HYDROGEOLOGICAL EVALUATION AND WATER BALANCE OF A THICKENED TAILINGS DEPOSIT NEAR TIMMINS, ON, CANADA[1]

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Abstract: Recent literature suggests that the thickened tailings deposition method has the potential to reduce acid generation and seepage, compared to conventional methods. A commonly studied site is the Kidd Creek deposit, located in northern Ontario. The present study was aimed at providing in-situ verification of the hydrology of that site. The field program included measurements of moisture content, hydraulic head and hydraulic conductivity. Precipitation, pan evaporation, and tailings water evaporation were monitored during the period 1991-93. Water balance components during average conditions (runoff 42% of precipitation, evaporation 51% and infiltration 7%) were similar to published predictions. Hydraulic gradients indicated that pore water in the saturated zone tended to move longitudinally with low average linear pore-water velocities (12 cm/y). The capillary fringe at the top of the tailings cone was observed to be less than 1 m from the surface of the tailings. Normally, the tailings are near 100% saturation after spring snowmelt; summer drying is replenished during the fall and with the following spring snowmelt. Dewatering during a drought year is predicted to have little impact on long-term saturation. When tailings disposal discontinues, the degree of saturation and water-table position are expected to resemble that presently observed in areas of the cone where deposition is not active. These conditions are favorable for decommissioning because the depth of oxidation is limited due to the sustained presence of near-surface saturated conditions. Release of metals and acidity from the tailings site to the environment should be slow because pore-water velocities are slow.

Additional Key Words: cone-shaped thickened-tailings deposit, tailings oxidation, acidic drainage, tailings decommissioning, high moisture retention, low hydraulic conductivity, energy balance and water balance.

Introduction

The use of the thickened-tailings disposition (TTD) method for tailings disposal was originally proposed by Robinsky (1975) for specific advantages such as low initial capital investment, low operational costs, good storage capacity, and the elimination of high perimeter dams, slime ponds and decant systems. The method involves the thickening of tailings slurry which is typically discharged in an elevated central spigot line, thereby producing a large cone-shaped deposit.

At the Second International Conference on the Abatement of Acidic Drainage, Robinsky et al. (1991) argued that the TTD method has the potential to reduce acid generation and seepage, compared to conventional deposition methods. This would be achieved by the creation of a relatively homogeneous tailings mass of low hydraulic conductivity and high moisture retention characteristics in which oxygen entry and the resulting tailings oxidation are very limited. The paper presented laboratory, field, and seepage modeling results from a study of the Kidd Creek thickened-tailings deposit, located in northern Ontario, near the town of Timmins. In a collaborative paper with the present authors, Barbour et al. (1993) subsequently reviewed the TTD method and compiled results of field and laboratory testing of hydraulic and geotechnical characteristics of the Kidd Creek tailings. Conclusions stated that the tailings tended to remain saturated to the surface above the water table, a favorable condition with respect to decommissioning of the tailings. The authors also concluded that the ingress of oxygen is minimized, reducing the long term potential for oxidation and the resulting development of acid drainage.

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The present paper describes the field testing in detail, and presents some of the findings to date. The program commenced in the summer of 1991 and included measurements of moisture content, hydraulic head, and hydraulic conductivity. Field monitoring included precipitation, pan evaporation, and evaporation from the tailings surface by the Bowen Ratio energy balance method. A monthly water balance was assembled for 1992 and calibrated to the measured water-table elevation. The water balance was estimated for average (i.e., steady state) conditions by using monthly meteorological normals from the Environment Canada meteorological stations. Extreme conditions were analyzed by substituting precipitation from the driest year of record and evaporation from the highest year of record. Results give insight to the degree of tailings saturation and therefore a sense for the likelihood of tailings oxidation.

Site Description

The regional topography is generally flat and forested, featuring elevated bedrock exposures rising above broad, wet lowlands. Since 1975, approximately 50 million mt of sulfide-mineral tailings have been deposited at a high point in the Porcupine River watershed, using the thickened-tailings disposal method. The thickener underflow density was gradually increased from 50% in 1976 to 61.5% at present (Yeomans 1985). The resulting tailings cone presently covers a circular area of 1,215 ha and at its center extends 23 m above the perimeter diking. It has a slight concave slope of about 1.5%. The Porcupine River flows along the west side of the site, to the north, and then shifting south to pass the east side of the site, almost encircling the entire deposit before reaching Nighthawk Lake to the southeast.

