MITIGATION OF ACID MINE DRAINAGE BY THE POROUS ENVELOPE EFFECT[1]

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Abstract: A porous envelope effect may occur in ground water systems when mine tailings of low permeability are placed within high-permeability soils. If the permeability contrast between the tailings and the natural soil is large, ground water will flow around the tailings mass rather than through it, and metal leaching will be minimal. A hydrogeological study at the Falconbridge Fault Lake tailings site suggests that conditions for porous envelope containment may be occurring. The tailings have been deposited in a kettle lake formed within glacial outwash sand and gravel. At present, the tailings are mostly above the water table, and surveys using a combination of electromagnetic geophysical methods and monitoring wells did not detect any presence of metals in the ground water. A 2-D finite-element numerical model was used to predict conditions that may occur if the water table would rise within the tailings. The model suggested that the contribution of tailings leachate to the regional ground water system would be small.

Introduction

In 1992, Noranda Technology Centre (NTC) undertook a hydrogeological investigation of the Fault Lake tailings site. The site is unique in that a "porous envelope effect" may be occurring. If this is the case, flow through the tailings mass is low enough, relative to the surrounding, more permeable till, that impact to the ground water by tailings oxidation is insignificant at the regional scale. The specific objectives of the investigation were to analyze the chemical and physical hydrogeology of the site, to delineate areas affected by acid mine drainage (AMD) generated from the tailings, and to verify the presence of the porous envelope effect.

Background

The Fault Lake tailings site is located northwest of the Falconbridge Sudbury operations, approximately 3 km north of Falconbridge and 0.5 km east of the Sudbury Airport. The tailings were deposited between 1965 and 1978 and were produced from the milling of nickel ore in the Sudbury area. Approximately 6.45 million mt of tailings containing as much as 50% pyrrhotite were deposited in a depression of a maximum depth of approximately 30 m. The tailings were contained by dams to the northeast and southeast of the site (referred to as north and south dams). The deposit has an approximate volume of 3.36×10^6 m^3 and a surface area of 22.2 ha (55 acres).

During the spring and fall, ponding occurs at the north dam, south dam, and various berms. The water slowly infiltrates into the tailings and evaporates from the ponds. During the summer, very little ponding has been observed. Tailings in areas where ponding has occurred are soft and gray, while the rest of the tailings are hard and crusty, showing orange traces of oxidation.

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Surficial Geology

Overburden thickness varies within the studied area, from 36 m to more than 60 m. Overburden mainly consists of coarse to fine glacial outwash sands and gravels, with some large boulders and silt lenses. Kettles, fluvial terraces, discontinuous crevasse fillings, and eskers within the Fault Lake tailings area are evidence of a glacial meltwater channel, partly choked with stranded ice blocks. The small round kettle lakes were formed after the late melting of the stranded ice blocks which were caught among the mass of glacial sediments. The sediments are assembled in longitudinal formations which follow a northeasterly direction.

Investigative Methodology

Installation of Ground Water Monitoring Stations

The routes by which acid water could be transported from the Fault Lake tailings site were examined by electromagnetic surveys (Geomar Inc. 1991 and 1992), and probable seepage routes were identified leaving the tailings site at the base of the north and south dams. Thirteen ground water monitoring stations were placed to sample the ground water in the sediments directly below the tailings deposit and along the seepage routes. In addition, one station (FS-2) was located upgradient of the tailings to characterize background conditions. Figure 1 shows the locations of all the stations and also shows the outline of the original kettle lake as determined from aerial photographs taken prior to tailings deposition. Bedrock in the vicinity of the tailings site was not believed to have an important influence on ground water flow in the area.

Measurements of in situ hydraulic conductivity were conducted at most of the monitoring stations using the "falling-head test." Interpretation of the water level versus time data was conducted using the Hvorslev (1951) method for point piezometers. Ground water was sampled from monitoring wells in December 1992 and in March 1993. Sample pH, temperature, oxidation reduction potential (Eh), and electrical conductance were recorded. Acidified portions were later analyzed for dissolved metal and major ions, and the nonacidified portion was analyzed for chloride. Tailings pore water and the five kettle lakes in the Fault Lake tailings area (fig. 1) were also sampled in 1992.

