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The hydrogeology of a tailings impoundment formed by central discharge of thickened tailings: implications for tailings management

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Abstract

The Kidd Creek Cu–Zn sulfide mine is located near Timmins, Ontario. Mill tailings are thickened and deposited as a slurry in a circular impoundment with an area of approximately 1200 ha. Deposition of tailings as a thickened slurry from a central discharge ramp results in a conical-shaped tailings deposit with low perimeter dykes, a uniform grain-size distribution, uniform and low hydraulic conductivity, and a tension-saturated zone above the water table up to 5 to 6 m thick. These characteristics provide benefits over conventionally disposed tailings with respect to tailings management. The thick tension-saturated zone within the tailings limits the thickness of unsaturated tailings that are susceptible to rapid sulfide oxidation. The conical shape of the deposit results in the formation of a recharge area near the centre of the impoundment and discharge in the peripheral areas. In contrast, the elevated nature of many conventional, unthickened tailings impoundments results in recharge over most of the surface of the impoundment, with discharge occurring outside the impoundment through large containment dykes. Three-dimensional pore water flow modelling suggests that approximately 90% of the total discharge from the thickened tailings occurs within the tailings impoundment. When discharge is confined within the impoundment, there is improved control over low-quality effluent, and an opportunity to design passive control measures to reduce treatment costs and minimize environmental impacts.

Keywords: Tailings; Mine-tailings; Hydrogeology; Hydrology; 3D modelling; Contaminant transport

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1. Introduction

Sulfide-rich ore deposits are important global sources of Cu, Pb, Zn and Ni. Mining activities extract and process the ore by grinding it to silt and fine-sand size to allow the extraction of sulfide minerals which contain the metals of interest. The residual comminuted rock materials, referred to as tailings, are disposed of in waste dumps. At most North American mine sites, low density tailings slurries (10 to 20 wt.% solids) are discharged to the dumps from spigots located around perimeter containment dykes. The water-content of these slurries is high, and the viscosity is low. This disposal technique causes hydraulic sorting of the tailings particles, and results in the formation of a deposit with coarsening grain size from the center toward the perimeter dykes (Fan and Masliyah, 1990). This conventional disposal method commonly results in the formation of a shallow basin-shaped deposit, surrounded by high containment dykes (Fig. 1) which contain large hydraulic gradients (Brawner and Campbell, 1973). The elevated perimeter dykes which surround these deposits cause mill-discharge water and precipitation, which do not immediately infiltrate into the tailings, to run off toward the center of the impoundment forming a pond. The water balance for these ponds is maintained through

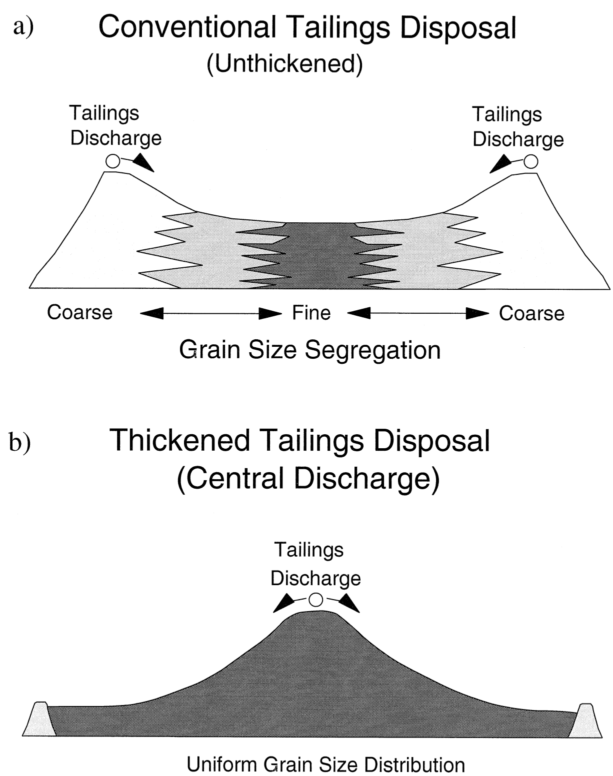

Fig. 1. Schematic cross sections illustrating differences in the shape of (a) conventional tailings deposits formed by discharge of low density tailings slurries from perimeter dams, vs. (b) deposits formed by central discharge of thickened tailings.

loss of water either by water reclamation for milling and mining, evapo-transpiration, or by groundwater flow toward the perimeter of the tailings impoundment (Coggans, 1992).

The Kidd Creek mining and metallurgical operation, located near Timmins, Ontario, has been in operation since 1965, producing approximately 10,000 tonnes of tailings per day. Presently there are over 100 million tonnes of tailings stored in an impoundment that is constructed on top of 1 to 5 m of glacial-lacustrine silt and clay which overlies Archean volcanic and metasedimentary bedrock (Fig. 2). Maximum topographic relief in