Beneath the tailings cone, the dominant overburden material is a varved clay, constituting part of a sequence deposited some 8,000 to 10,000 yr ago during the last phase of glacial Lake Ojibway (Quigley 1980). The clay is overlain by a thin layer of organic soil (peat) and underlain by uneven till and bedrock. A bedrock ridge exists underneath the present main embankment, where spigoting has taken place.

Field and laboratory testing of the tailings have been conducted by several researchers, most of which are reviewed by Barbour et al. (1993). The average hydraulic conductivity is 5×10^{-8} m/s. Porosity is about 46%, varying by $\pm 7\%$ with depth owing to alternating summer and winter deposition. In the summer, evaporation dewaters the surface of the tailings, thereby increasing the matric suction and consolidating the material to a lower porosity. The dry bulk density is about 1.7 g/cm^3 and specific gravity is 3.1. The tailings surface is nonvegetated and shows polygonal shrinkage cracks.

Regional Climate

The climate of northern Ontario may be classified as modified continental. The modification is mainly due to the presence of the Great Lakes on the south and, to a lesser extent, to Hudson Bay on the north (Chapman and Thomas 1968). A pattern of relatively low winter and high summer precipitation prevails in northern Ontario, although not to the degree that this occurs in the Prairie Provinces. This seasonal contrast decreases from northwest to southeast. Cold polar air masses producing dry, clear weather generally persist much of the winter. In the summer, a continuing succession of cyclonic storms sweeps over the area from west to east; warm, humid air masses from the south alternate with cooler and drier air from the north. This produces a typical pattern of 2 or 3 days of clear weather followed by warmer, more humid weather, often with changeable winds and rain for a day or two. The climate of the Kidd Creek region is particularly modified by Lake Superior; air masses generally track across the lake, which results in higher precipitation and a seasonal lag, retarding the onset of spring. The average annual precipitation at Timmins Airport is approximately 860 mm.

Investigative Methodology

Hydrometeorological Monitoring

A data-logger-driven monitoring station was installed on the tailings to measure precipitation, pan evaporation, and the evaporation of water from the tailings surface. Precipitation was measured with a tipping-bucket rain gage and pan evaporation was measured with a U.S. class A evaporation pan. Tailings evaporation was deduced from measurements of net radiation, soil heat flux, and vertical gradients of air temperature and vapour pressure. An energy budget by the Bowen ratio partitioning method of surface energy was used to calculate the latent heat flux from the tailings surface. The latent heat flux was then converted to a mass flux of water with the latent heat of vaporization. A summary of the method is found in Oke (1987). A snow density survey was conducted at the end of March to determine the water content of the snow pack before melting.

Hydrogeological Measurements

Instrumentation for measuring hydrogeologic parameters primarily consisted stations of 2 to 4 piezometers of different lengths. Several piezometer stations were located in the tailings (fig. 1): (1) along Section A-A', northwest from the top of the cone; (2) at Station B1, the hydrometeorological station; and (3) along Section C-C', southwest from the top of the cone. Section A-A' was selected to determine the horizontal hydraulic gradient in a portion of the site where tailings were not actively being deposited. At Section C-C', tailings were being deposited and the piezometer stations were located in the flow path of tailings slurry. C1 was located in an entrenched channel, above the point where the flow begins to spread and form a depositional fan, and C2 was located approximately 300 m downstream of C1 at the right (north) edge of the fan, where sheet flow had been actively depositing tailings. Station B1 included tensiometers which measured the hydraulic head above the water table.