Results

Physical Hydrogeology

Measurements indicated that the water table is 0 to 2 m below the base of the tailings, except at station FS-6, where there is evidence of a perched water table approximately 8 m above the base of the tailings. At station FS-12, which is the closest to the center of the original kettle lake, the measured water level was approximately 20 m below the tailings surface, near the base of the tailings. The fact that nearly all of the tailings are above the water table is surprising because water was visible in the kettle lake before tailings deposition. Low water infiltration in the tailings and changes in watershed configurations due to nearby quarry excavation are apparently causing the lowering of the water table. Regional ground water flow from the tailings watershed was determined to be northeast toward the small kettle lakes and southeast across the dam.

Hydraulic gradients were calculated for both vertical and horizontal directions. Vertical gradients were near zero at most of the monitoring stations surrounding the tailings deposit. Beneath the tailings deposit, significant vertical gradients indicate percolation. Upward gradients suggest partially confined conditions and/or localized flow paths below the tailings. Horizontal gradients were very small. At the north dam, the horizontal gradient was 0.0002; at the south dam, it was 0.007.

Measured hydraulic conductivities in the natural overburden were highly variable, ranging from 8×10^{-1} cm/s to 2.5×10^{-5} cm/s. The large variations in hydraulic conductivity are explained by the heterogeneity of the soil,

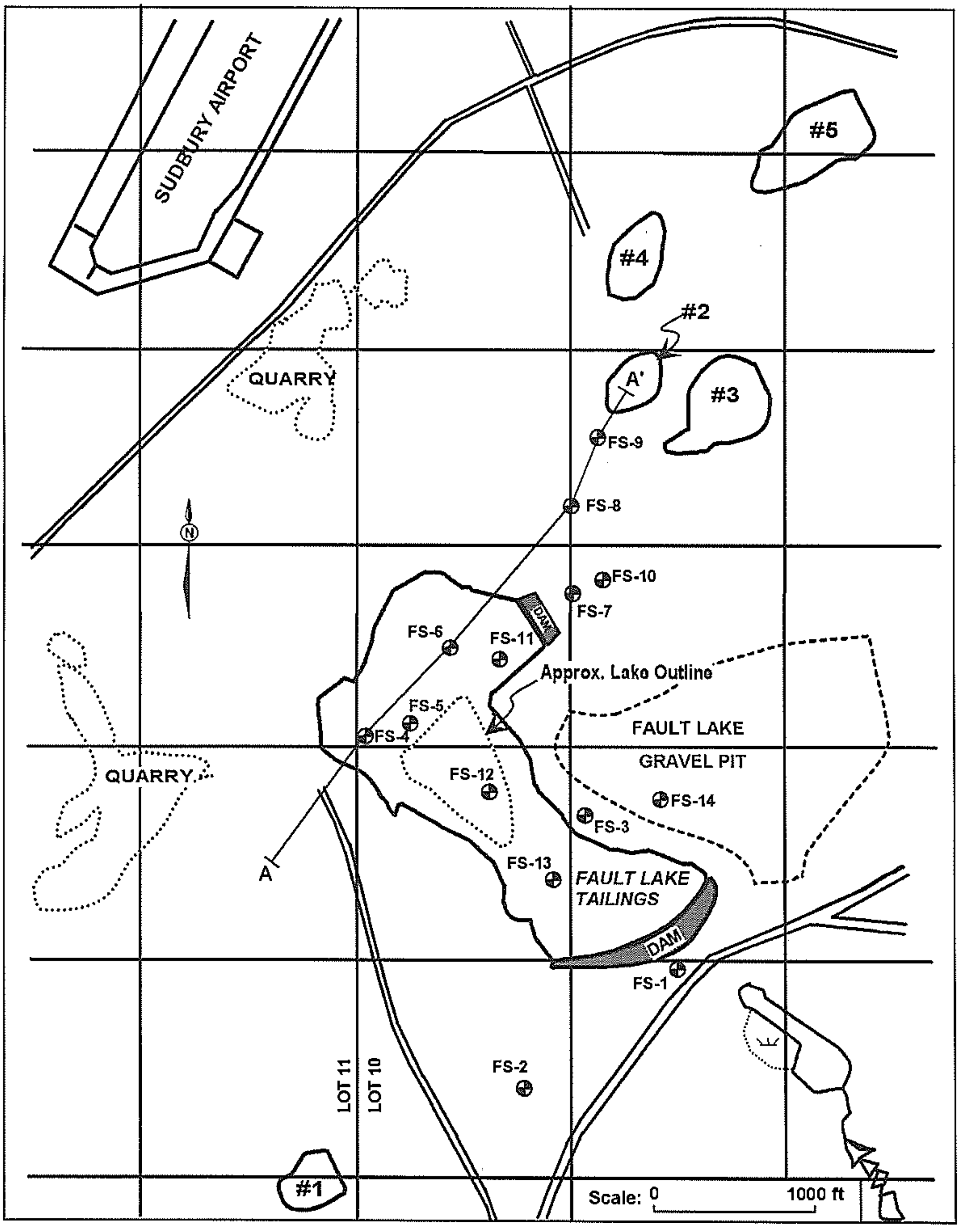

Figure 1. Fault Lake tailings.

