HYDROLOGY OF THE CENTRAL MANITOBA MINE TAILINGS

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ABSTRACT
Sulphide communication with oxygen in the Central Manitoba Mine tailings is interdependent with surface water and groundwater regimes, and the geotechnical properties of the tailings, which may control the acid mine drainage (AMD) potential of the 70 year old abandoned tailings. A site investigation and laboratory testing program, combined with a global positioning system (GPS) survey have identified three surface water regimes with a combined area of 16 hectares. The oxidized (upper) and non-oxidized (lower) tailings had an average hydraulic conductivity of 2.20×10-4 cm/sec and 3.90×10-5 cm/sec, and porosity of 51.2 % and 40.2 %, respectively. The low hydraulic conductivity of the tailings combined with an upward groundwater flow through underlying rock basin fractures, suggest that fluctuations of the groundwater elevation in the tailings are largely controlled by the regional hydrogeology and not by surface infiltration. The findings presented in this paper are an intermediate step to understand the hydrology of the Central Manitoba Mine tailings, and to help provide input in future remediation alternatives to be considered at this site.

RÉSUMÉ
Le flux d'oxygène dans les rejets miniers sulfureux de la mine abandonnée Central Manitoba est interdépendant avec les régimes d'eau de surface et d'eaux souterraines, et les propriétés géotechniques des rejets de concentrateur, qui peuvent influencer en mode direct le potentiel de production du drainage minier acide (AMD) a travers le site qui date de plus de 70 ans. Une étude de laboratoire et un programme d'investigation du site ont été évalués ensemble avec un système télémétrique de positionnement global (GPS) et ils ont identifié trois régimes d'eau de surface avec une superficie combinée de 16 hectares. Les rejets oxydés (en partie haute) et ceux non-oxydés (en profondeur) ont une conductivité hydraulique moyenne de 2.20×10-4 cm/sec et de 3.90×10-5 cm/sec, et une porosité de 51.2 % et de 40.2 %, respectivement. La basse conductivité hydraulique des rejets de concentrateur, combinée avec un régime d'eaux souterraines ascendant à travers des roches fracturés du basin, suggèrent que la fluctuation de la nappe phréatique dans les rejets miniers est en grande partie contrôlée par l'hydrogéologie du basin et pas par les infiltrations en surface. Les résultats présentés en cet article sont une étape intermédiaire de l'étude qui se poursuit afin de comprendre l'hydrologie des rejets miniers de la mine Central Manitoba, et pour aider fournir des concepts et des solutions pratiques pour une éventuelle réhabilitation du site.

1. INTRODUCTION

The Central Manitoba Mine is located in Nopiming Provincial Park, Manitoba, Canada, 170 km northeast of Winnipeg and accessible via provincial road 304. In production from 1927 to 1937, the Central Manitoba mine extracted approximately 5,000 kg of gold from 480,000 tonnes of ore from the Kitchener vein, located within the Rice Lake Archean Greenstone belt (Richardson & Ostry 1996). The tailings site, located adjacent to the mine, was abandoned after closure with no decommissioning or remediation plan. Covering 16 hectares, the tailings are predominantly quartz and feldspar with about 5% pyrite and chalcopyrite.

Currently, the top 0.1 - 1.0 m of the tailings consists of oxidized rust coloured material that overlies 1.0 - 2.0 m grey/blue non-oxidized homogeneous material. Tailings were deposited as slurry using water as the transport medium. The slurry was piped onto the existing bog with no mechanical processes of spreading the tailings. The slurry spread across the site due to gravitational processes only. Provincial road 304 did not bisect the

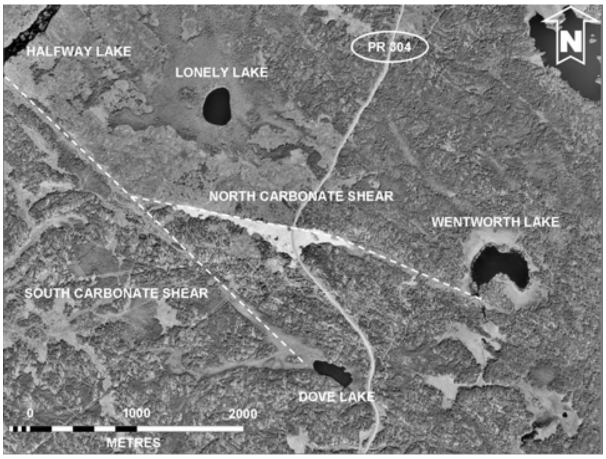

Figure 1. Orthophoto showing the surrounding lakes and their interconnectivity by the North and South carbonate shear zones.

site until after the tailings were deposited. The tailings were discharged as a slurry on top of a peat deposit within a granitic closed-catchment, bounded on the north side by a North Carbonate Shear zone (Figure 1).

Oxidized tailings have a pH range of 3.0-8.0 while the pH for non-oxidized tailings remains relatively constant at 7.5. Quartz and feldspar within the tailings are inert, but pyrite and chalcopyrite oxidize with the introduction of oxygen through erosion or seasonal fluctuations in the groundwater.