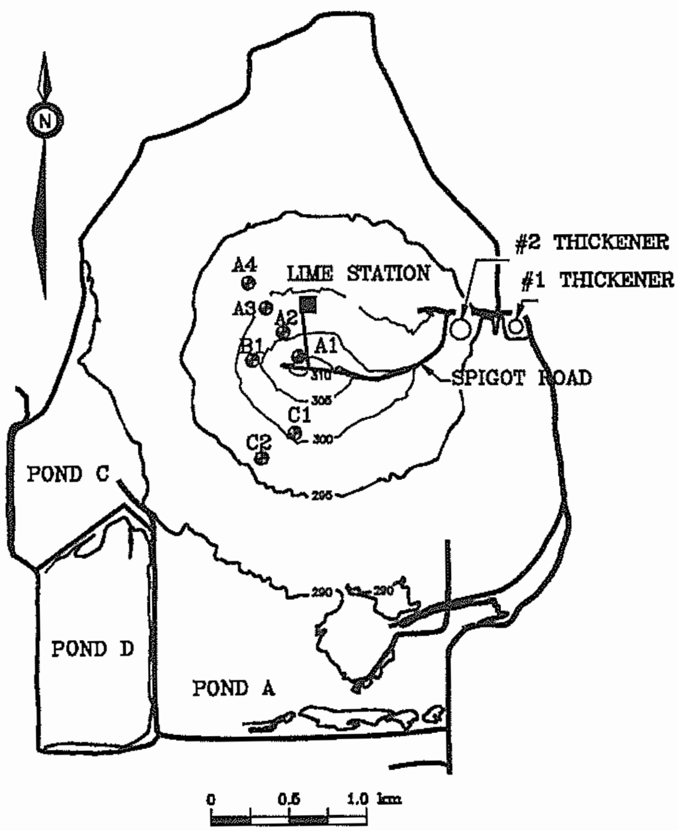

Figure 1. Piezometer nest location map.

Weekly water-level measurements were conducted in the spring, summer and fall. Monthly measurements were conducted in the winter. Continuous monitoring of the water level at B1 was conducted with submersible pressure transducers, connected to the data logger. Hydraulic conductivity measurements were conducted in each piezometer by the falling head method (Hvorslev, 1951). During 1991, soil-moisture content was measured at A1.

Available Data

Precipitation has been measured at Timmins Airport, ON since April 1955, and since 1968, pan evaporation has been measured at Amos, PQ, about 200 km to the east. Data from these stations were correlated to Kidd Creek data. Water-level measurements in a borehole network has been measured on a monthly basis by Kidd Creek personnel, since March 1991. A westwardly cross section of four boreholes were selected to illustrate the annual changes in water-table elevation. Each borehole was installed with a piezometer which had a screened section that extended the entire depth of the saturated zone. These piezometers averaged the pore-water pressures of the entire saturated zone; therefore, they measured the water-table elevation where vertical hydraulic gradients were small. Concurrent with the present study, a runoff and erosion study had commenced in 1991 (Paul Wisner and Associates et al. 1993). A runoff coefficient (C=R/P) was determined for each runoff event and each month.

Findings and Discussion

Hydrogeology

Pore-water Flow. Figure 2 shows interpolated hydraulic head contours along Section A-A' following the largest rainfall of 1992. Flow is perpendicular to the contours and therefore primarily lateral, along the length of the cone. Tendencies for downward flow are apparent at the top of the cone. Upward flow is presumably past A4, further down the cone, although no well defined seepage face is observed. Percolation from the base of the tailings is likely restricted by the underlying clay soil. The average lateral hydraulic gradient is 0.017 which is similar to the slope of the tailing surface (0.015). Using Darcy's law, a porosity of 0.46, and a hydraulic conductivity of 1 x 10^{-7} m/s, the calculated flow velocity is 0.12 m/y. This velocity is quite low. Specific discharge is 0.054 m/y, which is also quite low.

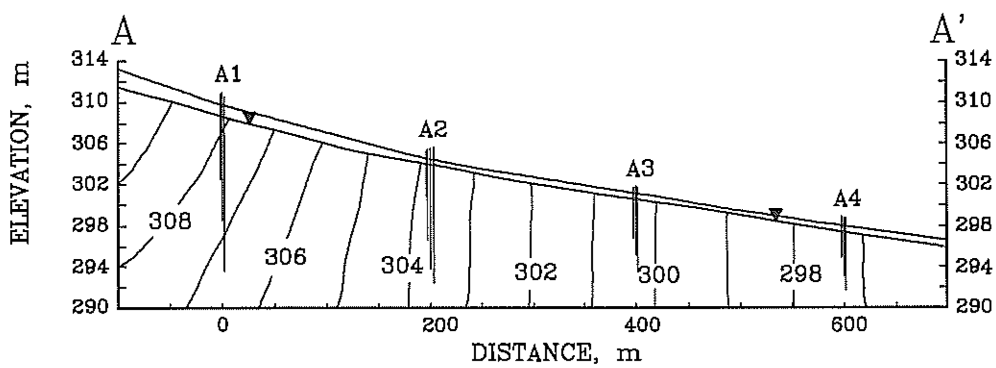

Figure 2. Hydraulic head contours at section A-A'.

