities began in 1986 and continued until 1996. The milling operation began in 1997. Mineralization is associated with pyrite, arsenopyrite and pyrrhotite hosted in a wollastonite-rich scarn. Total sulfide in the ore is estimated at 1–3%. Decommissioning of the mine site was initiated in 1995 and included the installation of several monitoring wells in the vicinity of the tailings dam and the initiation of a geochemical sampling program of the watershed in the vicinity of the mine site. In the Nickel Plate Mine area, seepage from the tailings pond is received mostly by waters of Cahill Creek by way of Nickel Plate Mine Creek (Fig. 2). Cahill Creek drains into the Similkameen River. The flow of water into the creek in the vicinity of the tailings dam can be accounted for both by seepage through the dam and by naturally discharging groundwater. However, it is difficult to determine the percentage of flow coming from each source. Leakage from the tailings pond is presently collected in swamps and is then pumped back into the pond. Despite these efforts, a portion of the leakage by-passes the "pump-back" system (i.e., the groundwater portion), and creek water has become contaminated.

Hydrogeological and/or hydrogeochemical methods are often used to estimate the amount of water that can potentially pass through a dam. When hydrogeological methods are used, the in situ physical parameters, including the permeability of the tailings dam, and the hydraulic gradient through the dam, must first be determined. Often accurate estimates of these parameters are difficult and expensive to determine. Compounding the problem are the possible hydraulic effects of piping, heterogeneities in the dam, and difficulties acquiring representative samples of the dam material for off-site permeability measurements, each of which can introduce significant errors in the hydrogeological assessment. The cumulative uncertainty may lead to very speculative flow estimates. Further, the presence of slurry, which affects the hydraulic conductivity, can complicate a hydrogeological assessment.

Hydrogeochemical approaches are typically based on the chemistry of the tailings pond and the receiving waters.
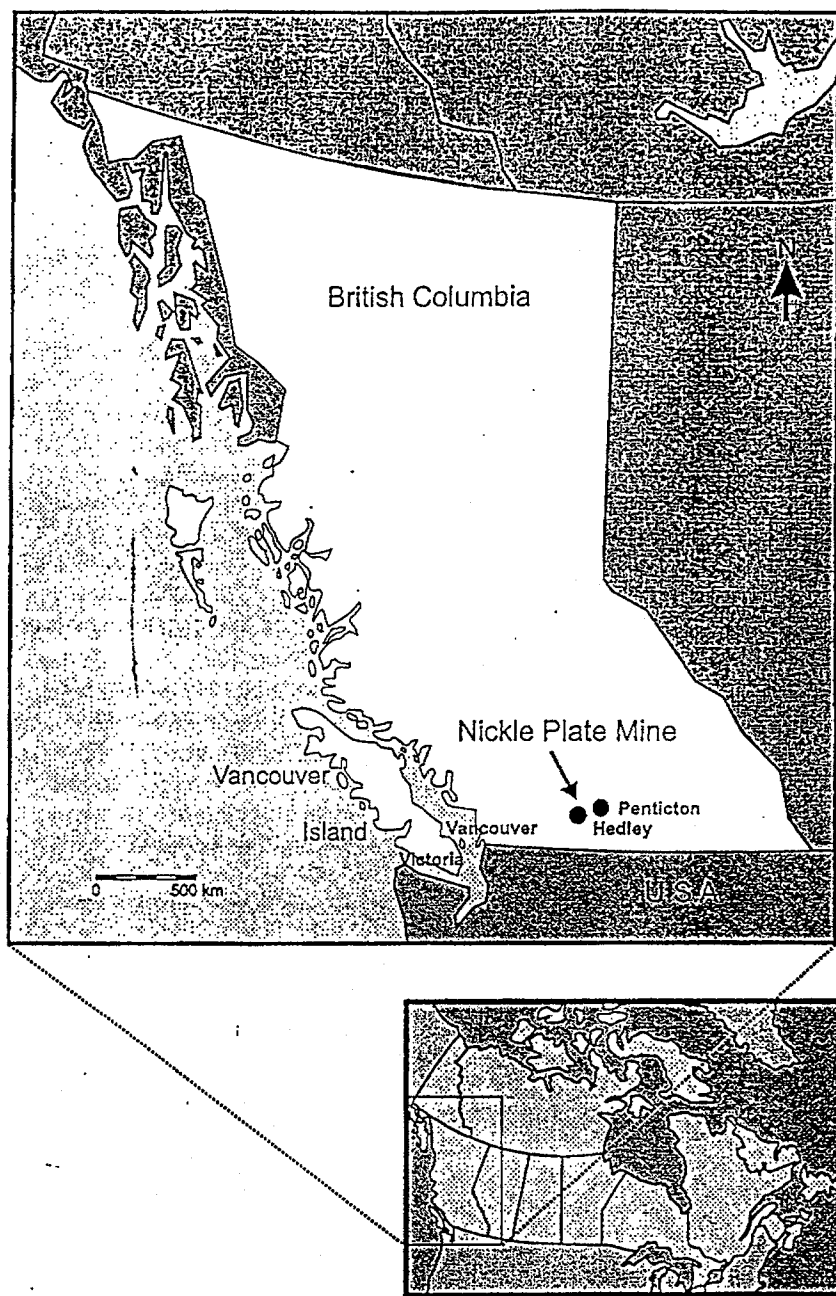
Fig. 1
Location of Nickel Plate Mine, British
Columbia