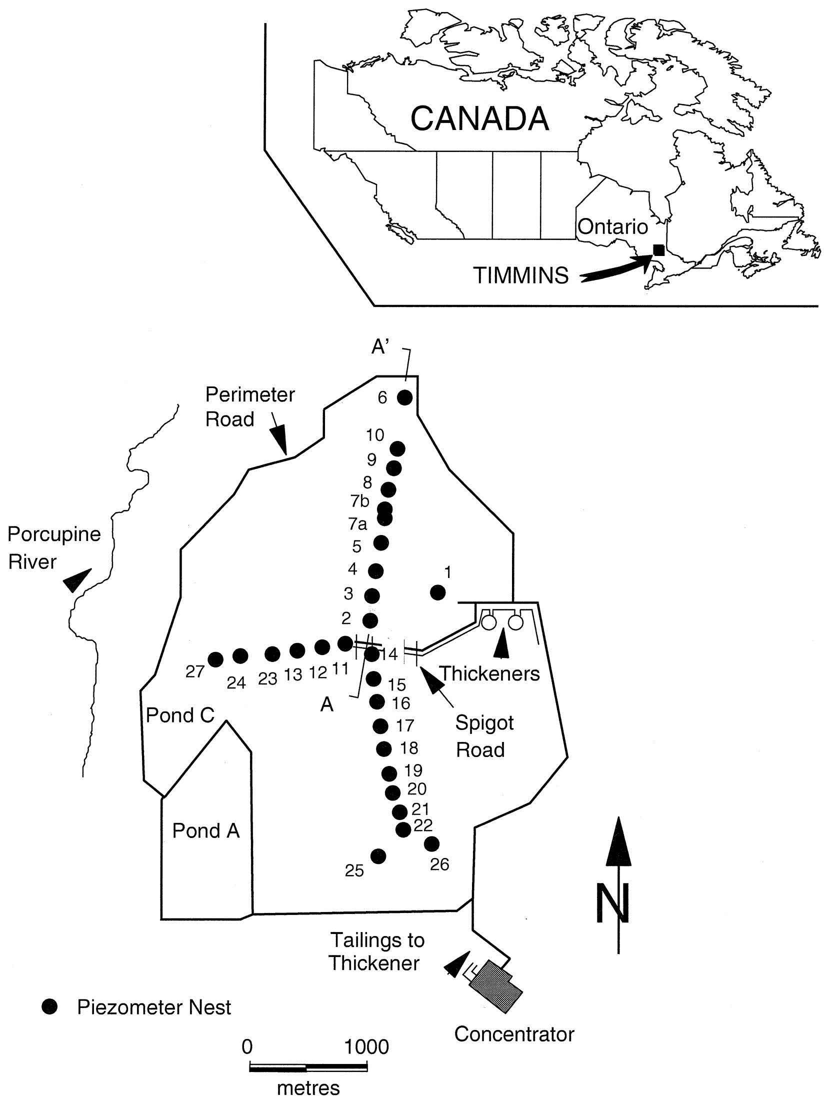

Fig. 2. Location plan of the Kidd Creek tailings impoundment showing piezometer nest locations.

the area is 20 m and drainage is discontinuous with swamp surrounding most of the tailings impoundment.

The Kidd Creek metallurgical operation utilizes a unique method of tailings disposal. The initial tailings slurry, which contains about 17 wt.% (6.4 vol.%) solids, is pumped from the mill to a thickener where excess water is decanted, and the slurry is upgraded to 62 wt.% (35 vol.%) solids. The thickened tailings are then pumped to a series of spigots located along an elevated central road, and are discharged into a 1200-ha impoundment (Fig. 2). Discharge of thickened tailings inhibits hydraulic sorting of tailings particles, resulting in a more uniform grain-size distribution (Fig. 3). Central discharge of thickened tailings also results in the formation of a cone-shaped pile (Fig. 1) which, at the study site, is 15 m high and 4000 m in diameter. This disposal method

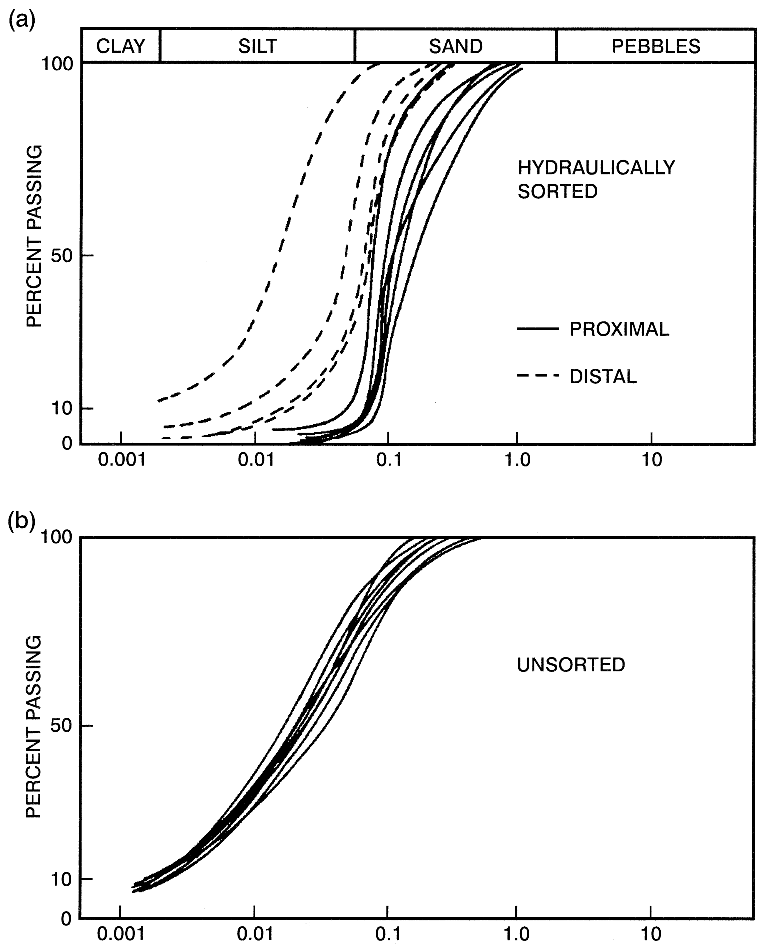

Fig. 3. Comparison of the grain-size distribution between (a) conventionally disposed tailings, and (b) thickened tailings (Robertson, 1994).