Figure 3 shows the monthly water-level measurements in boreholes along a westwardly cross section from BH1 to BH4. These data indicate that the water table is high after snowmelt and during the fall, and low during the summer and winter. Figure 4 illustrates hydraulic heads at piezometer nest B1 during the summer and fall of 1992 and 1993. The hydrograph generally depicts the trend that was observed at all stations where the lowered summer water table rises in response to precipitation and a waning evaporation rate, to remain at a high level through the autumn and early winter. The advent of the recharge period was earlier in 1992 because August 1992 was much wetter than August 1993. The upward gradients shown in figure 4 may be caused by local flow within the cone; at other stations they are less frequent.

Hydraulic heads readily responded to individual rainfall events, rising as much as a meter, only to fall again during the dry period that followed each storm. These large fluctuations in water table levels typically occur in fine-grained soils, a process which has been described by Abdul and Gillham (1984). It is related to the fact that the water table can rapidly rise through the capillary fringe (i.e., the tension-saturated zone) after an infiltration event of minor intensity.

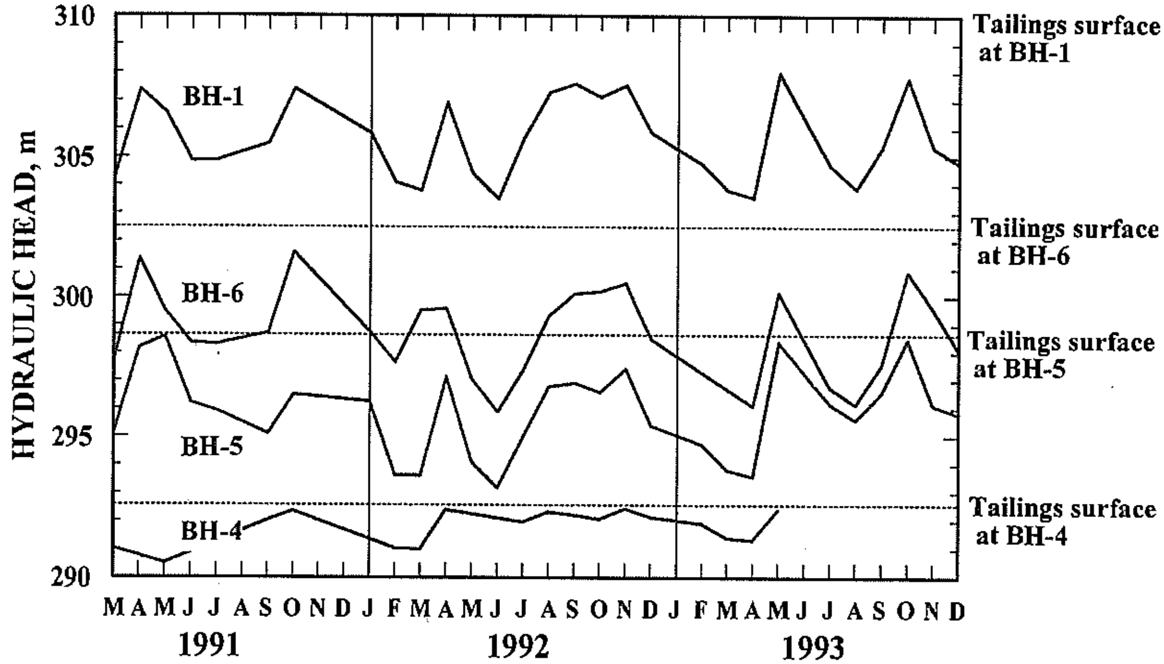

Figure 3. Borehole water-table elevations.