In this type of study, effluent and waters are sampled from each, and the relative concentrations are used to assess the performance of the dam. If a sound sampling protocol is followed, the water chemistry analysis is straightforward to undertake and interpret, and few analytical errors are generated. Potential errors in a hydrogeochemical approach can arise from an inappropriate choice for the tracing elements (or ions). These errors can be minimized if the study meets three conditions. Firstly, highly conservative elements (i.e., elements/ions remaining in the liquid phase) should be considered, as these are best suited to modelling (condition 1). Secondly, the concentration of the selected elements/ions in the source (tailings pond) should be

significantly above background concentrations (condition 2), and, thirdly, also be considerably different from that of the receiving waters (condition 3). The combination of these three conditions is not easily achieved.

At the Nickel Plate Mine site, an integrated hydrogeochemical approach was favoured for determining the mixing rates. This approach consisted of a hydrochemical mixing model and stable isotope study. The major objectives of the study were, first, to estimate possible levels of contamination reaching surface waters from leakage through the dam, and second, to determine the relative percentages of "seepage" that can be attributed to leakage through the dam and to natural groundwater flow beneath and around the dam. A third objective was to
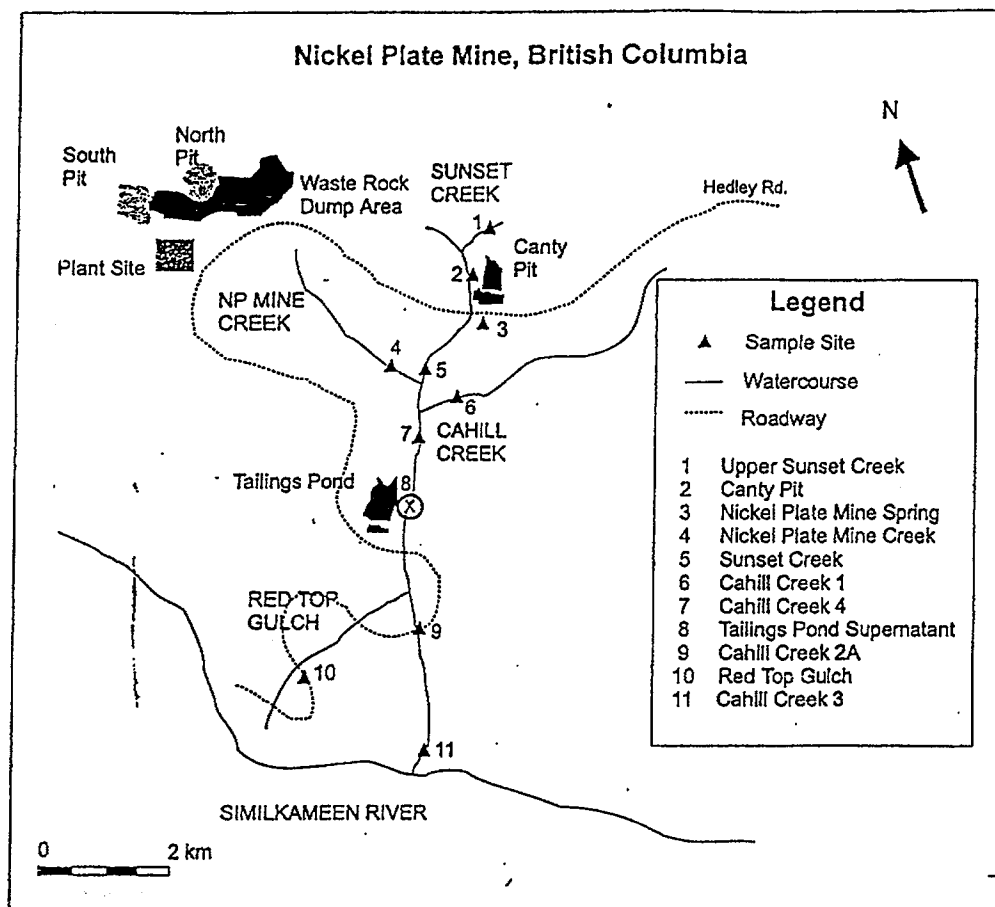
Fig. 2
Site location map for
environmental chemistry