typical of ice-contact deposits, which include silts, sands, gravels, and boulders. The higher hydraulic conductivities occur where fast meltwater flows have formed accumulations of well-sorted sands and gravels. The lower hydraulic conductivities occur where glacial abrasion and slow meltwater flows have left finer silts.

The geometric average of all hydraulic conductivity measurements in the overburden is 1.6 x 10^{-3} cm/s. This value is typical of a clean to silty sand and is considered to be representative of the overall effective hydraulic conductivity of the soils in which the tailings lie. Using the average hydraulic conductivity, a hydraulic gradient of 0.0002, and an estimated effective porosity of 0.30, the calculated velocity north of the tailings is approximately 30 cm/yr. With a horizontal gradient of 0.007, the calculated average velocity south of the tailings is 6 m/yr. This velocity is only approximate, and actual local velocities may vary by a factor of 10.

The hydraulic conductivity of the tailings was estimated using the Kozeny-Carman equation (Bear 1972), an estimated porosity of 0.45, and the median particle diameter, or d_{50}. The resulting estimated tailings hydraulic conductivities averaged 1.2 x 10^{-5} cm/s, which is consistent with measurements of similar tailings at other sites (Yanful and St-Arnaud 1992, for example). The measured hydraulic conductivities of tailings and overburden materials also agree with previous estimates done by Geocon (1985).

Chemical Hydrogeology

Water extractions were performed on six selected samples collected in November 1992 at each of the monitoring stations located on the tailings. Nickel concentrations ranged from 4 to 644 mg/L, sulfate concentrations ranged from 3,041 to more than 84,600 mg/L, and total iron concentrations were 0.5 to 466 mg/L. These values show evidence of sulfide oxidation within portions of the tailings deposit. Metal concentrations in the pore water are strongly influenced by downward water movement, chemical precipitation, and dissolution reactions that occur in the tailings mass. These effects seem to have attenuated nickel in the deeper parts of the tailings to concentrations of 5 to 8 mg/L. Thermodynamic calculations done on porewater quality data suggested nickel sulfate could be near saturation.

Differences in measured metal concentrations could be caused by variations in the intensity of oxidation across the surface of the tailings. Visual inspection of the tailings shows the development of cracks and crusty layers at the surface, which could locally influence water and oxygen entry as well as the resulting production of acid. Thorough investigations of the geochemical sources and evolution of metal concentrations have been done for other sulfide tailings sites (Blowes et al. 1988) and for the Falconbridge main pyrrhotite tailings site adjacent to the Fault Lake site (Nicholson and David 1991). The investigation of the geochemistry of the Fault Lake tailings was not part of the objectives of the present study and was therefore not pursued further than described above.

Background ground water monitoring station FS-2 showed a pH near 7 and nickel concentrations of 0.01 mg/L, iron 0.03 mg/L, and sulfate 30 mg/L. These metal concentrations can be accepted as background concentrations for ground water at the site since a second sampling showed similar results. Background pH could be lower than that measured at FS-2 (as low as 6) owing to the infiltration of acidic rainwater.

Ground water sampled near the tailings site in December 1992 and March 1993 had pH values above 6. Above-background concentrations of nickel were measured in wells FS-3A, FS-3B, FS-9C, and FS-10B; the highest of these concentrations was 0.5 mg/L (at FS-10) and was measured during only one of the sampling rounds. Only at FS-3 were the higher nickel levels associated with above-background sulfate concentrations of near 240 mg/L. Above-background sulfate concentrations were also encountered at station FS-1 (max 339 mg/L) but were not associated with any above-background metal concentrations.

Sampling results suggest that metal concentrations are not high enough to affect ground water quality. This is also suggested by the results of surface water quality sampling, which do not show the presence of any metal above background concentrations.