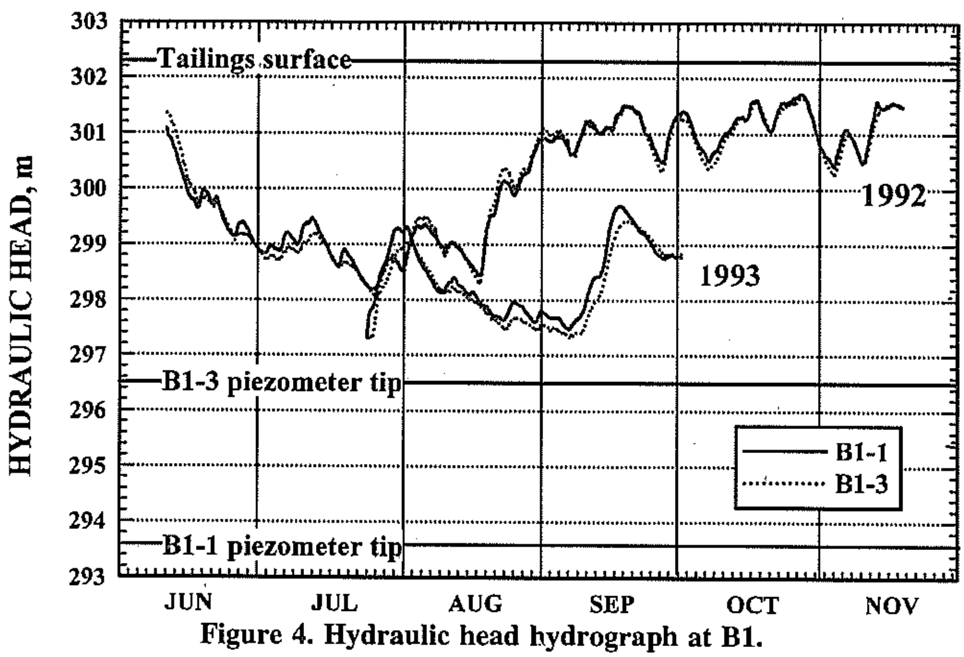

Figure 4. Hydraulic head hydrograph at B1.

The Capillary Fringe. Figure 5 shows soil-moisture content and water-table elevations at A1. Since this station is located near the top of the cone, the water table is farthest from the surface and the vadose zone is more developed than at other places on the cone. The water content profile shows the density layering from alternating summer and winter deposition. Full saturation is therefore depicted as a range from 22% to 27% (w/w). Figure 5 features a rising water table and capillary fringe, which is responding to infiltration. Most significantly, the thickness of the capillary fringe, the tension-saturated zone that extends above the water table, is delineated at approximately 4 m and is within 1 m of the tailings surface.

The capillary fringe is not always the same thickness. When the water table drops, the capillary fringe elongates, and when the water table rises (as in fig. 5), it retracts. The capillary fringe is held by surface tension, which causes its top to fluctuate with less magnitude than that of the water table. A plot of suction versus water content (drainage curve) best illustrates this phenomenon.

Figure 6 shows the drainage curve for the Kidd Creek thickened tailings (Yang et al, 1992). Matric suction is the force with which soil holds water by surface tension; it is equivalent to the negative pressure head, but expressed as a positive number. Pressure head is zero at the water table, positive below and negative above. Figure 6 indicates that up to a suction of about 6 m of water (60 kPa), significant drainage does not occur. Since this is the suction exerted at the top of the capillary fringe, 6 m is the predicted maximum thickness of the capillary fringe. If the water table drops below this, the larger voids at the top of the capillary fringe drain and therefore fracture the continuous water column. Recharge of water from infiltration causes the water table to rise and the thickness of the capillary fringe to diminish, as in figure 5. The larger voids at the top of the capillary fringe require significantly larger amounts of recharge to completely fill, which therefore limits the ability of the top of the capillary fringe to rise. Therefore, the thickness of the capillary fringe fluctuates, which is accompanied by the water-table fluctuation.