Hydrochemistry

investigate the conjunctive use of stable isotopes for assessing leakage from the tailings pond.

The occurrence of contaminated surface waters at the Nickel Plate Mine site and an estimate of the rate of effluent leakage from the tailings pond are based on the mathematics of dilution/concentration. The sulfate ion was selected as the tracing element because it satisfies all of the three prescribed conditions. Sulfate is a relatively conservative tracer (condition 1), it has a high concentration in the source (condition 2) and it is present at low concentrations in receiving waters (condition 3).

Sulfate concentrations were measured in water samples collected in various uncontaminated surface streams, swamps, creeks down-gradient of the tailings pond, waste-rock dump areas, wells, and the tailings pond itself (Table 1). These values (averaged for January–March 1995) range between 3.8 and 2906.6 mg/l. Figure 2 shows the locations of the samples listed in Table 1. Concentrations of sulfate in creek waters vary according to the position of the sample in the drainage basin and possible sources for contamination. Surface waters that are presumed uncontaminated are represented by sample

sites 1 and 6, with sulfate concentrations of 3.8 and 10.2 mg/l, respectively (average 7.0 ± 4.5 mg/l). Surface waters down-gradient of the waste rock pile (site 4), and which flow into the Nickel Plate Mine Creek, have elevated concentrations of sulfate (270.6 mg/l), reflecting possible contamination from the waste-rock dump area or the plant site. At site 7, the concentration of sulfate in creek water is elevated relative to the uncontaminated creek waters, but has a much lower concentration than the Nickel Plate Mine Creek. The lower rates are the result of dilution, which can be related to mixing of the Nickel Plate Mine Creek water (site 4) with the uncontaminated Cahill Creek water (site 6).

In the vicinity of the tailings pond, sulfate concentrations are typically high. The tailings-pond supernatant water (2906.6 mg/l) and the collection swamps beneath the tailings dam (average 1543.6 ± 471.7 mg/l) host waters with very high sulfate concentrations. Similarly, waters sampled in the various wells that are used to pump contaminated effluent from the swamps back up to the tailings pond have high sulfate concentrations. They range between 487 and 2312.8 mg/l (average 1738.8 ± 565.8 mg/l). By comparing the concentration of sulfate in the tailings pond and in the receiving swamps and pump-back wells, mixing rates for pond water and groundwater are calculated as 53 and 61%, respectively. Therefore, groundwater moving under the dam is diluting

Table 1
Average first quarter (Jan–March 1995) flows and sulfate concentrations of waters at Nickel Plate Mine site (Homestake Canada Inc., unpublished data). Wells, swamps and ponds are situated in the tailings area in Fig. 2; Nd (not detected); bold numbers used in hydrochemical mixing model for average flow and concentrations