has the advantage of not requiring high perimeter dykes (Robinsky et al., 1991), and therefore minimizes discharge of acidic pore water outside the impoundment which commonly results from the development of a thick unsaturated zone and large hydraulic gradients in the dykes associated with conventional tailings disposal (Morin et al., 1988; Johnson, 1993; Robertson, 1994; Devos et al., 1995).

Flowing pore water in tailings can transport dissolved constituents from the enclosed impoundment into the surrounding environment. An understanding of the flow system is therefore critical to accurately assess the environmental impact of tailings disposal. In addition, long-term water-treatment costs are affected by the amount, and quality of the effluent from the tailings. Important aspects of the groundwater flow system within the tailings and the surrounding natural geological materials are the direction and rate of groundwater movement, and the distribution of recharge and discharge areas. Delineating recharge areas is important because geochemical processes such as sulfide oxidation may degrade the quality of the recharging pore water, ultimately affecting the quality of the pore water throughout the impoundment. When the locations of recharge areas are known, steps may be taken during mine decommissioning to protect these areas from the effects of sulfide oxidation. Discharge areas, in contrast, represent locations where tailings pore water is released to the surface-water environment. Identification of discharge areas makes it possible either to collect discharging water and hold it for treatment, or to modify the material properties in the discharge area to allow for passive treatment of discharging water (Blowes et al., 1994).

The objectives of this paper are to evaluate the affect of thickened tailings disposal on groundwater flow, examine the distribution of recharge vs. discharge zones within the unique cone-shaped impoundment that results, and to discuss the implications for tailings management. The groundwater flow system is examined using field measurements of water content, hydraulic head, and hydraulic conductivity distribution, and is assessed with the assistance of a three-dimensional numerical flow model.

2. Methods

2.1. Field determination of hydrogeological parameters

To characterize the pore water flow system within the tailings, measurements were made of hydraulic conductivity (K), hydraulic head (ϕ), and the water table elevation at piezometer nests located within the tailings impoundment (Fig. 2). Measurements of K were conducted in more than 100 piezometers by the method described by Hvorslev (1951). Variations in K between the tailings matrix and zones affected by desiccation fracturing were measured by constant-head permeameter testing of core samples of undisturbed tailings. Vertical and horizontal hydraulic gradients were determined by measuring ϕ in all of the piezometers installed in the saturated zone. Transient variations in ϕ were recorded by repeated measurements over a 2-year period. The water table elevation at each piezometer nest was taken as the water level in the shallowest piezometer.

The volumetric moisture content of the tailings in the vadose zone was measured at all piezometer nest locations using a model 503DR neutron hydroprobe which was calibrated in tailings of known moisture content determined gravimetrically. Gravimetric moisture content determinations on core samples were done at two locations only. The total porosity was determined in water-saturated tailings by equating total porosity to the volumetric moisture content.

2.2. Pore water flow modelling

2.2.1. Model description

A three-dimensional finite-element numerical flow model, WATFLOW, (Martin, 1994; Molson et al., 1995) was used to simulate the distribution of ϕ and pore water velocity within the saturated zone of the tailings. The model uses triangular-prism elements which incorporate K as an elemental property and allows for an iterative solution of the water table position. The irregular topography of the top and bottom of the tailings was interpolated between known elevations using a kriging routine which is included in the finite-element grid generation program, GRIDBUILDER, (Martin, 1994; McLaren, 1995). When the steady-state hydraulic-head distribution has been calculated, the three components of the total pore water velocity vector are calculated using the Darcy equation:

$$\nu_i = \frac{K_i}{n} \frac{\mathrm{d}H}{\mathrm{d}x_i} \quad i = x, y, z$$

where: ν_i = pore water velocity [m/s], K_i = hydraulic conductivity [m/s], n = porosity, $(\mathrm{d}H/\mathrm{d}x_i)$ = hydraulic head gradient.

2.2.2. Boundary conditions

The tailings impoundment is located in a flat, forested area adjacent to the Porcupine River. Swamp surrounds the impoundment and the perimeter boundary of the three-dimensional domain was represented with constant-head values equal to the elevation of the water level in the swamp. The bottom boundary was represented as a zero-flux boundary based on low measured values for K in the silt/clay that underlies the tailings. A variable-flux boundary was used at the top surface to estimate the spatial distribution of recharge and discharge (Fig. 4).