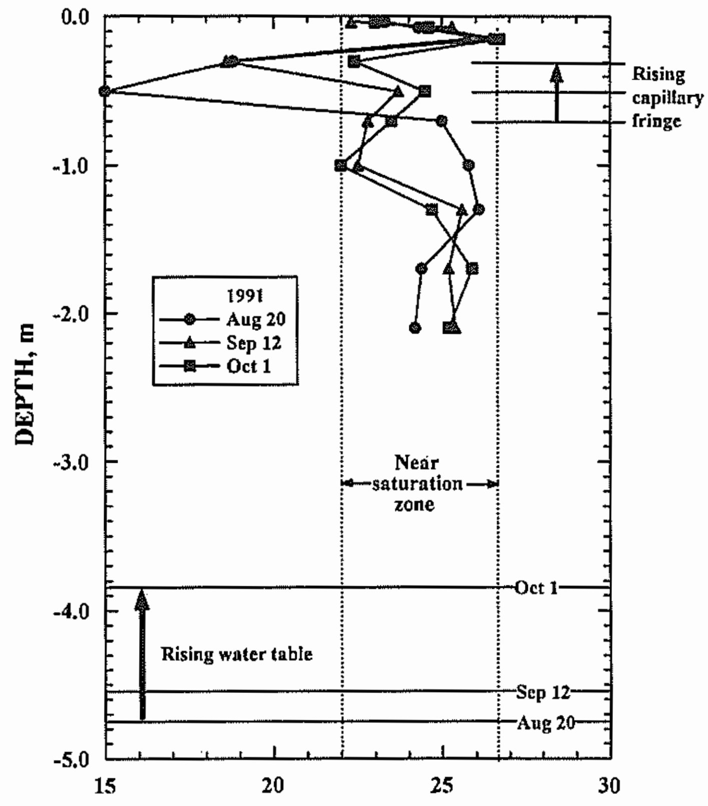

Figure 5. Recharge conditions at station A1.

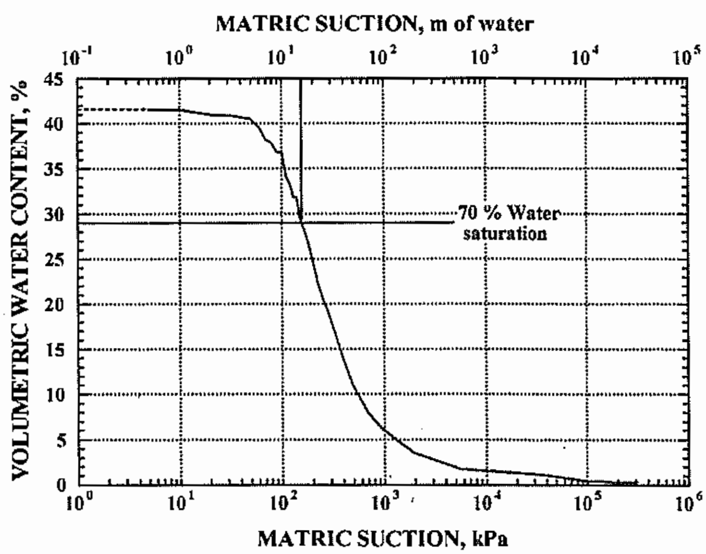

Figure 6. Drainage curve of the Kidd Creek tailings.

Oxygen Diffusion. In soils with a high degree of water saturation, the diffusion coefficient of oxygen (D_e) is the principal control on the rate of oxygen entry into the soil. Experiments using a well sorted till indicate that D_e does not significantly increase until the degree of water saturation drops below 70% (Yanful 1993). Applying this factor to the drainage curve from the Kidd Creek tailings (fig. 6), D_e would not increase until the matric suction is about 16 m of water (160 kPa). In other words, if the tailings were allowed to drain under gravity (and not evaporate), the water table position would have to be 16 m beneath the tailings surface before the rate of oxygen entry into the tailings would increase significantly. The results of ongoing diffusion experiments will help to confirm the applicability of this 70% factor on the Kidd Creek tailings.

The depth to water was between 6 and 7 m at the top of the cone and between 1 and 2 m at the base of the cone. Therefore, if it were not for drying at the surface by evaporation, the flux of oxygen into the soil would be constant and slow. Therefore, for practical purposes, gravity drainage will not promote oxidation.

Infiltration. One of the hydrogeological concerns is whether the water-table elevation is sustained by the infiltration. Infiltration is caused by precipitation and tailings-slurry water. Infiltration from precipitation is addressed in the water balance section, and infiltration from slurry water is adressed in this section.

Tailings slurry generally flows down the cone in a small braided channel. When the flow reaches the end of the channel, it spreads out as sheet flow, about 500 m down the cone where the grade decreases. The increase in width is accompanied by a decrease in depth and velocity, causing deposition of tailings and the formation of a fan. The wetted areas of the channel and fan were determined by planimetry of infrared areal photographs (1:5000 scale), and consisted of 1% of the total tailings area (maximum).

At section C-C', where tailings slurry was actively flowing, the water table fluctuated and responded to precipitation and dry spells in a similar manner to that observed at the other stations. Vertical gradients were also similar to those observed at the other stations. These data indicate a control of the tailings pore-water flow beneath the channel and fan area by the pressure dynamics of the cone. However, the water-table fluctuation was about 1.5 m, much less than that at the other station, and the depth to water table was shallower (0.4 to 1.8 m at C1, and 0 to 1.2 m at C2) in comparison to the other piezometer nests. At C1 and C2 water levels are controlled more by the topography than by the ponds. These facts suggest some contribution of water by tailings slurry discharge. However, considering the channel areas constitute only 1% of the tailings, infiltration by thickened tailings discharge is negligible in the water balance (less than 1% of precipitation).