Sample	Sample ID	Location number on map	Flow rates (l/s)	Sulfate (mg/l)
Well no.1	W1		3.43	1783.8
Well no.2	W2		Nd	487.0
Well no.3	W3		0.19	2001.6
Well no.4	W4		0.05	2312.8
Well no.5	W5		0.05	2134.6
Well no.6	W6		0.01	1931.0
Well no.7	W7		0.63	1797.2
Well no.8	W8		0.06	1462.5
Well no.11	W11		0.006	1965.8
Tailings pond supernatant	TP	8	Nd	2906.6
Seep from pond	TPS			
Upper Sunset Creek	USC	1	0.32	3.8
Canty Pit	CP	2		
Sunset Creek	SC	5	19.40	19.2
Spring at Hedley Rd.	S	3		
Nickel Plate Mine Creek	NPMC	4	1.45	270.6
Fresh pond	FP		0.0	257.0
East Swamp	ES		5.79	1754.2
DI Swamp	DI S		0.90	1003.3
Control swamp	CS		0.39	1873.4
Red Top Gulch	RTG	10	1.44	134.8
Cahill Creek 1	CC1	6	11.56	10.2
Cahill Creek 2 A	CC2 A	9	23.82	28.2
Cahill Creek 3	CC3 S	11	25.74	30.2
Cahill 4 Creek	CC4	7	23.55	12.9
Cahill Creek 3 (snow)	CC3			
South Dump (snow)	SDS			
Averages for all waters			—	1099.1 ± 973.9
Tailings pond				2906.6
All surface waters				85.2 ± 108.7
All swamp waters				1543.6 ± 471.7
All wells				1738.8 ± 565.8

the concentration of the effluent entering the swamps to about half its amount in the tailings pond.

In creek waters below the tailings pond area, the sulfate concentration data are slightly more difficult to interpret. At site 10, the sulfate concentration is elevated significantly (134.8 mg/l) compared to that measured immediately downstream of the tailings pond. These high values may imply that there is an additional seepage from the tailings pond toward Red Top Gulch. The creek located immediately south of location 10 is not, however, connected to Cahill Creek; it appears to be situated within a separate smaller watershed.

Finally, between sites 9 and 11 just above the mouth of Cahill Creek into the Similkameen River, the sulfate concentrations are relatively unchanged, indicating that there is no further contamination of Cahill Creek. The final concentration of sulfate in the water entering the Similkameen River from Cahill Creek is 30.2 mg/l.

Hydrochemical mixing model

Figure 3 shows a schematic diagram of the tailings dam and collection swamps. The difference in concentration between sulfate in the tailings (2906.6 mg/l) and average
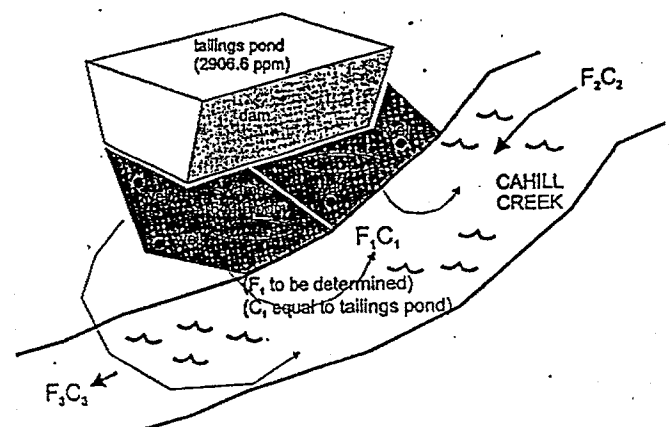

Fig. 3
Schematic diagram of tailings pond, dam, swamps, extraction wells and possible leakage

NICKEL PLATE MINE
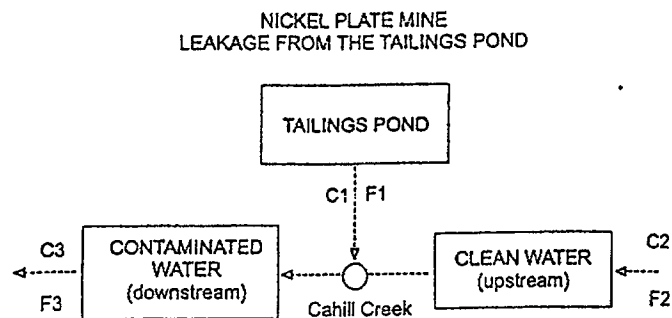LEAKAGE FROM THE TAILINGS POND

Fig. 4
Nickel Plate hydrogeological mixing model

sulfate in the swamp waters (1543.6 mg/l) can be accounted for by dilution and mixing between tailings pond effluent, rainwater and natural groundwaters circulating beneath the dam. The wells, which have sulfate concentrations similar to the average for the swamps, pump water from the swamps back to the tailings pond. However, it is expected that some contaminated water is by-passing this pumping cycle, thereby entering nearby Cahill Creek.