2.2.3. Model calibration

The flow model was calibrated in a series of steps:

1. K values determined from piezometer response tests were assigned to the layers within the domain.
2. The top boundary flux was varied to achieve a good fit to the measured water table position.
3. Vertical velocities calculated by the model were compared with vertical velocities measured by chemical tracer (Al et al., 1994a).
4. K values were changed to adjust the calculated velocity to be consistent with the measured velocities.

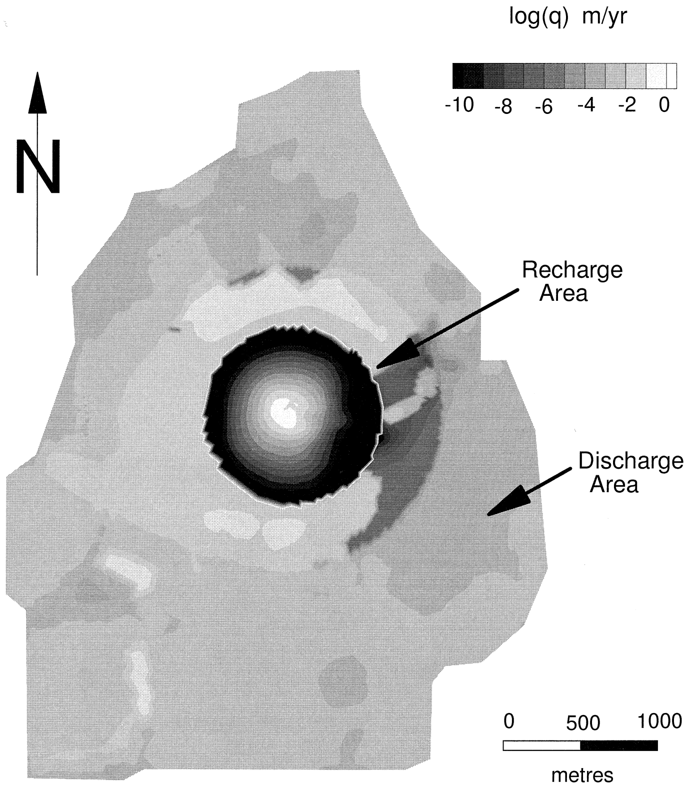

Fig. 4. Plan view of the top surface of the tailings showing the spatial distribution of recharge and discharge flux.

5. Steps 2, 3 and 4 were repeated until the calculated velocities were consistent with the measured velocities and the simulated water table matched field measurements.

3. Results and discussion

3.1. Hydrogeology

Hydraulic conductivity measurements by the Hvorslev method (Hvorslev, 1951) range between 10^{-9} to 10^{-6} m/s (Fig. 5). The values obtained using the constant-head permeameter were consistent with this range, with fractured samples displaying K values up to one order of magnitude greater than the matrix (10^{-7} vs. 10^{-8}). The narrow distribution of K within the tailings is a reflection of the uniform grain-size distribution. There is a trend toward decreasing K with increasing depth (Fig. 6) which may be due to consolidation of the tailings. The lowest values of K ($< 1 \times 10^{-8}$ m/s) are obtained from the deepest piezometers, which are thought to be installed within the underlying silt and clay (Al et al., 1994b).

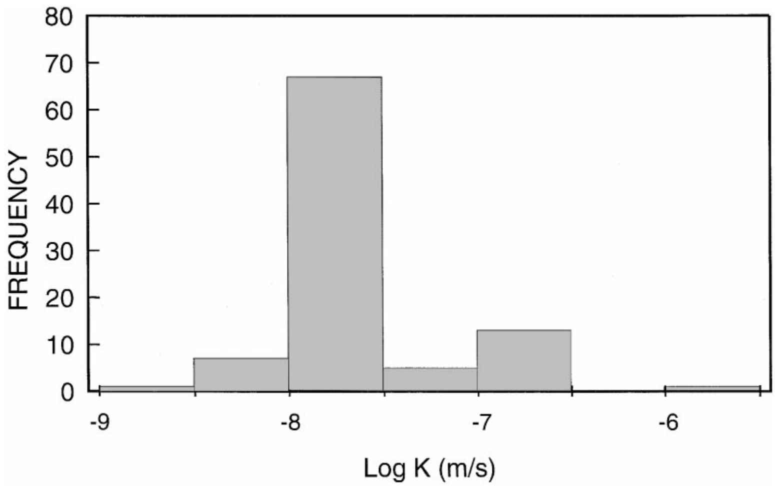

Fig. 5. Frequency histogram showing the distribution of K within the tailings. All measurements were made with piezometer rising head data and interpreted with the method of Hvorslev (1951).

Measurements of ϕ indicate that (1) gradients are downward in the central area of the impoundment, near the apex of the conical tailings pile, (2) gradients are horizontal along the slopes of the pile, and (3) gradients are upward in the area of flat-lying tailings around the periphery of the cone. The downward gradients near the apex of the cone are