Water Balance

The water balance was used to quantify infiltration and analyze its affect on water-table position. Monthly water balances were assembled for three separate conditions: (1) for the studied year 1992, which was calibrated to the measured water table elevation; (2) for average (i.e., steady state) conditions by using monthly meteorological normals from the Timmins Airport station and Amos station; and (3) for extreme conditions by substituting precipitation from the driest year on record at Timmins Airport and from the highest evaporation on record at Amos.

Description of Data. In the Timmins area, it generally rains from May through October and snows from November through March. The snow cover, which accumulates during winter, melts mostly during April. Monthly runoff was estimated with runoff coefficients. Environment Canada data was correlated to site measurements to extend the Kidd Creek record. The ratio of runoff (R) to rainfall (P) is defined as the runoff coefficient ($C=R/P$). Monthly runoff coefficients were determined on site for the year 1992 (Paul Wisner and Associates et al. 1993). These coefficients were adapted for average and extreme conditions by considering the monthly precipitation and season. Both pan evaporation and evaporation from the tailings surface were measured on site. Evaporation coefficients ($C_E=E_{tailings}/E_{pan}$), the ratio of tailings water evaporation to pan evaporation, were calculated for each month (table 1). The average C_E for each month was applied to the pan evaporation to estimate the evaporation of water from the tailings surface.

Table 1. Monthly evaporation coefficients at Kidd Creek thickened tailings site.					
Year	June	July	August	September	October
1991	no data	no data	0.37	0.66	0.46
1992	no data	no data	no data	no data	no data
1993	0.56	0.69	0.45	0.65	no data
Average	0.56	0.69	0.41	0.65	0.46

Infiltration (I) is quantified in the water balance by subtracting runoff and evaporation from precipitation (i.e., rainfall and snowmelt), leaving drainage (D) and the change in tailings moisture storage (ΔS) as unknowns. ΔS is the change in water-table elevation and tailings saturation. By arbitrarily setting ΔS to zero at the end of snow melt, negative values for succeeding months indicate a loss of moisture and a lower water table, and positive values indicate a gain of moisture and a higher water table. Water-table measurements during 1992 were used to calibrate the water balance. D (unknown) is adjusted to match ΔS to the water-table position. The specific discharge (54 mm/y) was used as D and gave reasonable values of ΔS.

Results. Figure 7 shows the monthly water balance results and table 2 summarizes the annual results. 1992 was a year of normal precipitation and normal evaporation. Evaporation, was high during May, and precipitation was high during August. Storage decreased during May and June and increased through the rest of the year. The position of the water table during 1992 confirmed the predicted trend. In December, a storage deficit was 35 mm. The water table position was observed to drop about 2 m by the end of 1992 (fig. 3), accompanied by the 35-mm deficit in the water balance. This gives a calculated specific yield (S_y) of 0.02 (35 mm/2 m). Since the usual range of S_y in unconfined aquifers is 0.01-0.3, a value of 0.02 seems reasonable for a soil (like the Kidd Creek tailings) with a high moisture retention capacity.

For average conditions, as in 1992, storage decreases following snowmelt and increases after summer. However, ΔS decreases less for the 3-month period May through July, is low during August, and increases from September through November. By the end of November, ΔS is at its original level. During winter (December-March), ΔS decreases slightly, only to be replenished by spring snowmelt. No annual deficit of ΔS was found. Infiltration during average conditions is similar to the 9% that was predicted with the Hydrological Evaluation of Landfill Performance (HELP) model by Robinsky et al. (1991).

For extreme dry conditions, storage decreased from May through August and stayed low for the remainder of the year. Furthermore, from August through the end of the year, ΔS was similar to that of July 1992. Therefore, the moisture conditions observed during July of 1992 reflected those of an extreme dry year. Since moisture was nearly replenished by the end of 1992, the dewatering following an extreme dry year should be replenished with normal rainfall. However, also considering that an additional year of evaporation would follow, average conditions may sustain the dry condition; above-normal rainfall would be necessary for replenishment.