Simple hydrochemical modelling was undertaken in order to quantify the mass flux of sulfate at different locations and to estimate the amount of leakage coming from the tailings pond area. The adopted mixing model (Fig. 4) is based on the conservation of mass, both for the tracing element [Eq. (1)] and for the flow [Eq. (2)] as follows:

$$\sum F_{i(t)} \bullet C_{ij(t)} = 0 \qquad (1)$$

$$\sum F(t)_i = 0 \qquad (2)$$

where, $F_i(t)$ is the flow out of the source i at some time t and $C_{ij}(t)$ is the concentration of the element j in the source i at time t. Equation (1) is based on the mass balance for element j, and Eq. (2) is based on the mass balance for water.

Changing the parameters in Eq. (1) and substituting the known parameter leads to a system of n linear equations with m unknowns. If m is equal to n, the system of equations can lead to a single solution. If m is less than n, a method based on least squares fitting can be adopted to determine the best solution.

The adopted parameters were as follows:
– $F_1(t)$ Flow contribution of the tailings pond to the creek at time t.

– $F_2(t)$ Flow contribution of uncontaminated waters (i.e., surface waters) to the creek at time t.
– $F_3(t)$ Total flow of the creek below the tailings dam at time t.
– $C_{1sulfate}(t)$ Sulfate concentration of the tailings pond at time t.
– $C_{2sulfate}(t)$ Sulfate concentration of the uncontaminated waters (background levels).
– $C_{3sulfate}(t)$ Sulfate concentration of the creek waters below the tailings dam (presumed contaminated)

Average water flows and average sulfate concentrations measured in the first quarter of 1995 (Table 1) were used to calculate an average flow rate, F_8, into the creek waters from the tailings pond and/or collection ponds. The relevant equations are:

$$F_9 = F_7 + F_8 \qquad (3)$$

$$F_9 C_9 = F_7 C_7 + F_8 C_8 + \delta \qquad (4)$$

where δ term in Eq. (4) is a source/sink term for sulfate. However, assuming sulfate is conservative in the system, two simple direct solutions are possible. First, using Eq. (4), it is possible to solve for the mass flux from the tailings area ($F_8 C_8$) by simply dividing by the concentration of the tailings pond (C_8) to yield a flow, F_8, equal to 0.13 l/s. Using Eq. (3) it is possible to solve directly for the flow, F_8, giving 0.27 l/s. If the average concentration of the swamps is used in place of the concentration of the tailings pond, the flow, calculated using Eq. (3), is 0.24 l/s.

The main problem with this simplistic approach is that the flow rates at site 9 downstream may not be representative of the flow of water in Cahill Creek immediately adjacent to the tailings pond (designated with an X in Fig. 2). Groundwater is often used for irrigation at a property located immediately south of the tailings pond in the Red Top Gulch area. Thus, the groundwater extraction may periodically lower the flow rates measured in Cahill Creek. This could result in higher estimates of tailings pond leakage.

A more rigorous solution approach, based on the solution of a system of linear equations with several unknowns, was used to estimate the seepage from the tailings area. Known data included flows and concentrations at site 7, concentrations at site 8 (tailings pond), and concentrations downstream at site 9, for January and March 1995 (Table 2). A system of five equations was used with the variables indicated in Table 3. The first four equations represent Eqs. (1) and (2) (twice) and the

Table 2
Concentrations and flow rates used in hydrochemical mixing model (Januar and March 1995 data)

Location	Location number	Flow January 1995 (l/s)	Concentration March 1995 (mg/l)	Flow March 1995 (l/s)	Concentration March 1995 (mg/l)
Tailings pond	8		3050		3120
Clean water (upstream)	7	25.87	10.5	11.36	20.8
Contaminated water (downstream)	9		21.4		52.1