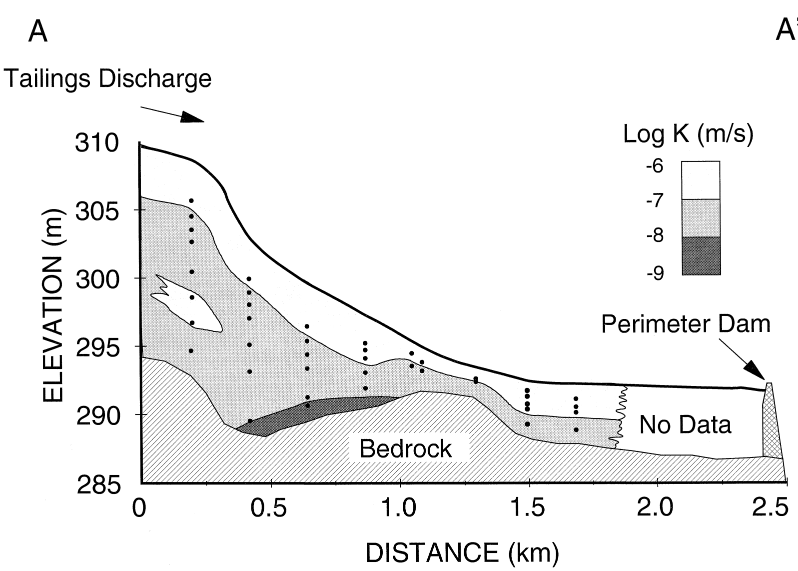

Fig. 6. The variation of K vs. depth along cross section A–A′ (Fig. 1). The cross-hatched area represents underlying bedrock, black dots are measurement points (piezometers).

divergent; near the permeable spigot-road pore water flow converges toward the road, and at greater distance from the road, pore water flows radially outward toward the perimeter. Pore water flow from the tailings toward the spigot road is consistent with observations of pore water discharging from the spigot road onto the tailings at lower elevations along the road.

Changes in the water table position were monitored closely in 1992. In early May, after the snow-melt, the water table was at the surface throughout the impoundment. By the end of May, the water table had reached a relatively steady state where the depth to the water table varied from 5 m ($\pm$1 m) near the spigot road, to approximately 1.5 m ($\pm$0.5 m) in the peripheral flat-lying areas. The uniform grain-size distribution of the tailings supports the formation of a thick capillary fringe when the water table declines in the spring. Moisture-content profiles measured at various locations during a week-long dry period in late July (Fig. 7) indicate that the tailings maintain saturation to within 0.3 to 0.4 m from the surface at all locations, whereas the water table depth ranged between 1.75 m (KC24) and 5.8 m (KC11). The thick capillary fringe causes rapid increases in the water table elevation in response to rainfall as the tension-saturated capillary fringe is converted to a pressure-saturated zone (Al and Blowes, 1996).

The storage capacity of the vadose zone varies according to the depth to the water table, and increases toward the central area of the tailings impoundment. This trend is consistent with observations during rainfall events that surface run off from the tailings

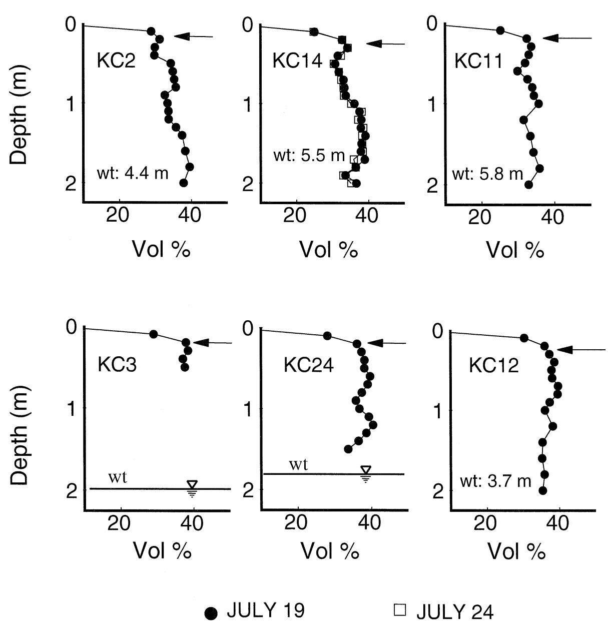

Fig. 7. Volumetric moisture content in the vadose-zone of the tailings measured with a model 503DR neutron moisture probe. The depth to the water table is indicated (wt). The approximate level of the top of the tension-saturated zone is indicated by the arrow. The observed similarity in the repeat measurements at KC-14, where the vertical hydraulic gradients are highest, suggests that temporal variation would be even smaller at other locations.

occurs first in the peripheral area of the impoundment, and progresses up the slope of the tailings cone toward the centre of the impoundment. These observations suggest that the recharge and discharge flux also varies with radial distance from the centre of the impoundment.

The thick zone of tension saturation above the water table results in conditions favourable for evaporative losses of water from the surface of the tailings. The moisture-content data at Kidd Creek indicate that tension saturation is maintained up to 5 to 6 m above the water table over time intervals of 2 or 3 weeks. Therefore, where the water table is only 1 to 2 m deep, such as at KC24, the observed unsaturated zone probably forms as a result of evaporation losses at the surface which exceed the upward flow of water due to capillarity. The water flowing upward due to evaporation at the surface contains solutes which form precipitates on the tailings surface. During dry periods of several days to weeks, the surface of the tailings becomes coated with white salt precipitates that are probably dominantly composed of gypsum [$CaSO_4 \cdot 2H_2O$] and thenardite [Na_2SO_4]. Jambor et al. (1993) observed gypsum and thenardite coatings on the surface of air-dried core samples from the Kidd Creek tailings. These salts may be remobilized by surface run off during rainfall events, decreasing the run-off quality.