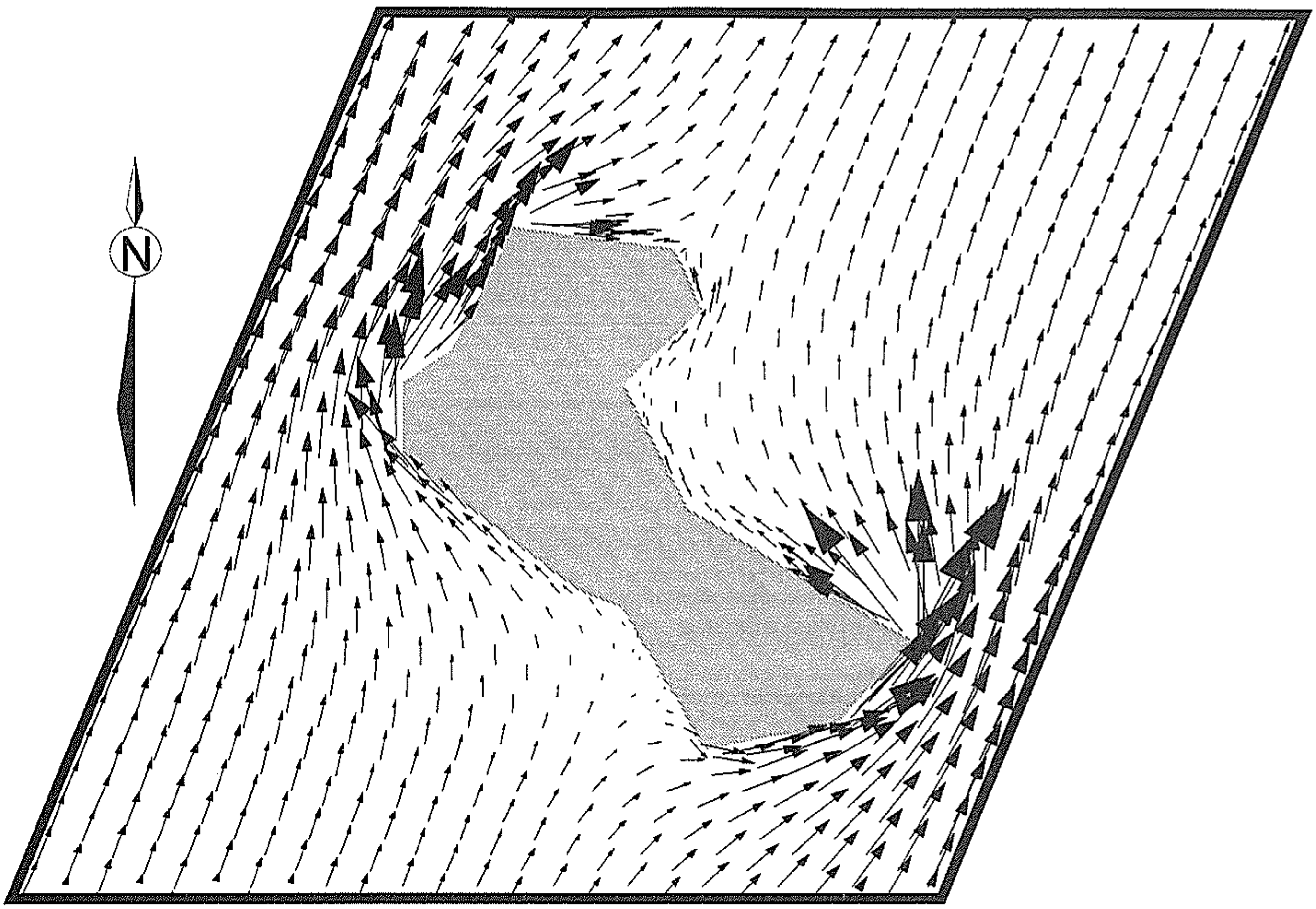

Figure 2. Plan view modeling results.

Ground Water Flow Modeling

Modeling Procedure

Ground water flow around the tailings was simulated using the saturated-unsaturated flow modeling program SEEP/W (GEO-SLOPE International 1992). In order to determine the flownet, SEEP/W requires the definition of i) a domain (finite-element grid), ii) soil hydraulic conductivities, and iii) boundary conditions.