Table 3
Variable definitions and equations for hydrochemical mixing model (variables as shown in Fig. 4; concentrations in mg/l and flows in l/s)

Variable	Value	Equations
t_1	January average	
t_2	March average	
C_{1t1}	3050	Eq. (1): $F_{31} = F_{21} + F_{11}$
C_{1t2}	3120	Eq. (2): $F_{32} = F_{22} + F_{12}$
C_{2t1}	10.5	Eq. (3): $F_{31}C_{31} = F_{21}C_{21} + F_{11}C_{11}$
C_{2t1}	20.8	Eq. (4): $F_{32}C_{32} = F_{22}C_{22} + F_{12}C_{12}$
C_{3t1}	21.4	Eq. (5): $F_{11} = F_{12}$
C_{3t2}	52.1	
F_{1t1}	Unknown	
F_{1t2}	Unknown	
F_{2t1}	25.87	
F_{2t2}	11.36	
F_{3t1}	Unknown	
F_{3t2}	Unknown	

fifth equation was generated based on the fact that the leakage from the tailings pond is likely to remain constant. This is a reasonable assumption considering that leakage rate is primarily a function of the permeability of the dam and the gradient is unlikely to change significantly between January and March.

The solution is non-unique and provides two estimates of the flow rate (F_8) from the tailings dam (0.09 and 0.12 l/s). These values are approximately half of those derived from the simplified approach above, suggesting that groundwater extraction downstream of the tailings area may be contributing to lower flow rates in Cahill Creek. The values also support the hypothesis that there is a fairly low, but measurable seepage from the tailings area that may be contributing to the contamination.

A similar mixing model approach could also be used to estimate the loading of various other constituents in the creek waters, provided they are conservative in their chemical nature.

Stable isotope study

Stable isotopes are used in hydrology, hydrogeology and hot spring (geothermal) studies. The most commonly used stable isotopes are oxygen-18 (^{18}O) and deuterium (D or ^2H). Oxygen and hydrogen isotopes can be very useful in environmental studies for the following reasons:
1 They are constituents of the water molecule.
2 They are conservative under near-surface temperature conditions. ___
Another important attribute of oxygen and hydrogen isotopes is the fact that isotopes of light elements are easily fractionated in the course of certain physical and chemical processes commonly occurring in nature (e.g., evaporation, condensation and weathering).
In the Nickel Plate Mine area, fractionation of oxygen and hydrogen isotopes by evaporation can be used to

distinguish between the tailings pond and receiving waters and to estimate the rate of leakage from the pond. The methodology is based on the assumption that tailings pond waters should be significantly richer in heavy isotopes (due to exposure and subsequent intense evaporation). In situations where the isotopic values for the tailings pond are highly positive (suggesting enrichment of the heavier isotope), it should be possible to assess the mixing rate between the surface waters and waters from the tailings pond.

Sampling and data analysis
In order to provide base line data to conduct the study (i.e., define the meteoric water line), 11 surface and meteoric water samples were collected from rain, snow, surface waters, tailings pond waters and seep waters from the pond (Table 4). The samples were analyzed at the Ottawa-Carleton Geoscience Centre stable isotope facility. The isotopic ratios of $^{18}O/^{16}O$ were measured using a VGSIRA-12 gas-source mass spectrometer, on CO_2 gas prepared by standard equilibrium with water samples at 25° $D/^2H$. Isotopic ratios were measured by hydrogen gas extracted from water by reduction on uranium metal at 800 °C. Stable isotope ratios are expressed as delta in per mil (δ‰) relative to the known standard SMOW (standard mean ocean water). The isotope analytical precision is ± 0.15‰ for ^{18}O and ± 1‰ for D.