3.1.1. Chemical tracers of groundwater movement

The distribution of hydraulic gradients described above provides some indication of the direction of pore water flow within the tailings. The hydraulic gradients, combined with measurements of the hydraulic conductivity and porosity of the tailings, may be used to estimate the velocity of the pore water. Although these estimates are based on field measurements, spatial variability within the system causes the actual pore water velocity to differ from the estimates and it is useful to obtain independent estimates of the pore water velocity for comparison. Independent measurements of pore water velocity are commonly obtained by using chemical tracers, and in this study we have used the dissolution products of a waste material which has been deposited in the tailings as a tracer of vertical pore water flow velocity. The waste material, natrojarosite [$NaFe_3(SO_4)_2(OH)_6$] is produced in the Kidd Creek zinc refinery, and it has been codisposed with the tailings since 1985. The natrojarosite is unstable and dissolves, releasing Na, Fe and SO_4 to the tailings pore water (Al et al., 1994b). The depth of natrojarosite occurrence within the tailings has been established through mineralogical studies (Jambor et al., 1993) at the piezometer nests along section A–A′ (Fig. 2). The recharge rate and vertical pore water velocities since 1985 are calculated from the vertical distance between the depth of natrojarosite occurrence, and the maximum depth of elevated Na concentrations caused by natrojarosite dissolution. It is not possible to determine the horizontal pore water velocity in this way because natrojarosite has been deposited uniformly across the tailings surface since 1985.

The maximum vertical velocity determined by this method is approximately 0.6 m/yr at the piezometer nest closest to the spigot road. The calculated velocities decrease with distance from the spigot road, and the distance where the downward vertical pore water velocity declines to zero (approximately 1000 m from the centre of the cone along section A–A′ coincides with the transition between pore water recharge and discharge zones.

3.1.2. Pore water flow modelling

Measured K values plotted vs. depth (Fig. 8a) define a distinct envelope bounded by a minimum value of 1×10^{-8} m/s and skewed to maximum values of approximately 1×10^{-6} m/s obtained at shallow depths. The mean of the log-normalized K values from the tailings in the perimeter area of the impoundment is greater than the mean of values from the central area of the impoundment (level of significance 0.01). This variation is accounted for in the simulations by defining a slightly higher K in the perimeter area for each respective elemental layer (Fig. 8b). One layer of elements at the bottom of the domain was used to represent the silt/clay layer that underlies the tailings. The K of this bottom element layer has been set at a low value (1×10^{-9} m/s) which is consistent with field measurements. In several locations, this natural soil surface protrudes through the tailings and is exposed at the surface of the impoundment. All areas in the overlying grid layers where the natural silt/clay extends upward through the tailings have been assigned a similarly low K (1×10^{-9} m/s).

The steady-state pore water flow system that exists during most of the summer, fall and winter has been simulated. Field measurements of ϕ at the piezometer nests (at the water table and at 2/3 of the distance to the base of the tailings) were used to calibrate the model. The similarity between the observed and simulated values at the water table and at depth, indicates that the hydraulic gradients calculated by the model are consistent with the measured gradients.

When a steady-state solution was obtained for ϕ, the pore water velocity in each element was calculated. The velocity values are a function of the tailings porosity which is equal to the volumetric moisture content in the saturated tailings. Total porosity obtained from both gravimetric and neutron-probe measurements of moisture content range from 0.35 to 0.51; the higher values being associated with gravimetric moisture-

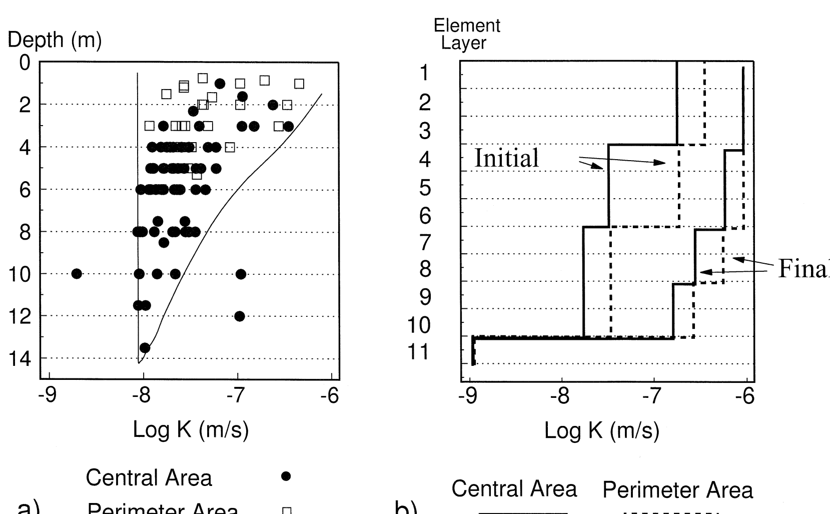

Fig. 8. The distribution of K: (a) vs. depth from piezometer response tests in the tailings, and (b) for each elemental layer as applied for the flow simulations. The thickness of the element layers varies according to the total depth of the tailings.