Two models were defined in order to obtain a quasi-three-dimensional perspective of the ground water flows in the Fault Lake tailings area. The first model was a plan model and was defined as a rectangle with the long edges parallel to the main flow direction inferred from previous analysis. This model was conceptual only, representing the flow of water directly beneath the soil surface as affected by the hydraulic conductivity contrast between the tailings and the surrounding sediments. This did not include the effects of topography or infiltration.

The second model was a cross section across stations FS-4 to FS-9 (**A-A'** in fig 1). The model domain started southwest of piezometer FS-4, extended northeast of FS-9, and passed through FS-6 and FS-8. Elevations were taken from the monitoring well data where possible; otherwise, the topographic map was used. Representative hydraulic conductivities (K) for the soils and tailings were derived from the geometric mean of the field measurements, as described earlier.

Constant-head boundary conditions were defined at both ends of the model domains. In the first model, the constant-heads were set equal to the elevation of the nearest lakes: lake #1 in the south and lake #3 in the north.

In the second model, a water table elevation slightly higher than that measured at FS-4 was used at **A**; for **A'**, the elevation of lake #2 was taken from the topographic map. The infiltration flux across the top boundary was determined using previous estimates from Yanful et al. (1993) obtained using the HELP (Hydrologic Evaluation of Landfill Performance) computer program of Shroeder et al. (1984). Different fluxes were used in the SEEP/W modeling, depending on the slope and nature of the ground surface. The tailings surface infiltration was set to 200 mm/yr, sloped till 250 mm/yr, and flat till 350 mm/yr. It was determined that infiltration into the till would be higher than that into the tailings since the hydraulic conductivity is higher and the water table is low. This would cause precipitation to be absorbed by the till and transferred away from the surface (to the water table), thereby limiting evaporation. On the tailings, evaporation is enhanced by surface ponding, thereby reducing infiltration.

Modeling Results

Flow vectors for the first model are shown in figure 2. The flow vectors illustrate the direction of flow, with their length being proportional to the flux. The figure clearly shows how the water would flow mainly in the till and around the tailings because of the higher hydraulic conductivity of the till. Figure 2 is only a conceptual illustration of actual conditions since this modeling procedure is highly simplified. For realistic results in a plan view, topography, depth of soils, and infiltration would need to be included into a three-dimensional modeling program.

Figure 3 depicts the flow characteristics for the cross-sectional model. The figures indicate that the horizontal flow is predominantly in the till and does not enter the tailings. The only water flowing through the tailings is the water that infiltrates from precipitation.

The flow vectors in figure 3 show a ground water divide left of the tailings (southwest). Although the general flow was calculated to be toward the northeast, it is possible that local gradients occur that cause some water to travel southwest. Such digression in the flow could be caused by manmade changes, such as the gravel pits in the area. From aerial pictures taken before tailings deposition, it is known that this area was once a lake. The fact that the water table is now below what used to be the lakebed suggests that local excavation may have greatly affected regional ground waters. A second influence to the water level is the tailings, which, by decreasing infiltration and promoting evaporation, reduce recharge to the aquifer. Other human disturbances, such as the building of roads, may have affected watersheds and ground water flow directions. It is also possible that the present conditions are temporary, and that the water table could eventually return to previous levels.

To verify the effects that would occur if the water table were to rise into the tailings and saturate the bottom portion of the impoundment, the constant-head boundary functions at either end of the section were raised. The results of this simulation showed that, although the bottom 5 m of the tailings are saturated, the flow within the tailings remains insignificant. This suggests that the increase in metal loading in the ground water due to the water table rise would not be important.

The use of a 2-D flow model to assess the conditions on the Fault Lake site has inherent limitations. In particular, any quantification of flow volumes is affected by the fact that all the water is assumed to move only in the reference plane, while in reality water also moves across the plane. Model predictions based only on ground water flow can also lead to overestimation of chemical loadings, since metal transport is usually slower than water velocity owing to chemical attenuation. The flow model can, however, be used to predict the worst-case scenario where no chemical attenuation takes place. Predictions that account for chemical attenuation are complex and were not part of the objectives of the present study.