Table 2. Water balance summary expressed as percent of precipitation.			
Hydrologic Component	1992	Normal Conditions	Extreme Dry Conditions
Runoff	48	42	39
Evaporation	51	51	72
Infiltration	1	7	-11

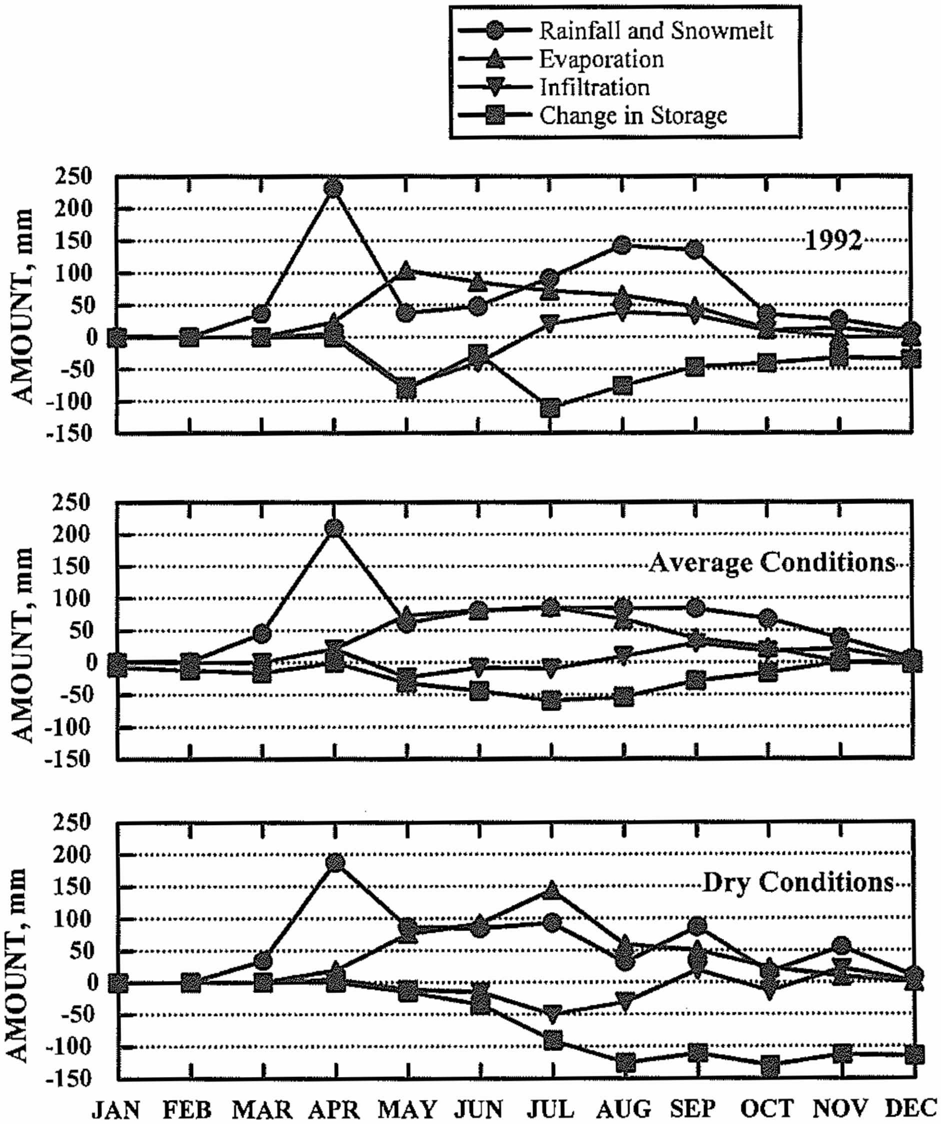

Figure 7. Water balance of the Kidd Creek tailings cone.

Summary and Conclusions

This paper reviewed hydrologic and hydrogeologic field data collected at the Kidd Creek thickened-tailings site. The findings confirm that very little slurry water contributes to water-table recharge, and if tailings deposition presently discontinues, then tailings saturation and water table position are expected to resemble that presently observed in areas of the cone where deposition is currently not active. Observations at the top of the cone, where the unsaturated zone is more developed, indicated near-saturated conditions within 1 m from the tailings surface. In this upper 1 m zone, where the top of the capillary fringe fluctuates, oxygen diffusion is predicted to be slow owing to the water saturation. Water balance modeling indicated that dewatering during a dry year is expected to have little impact on long-term saturation of the tailings. These conditions are favorable for decommissioning because the depth of oxidation is limited due to the sustained presence of near-surface saturated conditions. Release of metals and acidity from the tailings site to the environment should be slow because pore-water velocities are slow.

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