Stable isotope results
$\delta^{18}O$ for all waters ranges between -13.19 and -29.96‰ (average of -26.09 ± 1.35‰), while δD ranges from -111.9 to -220.7 (average of -125.06 ± 6.21‰). All surface water samples, with the exception of one spring water sample, have relatively similar isotopic characteristics. $\delta^{18}O$ range between -16.79‰ and -17.12‰ (average of -16.86 ± 0.06‰). δD values range between -128.0 and -129.5‰ (average of $128.65 \pm .62$‰).
The single spring sample at Hedley Rd. (Fig. 2) demonstrates a remarkably different isotopic signature with $\delta^{18}O = -16.21$‰ and \$\delta D = -124.4$‰. This sample, being distinctly heavier than the other surface waters, suggests that groundwater (coming to the surface as a spring) has been recharged either from precipitation in relatively low-level areas or from an area west of the mine. Hydrogeological constraints make the latter assumption more reasonable. The lower elevation precipitation is commonly richer in heavier isotopes, as is precipitation closer to the coast (Ghomshei and Clark 1993; Ghomshei and Allen 2000).
The two snow waters are significantly depleted in heavy isotopes, with $\delta^{18}O$ values of -21.52 and -29.96‰ (average of -25.74 ± 5.96‰), and δD values of -168.7 and 220.7‰ (average of -194.70 ± 36.77‰). The isotopic values for precipitation (snow) samples are significantly dispersed, while running surface waters are isotopically similar, albeit at higher average value and much lower standard deviation.

Table 4
Stable isotope composition of waters at Nickel Plate Mine site sampled 3-4 February 1996

Sample	Sample ID	Location number on map	$\delta^{18}O$ (‰)	δH (‰)
Tailings pond supernatant	TP		− 13.19	− 111.9
Seep from pond	TPS		− 14.96	− 120.1
Upper Sunset Creek	USC	1	− 17.12	− 128.9
Canty Pit	CP	2	− 16.97	− 129.5
Sunset Creek	SC	5		
Spring at Hedley Rd.	S	3	− 16.21[a]	− 124.4[a]
Nickel Plate Mine Creek	NPMC	4	− 16.93	− 128.5
Fresh pond	FP			
East swamp	ES			
D1 swamp	D1 S			
Control swamp	CS			
Red Top Gulch	RTG	10	− 16.79	− 128.6
Cahill Creek 1	CC1	6	− 16.88	− 129.5
Cahill Creek2 A	CC2 A	9		
Cahill Creek 3	CC3 S	11	− 16.82	− 128
Cahill 4 Creek	CC4	7		
Cahill Creek 3 (snow)	CC3		− 21.52	− 168.7
South Dump (snow)	SDS		− 29.96	− 220.7
Average for all samples			− 16.09 ± 1.35	− 125.06 ± 6.21
Tailings pond			− 13.19	− 111.9
Seeps (wells and swamps)			− 14.96	− 120.1
Surface waters			− 16.86 ± 0.06	− 128.65 ± 0.62
Snow			− 25.74 ± 5.96	− 194.70 ± 36.77

[a] Not included in average for surface waters

Correlation of the two isotopes is shown in Fig. 5. There is a clear linear trend to the meteoric/surface water data points that defines the local meteoric water line (LMWL):

$$\delta D = 7.1\ \delta^{18}O + 3 \qquad (5)$$

$$\delta D = 8\ \delta^{18}O + 10 \qquad (6)$$

The data points related to the tailings pond and the seeps from the pond (manifested as swamps) do not appear to fall on the local meteoric water line. The single sample from the tailings pond is clearly enriched in heavy oxygen and deuterium (i.e., it has higher δD values). The sample related to the seep from the pond appears to be a mixture of meteoric waters and waters from the tailings pond.
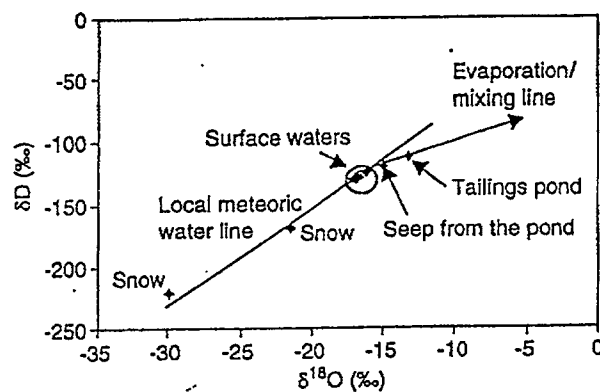

Fig. 5
Stable isotope correlation at Nickel Plate Mine

Evaporation is the reason for the distinct isotopic signature of the tailings pond waters. Evaporation leads to fractionation or partitioning of the heavy and light isotopes. The heavier isotopes prefer to remain in the liquid. Fractionation that occurs during evaporation is more dominant in the oxygen than in the hydrogen because of oxygen's heavier molecular weight (20 instead of 18). The hydrogen fractionates as well, but the difference in molecular weights between H_2O and D_2O renders the process less significant.