content determinations. Based on the moisture content data (Fig. 7), it was assumed that the tailings porosity can be represented by an average porosity of 0.4. The flow model was calibrated by systematically varying the elemental K values in order to match the calculated vertical velocities with the vertical velocities determined from chemical tracers, and the calculated ϕ values with measured ϕ values. The final values for K were approximately one order of magnitude greater than the values from the field measurements (Fig. 8b). Similar differences between localized measurements of K, and the large-scale K values required to obtain pore water velocities consistent with conservative tracer velocities have been reported (Bredehoeft et al., 1983; Neuzil, 1986; Carrera, 1993). The observed scale-dependence of K has been attributed to fracture-enhanced permeability (Neuzil, 1986; Carrera, 1993). Following deposition of the tailings, the rapid loss of water by evaporation causes the formation of desiccation fractures that are observed to penetrate to depths of 1 to 2 m. Measurements of K in fractured tailings at Kidd Creek indicate that the fractures represent zones of increased K. The interconnecting network of desiccation fractures in the tailings could account for the increase in hydraulic conductivity in the simulations required to match pore water velocities from chemical tracers.

Based on the simulated velocity distribution, the maximum pore water velocities occur in the relatively high-K perimeter and spigot roads (Fig. 9). The maximum pore water velocities in the tailings (between 0.001 and 3.5 m/yr) occur in the central area of the impoundment where the hydraulic gradient is steepest. Pore water velocities in the tailings decrease with depth and with distance from the centre of the tailings.

The simulated velocity distribution is consistent with field observations, indicating that the pore water infiltrates near the centre of the impoundment, flow becomes increasingly horizontal with greater distance from the centre, and the pore water discharges to the water table in the flat-lying peripheral area. The calculated high pore water velocities (up to 20 m/yr) where the tailings intersect the spigot road are consistent with the observed downward-directed hydraulic gradients in the tailings near the spigot road and with the observed discharge of pore water from the spigot road onto the tailings surface.

3.1.3. Discharge characteristics of thickened tailings

The discharge of low-quality pore water to the surface within the tailings impoundment affects both the long-term effluent-treatment plans and the design plans for tailings decommissioning. The specified top-boundary flux for the flow simulation represents an estimate of the spatial distribution of pore water discharge to the water table surface (Fig. 4). Integrating the recharge and discharge flux from Fig. 4, the total volumetric discharge to the water table within the tailings impoundment is 7075 m^3/yr, which represents 91% of the total recharge. The simulations represent steady-state conditions, therefore the 9% difference represents discharge from the perimeter boundaries of the tailings impoundment.

The estimate of discharge to the water table cannot be equated to surface run off from the tailings because the pore water that discharges to the water table also may be removed through evaporation. Drainage channels that form a radial pattern on the surface of the tailings conduct water only during the 2 to 3 weeks of spring run off and

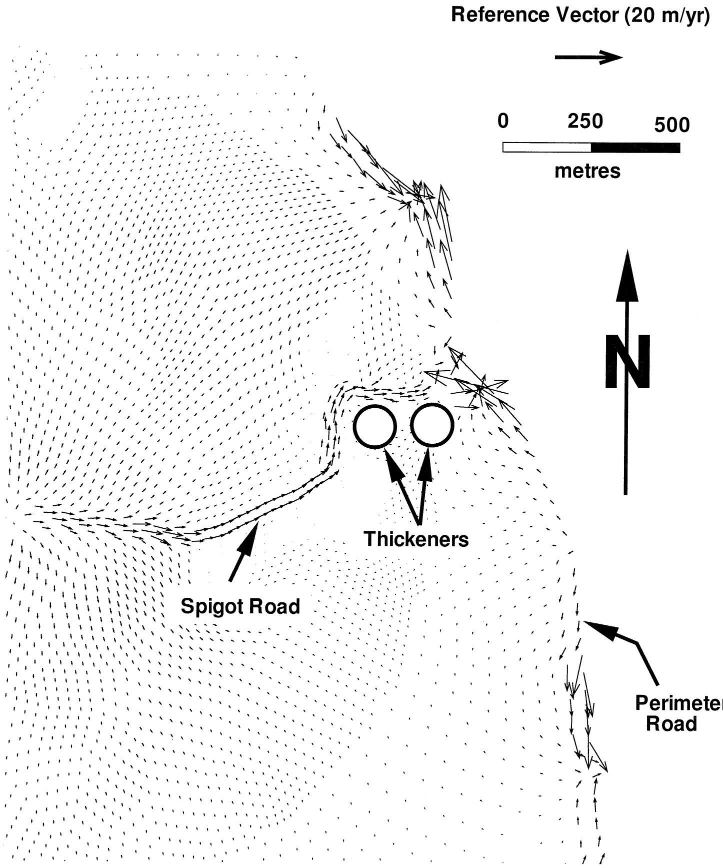

Fig. 9. Plan view of the velocity-vector distribution in the element layer closest to the surface. The X and Y components of the velocity magnitude are proportional to the length of the arrow and a reference vector magnitude is provided. The area shown is located in the eastern portion of the tailings impoundment where the spigot road intersects the perimeter road (see Fig. 2).

during storm events (Al and Blowes, 1996). The remainder of the year, there is no surface run off from pore water discharge areas (defined by upward hydraulic gradients). This suggests that much of the low quality pore water estimated to discharge to the water table within the tailings impoundment (7075 m^3/yr) is balanced by evaporative losses from the tailings surface. This inference is supported by results of a water balance for this tailings deposit (Woyshner and St.-Arnaud, 1994) which indicate that evaporation accounts for between 50 and 70% of total precipitation. Total annual precipitation over the tailings is estimated to be on the order of 10^7 m^3/yr (Environment Canada precipitation records, 1950–1990); therefore, evaporative losses from the tailings surface could easily account for the relatively small amount of discharging pore water. The remainder of the annual precipitation that is not evaporated (between 3 and 5×10^6 m^3) runs off the surface and is collected in ponds (Fig. 2) for treatment and subsequent recycling or release to the Porcupine River. Therefore, the principal source of effluent from the tailings impoundment is expected to be from spring meltwater, and storm run off, rather than discharge of tailings pore water.