Discussion

The glacial sediments surrounding the Fault Lake tailings site are characterized by their elongated formation and relatively high bulk hydraulic conductivities. This creates a flow system with a relatively flat and deep water table. Several favorable factors contribute to limit the observed metal concentrations downgradient of the tailings. These factors and their probability of occurring elsewhere follow:

1. Hydraulic conductivity contrast: Sediments of high hydraulic conductivities such as sands and gravels occur commonly in Canada. The ice-contact deposits surrounding the Fault Lake area possess a high average hydraulic conductivity, but are also characterized by a high variability due to the process by which they were deposited. Other sands and gravels may be more uniform, showing less heterogeneity in hydraulic properties and possibly a higher bulk hydraulic conductivity. As for tailings, measurements at several sites by Blowes et al. (1988) and Yanful and St-Arnaud (1992) have yielded values close to 10^{-5} cm/s, as measured at the Fault Lake tailings. Large hydraulic conductivity contrasts between tailings and surrounding sediments are therefore possible.

2. Deep water table: The water table in well-drained sand and gravel formations in temperate climates will usually be far below the ground surface. The depth to water table is also largely affected by topographical features. The hummocky terrain surrounding the Fault Lake site is largely controlled by the occurrence of the kettle lakes. In other similar glacial outwash areas, the coarse glacial deposits are commonly elevated, and deep water tables can result, depending on bedrock topography.

3. Limited infiltration: Infiltration of water through tailings surfaces is usually less than through natural soils. This is due to the relatively low bulk hydraulic conductivity of the tailings, the high potential for evaporation at the tailings surface, and the formation of dense crusts which can further reduce conductivity at the tailings surface. At the Fault Lake tailings site, infiltration could be reduced by encouraging runoff, thus preventing ponding along the dams.

4. Dilution by regional ground water flow: Large glacial outwash sediment formations normally have high ground water discharges, which are less susceptible to degradation by point contamination sources. In the case of the Fault Lake site, results from the second model (**A-A'** cross section) suggest that flow upstream of the tailings site would not be very large. The occurrence of much larger regional flow systems at other sites is possible.

5. Chemical attenuation: Some chemical attenuation in the form of precipitation and adsorption reactions occurs in most tailings. The degree to which these reactions take place depends on geochemical and mineralogical factors, in particular those that influence the neutralization potential of the tailings. Chemical attenuation in the Fault Lake tailings is suggested by the tailings pore water data and could also occur within the natural overburden deposits.

All five factors outlined above contribute to create the porous envelope effect; these factors could probably be present at other locations near mine sites. Tailings deposition in these types of environments could be done with little effect on ground water quality, if thorough site evaluations are performed and appropriate control is enforced at the time of deposition.

Conclusions

1. The piezometric elevations throughout the Fault Lake site, combined with lake elevations, suggest that the regional direction of subsurface flow is toward the northeast, along with the alignment of the kettle lakes. Some subregional flow systems could be moving ground water in other directions.

2. The base of the tailings is at the same level or higher than the water table across most of the site. Low water infiltration in the tailings and changes in watershed configurations due to nearby quarry excavation are suggested as causes for the apparent lowering of the water table.

3. The average bulk hydraulic conductivity of the soil surrounding the tailings is estimated at 1.6 x 10^{-3} cm/s. The hydraulic conductivity of the tailings was estimated using grain size correlations at 1 x 10^{-5} cm/s. These values agree with previous estimates.

4. Analysis of tailings pore water showed elevated values of nickel, iron, and sulfate, indicating the presence of sulfide oxidation products within portions of the tailings deposit. Metal concentrations are attenuated in the deeper parts of the tailings. Heterogeneity in measured metal concentrations could be caused by variations in the intensity of oxidation across the surface of the tailings due to surface effects such as ponding and cracking.

5. Water quality sampling in monitoring wells outside the tailings did not show any evidence of above-background metal concentrations, which suggests that leaching of metals from the tailings would be minimal. This is also suggested by the results of water sampling in nearby lakes.

6. Two-dimensional ground water models showed that the flow is diverted around the tailings mass owing to the hydraulic conductivity contrast between the tailings and the surrounding sediments. The models also showed that flushing of the tailings by ground water should not contribute significantly to the regional ground water flow system under present water table conditions, as well as under conditions of moderate rise in water table level.

7. Factors that contribute to limit metal concentrations downgradient of the Fault Lake tailings are:
- the large hydraulic conductivity contrast between the tailings and the surrounding sediments.
- the low position of the water table relative to the tailings bottom.
- the limited infiltration through the surface of the tailings.
- the dilution of metals flushed from the tailings by water flowing around and below the tailings.
- chemical attenuation of metals in the tailings and overburden.

8. These factors could probably be present at other locations near mine sites. Tailings deposition could be done at these sites with little effect on ground water quality if thorough site evaluations are performed and appropriate control is done at the time of deposition.

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