Evaporation lines are commonly defined by an isotopic signature of:

$$\delta D / \delta^{18}O = 3\ \text{to}\ 5 \qquad (7)$$

It is assumed that the single data points for the tailings pond and the seep are accurate, the evaporation slope for the Nickel Plate Mine area will be close to 4 ($\delta D / \delta^{18}O = 3.9$). Assuming that the seep sample is a mixture of the waters from the tailings pond and surface waters (as illustrated in the graph shown in Fig. 5), the mixing rate can be calculated. The isotope data suggest that the seep sample is approximately half "real seepage" from the pond and half meteoric waters. A larger data set is needed to confirm this mixing rate. However, sulfate data discussed earlier also indicate dilution of the seep waters with respect to the tailings pond waters.

Average stable isotope values both for ^{18}O and D (Table 4) have been plotted versus average 1995 sulfate data for surface waters, seep waters and tailings pond water. A clear linear trend is apparent (Fig. 6). This graph agrees well with mixing rates estimated from sulfate data, and suggests that the seep from the pond is an
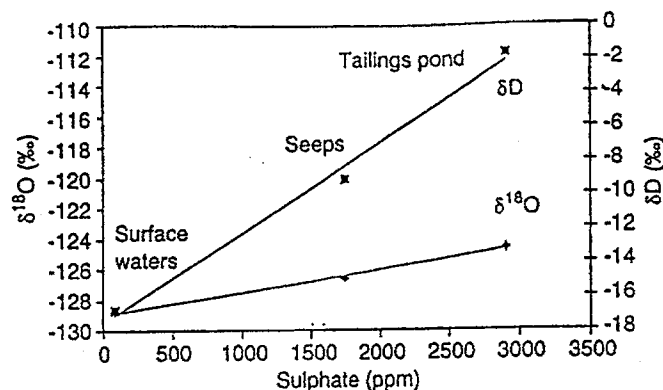
Fig. 6
$\delta^{18}O/\delta^2H$ and sulfate concentration data for surface waters, seeps and the tailings pond

approximately equal mixture of pond waters and meteoric water (groundwater and surface water). This mixing is observed both in ^{18}O and ^2H data, which suggests that fractionation occurs in both oxygen and hydrogen. Because a similar trend is observed between sulfate and both ^{18}O and ^2H, no other processes appear to contribute to fractionation (such as high temperature exchange of O_2 with rocks, hydration of silicates, exchange with CO_2, etc.).

data, the mixing rate is approximately 50% between meteoric and tailings pond effluent entering the swamps and pump-back wells. A mixing model based on sulfate concentrations suggests that the leakage from the tailings pond partially by-pass the collection (and pump-back) system at a rate of between 0.09 and 0.12 l/s. Relatively high levels of other contaminants might be expected in the creek due to contamination that by-passes the pump-back system.

Stable isotope data indicate that tailings pond waters have undergone fractionation during evaporation and data plot along an evaporation line of slope 3.9 that extends away from the meteoric water line. Seepage waters also plot along the evaporation line approximately midway between the meteoric water line and the tailings pond sample. Isotope data indicate that mixing between groundwater and tailings pond waters is present and that groundwater or other surface waters dilute the tailings pond waters by one half. A more extensive stable isotope sampling program, including several samples from the tailings pond (summer and winter) and different seeps from the pond, will provide better information on the hydrological/environmental parameters of concern in the Nickel Plate Mine area.

Conclusion

There appear to be high levels of sulfate in creek waters downstream of the waste-rock dump area at the head of the Nickel Plate Mine Creek and downstream of the tailings pond (Fig. 2). Higher sulfate concentrations downstream of the tailings pond suggest that leakage from the tailings pond may be significant. However, the source for the leakage is uncertain. Contaminated waters may enter Cahill Creek directly at the tailings site, or they may enter the creek further downstream via an alternative route through the Red Top Gulch area (Fig. 2). The "seepage" from the pond into the swamps is a mixture of waters leaking directly from the pond and both groundwater and other surface waters. Based on sulfate

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