During rainfall events when evaporation ceases and the water table in the tailings approaches the surface, pore water that discharges from the tailings contributes to surface run off from the impoundment. Al and Blowes (1996) used chemical mass-balance techniques to separate the storm hydrograph for a stream draining the tailings surface into rainfall-runoff and pore water components. Their data suggests that the fraction of pore water contributing to run off from the thickened tailings is lower than for conventional, unthickened tailings. This is probably due to differences in the physical properties of thickened and unthickened tailings such as the lower and spatially uniform hydraulic conductivity in thickened tailings, relative to unthickened tailings.

4. Implications with respect to tailings management

Oxidative dissolution of sulfide minerals in mine-tailings impoundments is most rapid where O_2 enters the tailings by diffusion through gas-filled pore spaces in the unsaturated zone. The uniform grain-size distribution that results from tailings thickening promotes the formation of a thick tension-saturated zone above the water table, which limits the thickness of unsaturated tailings, thereby confining rapid rates of sulfide oxidation to the upper 0.3 to 0.4 m of tailings. Based on observations of hydraulic gradients, the water table depth and the tailings moisture content, the formation of unsaturated conditions suitable for sulfide oxidation to occur may be due primarily to evaporative losses from the vadose zone. Therefore, application of methods to control evaporation from the surface of the thickened tailings would be effective in maintaining tension saturation to the surface of the tailings and limiting sulfide oxidation. The low hydraulic conductivity of thickened tailings results in a small flux of pore water to the surface as a result of flow in the saturated zone. However, the high levels of tension saturation in the vadose zone, combined with evaporation at the surface, provide ideal conditions for upward transport of solutes released by sulfide oxidation or dissolution of soluble mineral phases. Therefore, it is likely that dissolution of soluble secondary minerals at the tailings surface, and transport of the solutes with storm run off, represents one of the principal mechanisms contributing to low-quality effluent from the thickened tailings impoundment.

Steps taken to limit evaporation would be effective in maintaining tension saturation near the surface of the tailings, thereby preventing rapid rates of sulfide oxidation, and minimizing the upward flux of solutes that leads to the formation of secondary-mineral coatings at the tailings surface. Saturated tailings, and the desired low rate of sulfide oxidation, may be obtained with a low moisture-retention cover that limits evaporation such as sand or gravel. By contrast, in conventional unthickened tailings, capillarity is not effective in maintaining tension saturation higher than 0.5 to 1 m above the water table. In this case, unsaturated conditions develop in the vadose zone due to gravity drainage. The most common types of covers that are proposed for controlling sulfide oxidation in conventional sulfide-rich tailings employ fine grained layers which are capable of maintaining tension saturation, and thereby limiting oxygen diffusion to the underlying tailings (Nicholson et al., 1989; Akindunni et al., 1991). The design of these covers also may include a coarse grained capillary-break layer below the oxygen diffusion barrier, and a coarse-grained protective layer above the diffusion barrier. This sort of elaborate cover design should not be necessary for the thickened tailings provided evaporation can be minimized, because tension saturation of the tailings provides the necessary oxygen diffusion barrier.

The principal environmental benefit of the central-discharge method of tailings disposal is the resulting development of a pore water flow system that contains the discharge of the majority of the low-quality pore water within the impoundment. Simulations of pore water flow suggest that 91% of the recharge in the central area of the impoundment discharges to the water table in the peripheral area of the impoundment. Discharge of low-quality pore water within the impoundment, where it can be held for treatment, provides improved control of effluent compared to conventional impoundments. Maximizing the discharge within the impoundment also provides the opportunity to design reactive tailings covers or reactive zones within the tailings, located in pore water discharge areas, to treat discharging pore water passively, resulting in improved pore water quality and lower treatment costs. The formation of a conical deposit due to central discharge of the tailings creates a physically unstable situation, and although the slope of the tailings is quite low (between 1 and 5%), the tailings are prone to significant erosion (AGRA Earth and Environmental, 1994, unpublished data). It is likely that the erosion and water quality issues could be addressed together by placing a coarse grained evaporation-limiting barrier over the tailings, and possibly establishing vegetation on the surface.

Although much of the data and interpretation presented here are specific to the Kidd Creek site, the physical and hydrologic properties of thickened tailings that have been described are not site specific. Based on the results of this work, it appears that thickening and central discharge of sulfide-rich tailings provides some advantages over conventional methods of tailings disposal with respect to environmental management. In general, hydrogeological field investigations, combined with three-dimensional simulations of pore water flow are useful to help define the distribution of recharge and discharge areas in order to optimize the distribution of reactive cover materials, and the cost of cover construction.

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