Erosion across the site is most evident in areas adjacent to rock outcrops and coincide with the higher elevations and the location of the tailings discharge point. It was observed that some fractured rock outcrops located adjacent to the tailings deposit, discharged groundwater that drains onto the tailings site as surface water (Figure 2). Erosion was prominent in these areas and exposes non-oxidized material to the atmosphere promoting their oxidation.

Figure 2. Photograph of rock fractures along north boundary rock outcrop.

The oxidized layer is about 0.1-0.6 m thick, rust coloured, with a Munsell hue of 10 YR 4/4. The blue-grey non-oxidized tailings have a Munsell hue of 5 BG 5/1 (Salzsauler 2001).

Two ponds located on site were used as landmarks and were referred to as the “blue pond” and the “green pond” (Figure 3). The blue pond is coloured by a high concentration of copper sulphate and a pH of 4.5 resulting in an absence of plant life. The green pond is bounded by the road on the east, has a pH of 7.5. The green pond supports horsetails, frogs, and sandpipers, which is in sharp contrast with the environment developed around the blue pond just 150 m away.

This paper presents the field and laboratory-testing programs undertaken in order to understand the hydrology at the Central Manitoba mine site and its influence on the acid generation process from the abandoned tailings.

Figure 3. Aerial photo taken May 2003 showing landmarks Green pond, Blue pond, and PR 304 looking easterly.

2. METHODOLOGY

2.1 Approach

The following steps were undertaken in this part of the project.

- Introduce absolute Universal Transverse Mercator (UTM) coordinates on site.
- Obtain tailings samples (disturbed and undisturbed) and install piezometers at the site
- Measure geotechnical properties of the oxidized and non-oxidized tailings
- Measure the topography and assess the surface water regimes
- Measure groundwater table elevations over the site throughout the year
- Examine the inter-relationship between geochemical reactions and geotechnical properties, surface, and groundwater flow regimes.

2.2 Field Analysis

A combination of field and laboratory analysis was used for this project. Aerial photographs of the site and surrounding area were taken in May 2003. A Global

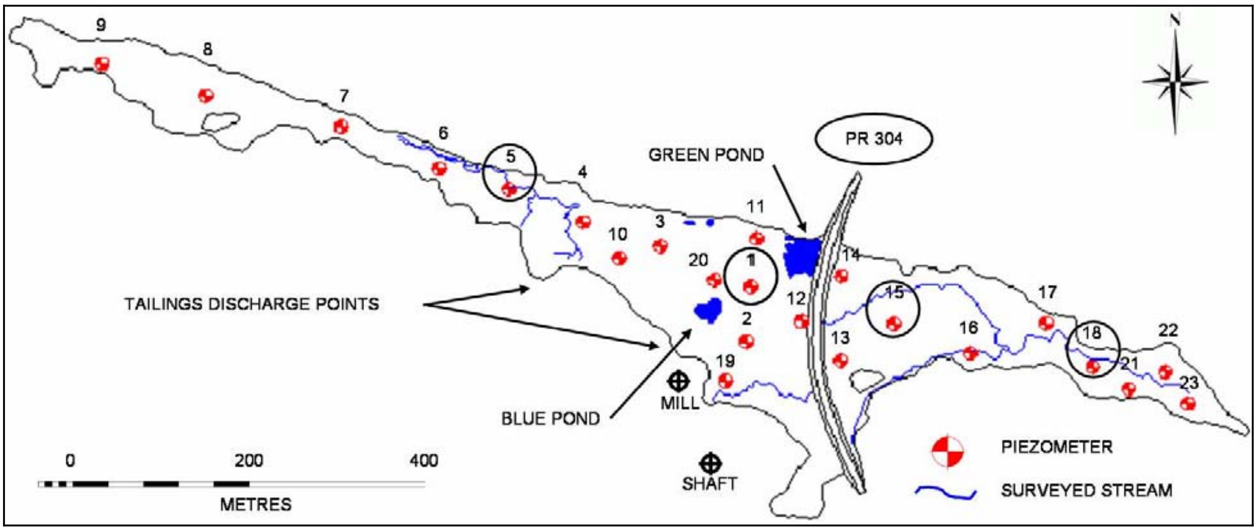

Figure 4. Plan view of the Central Manitoba tailings site showing piezometer and Shelby tube sampling locations (circled).

Positioning System (GPS) survey, consisting of over 6000 points, defined the topography and surface water regimes. GPS control was established using benchmarks located in Bissett and Beresford Lake, 27.1 and 8.1 km from the site respectively. GPS survey data was processed using Trimble Geomatics Office®, AutoCAD 2002®, AutoDesk; Land Development Desktop 3®, Map 5®, Raster Design 3®, and MicroSurvey 2001®. A triangulated irregular network (TIN), digital terrain model (DTM), contour plan, site plan, and a surface flow line plan were created.

Groundwater fluctuations and the depth to the oxidized and non-oxidized boundary in the tailings were measured using twenty-three shallow piezometers installed across the site, ranging in depth from 0.4 to 2.3 metres. Figure 4 shows the piezometer locations.

Shelby tube samples of undisturbed oxidized tailings were taken adjacent to piezometers # 5, # 1, # 15, # 18, and, undisturbed non-oxidized tailings adjacent to piezometers # 5 and # 1 (Figure 4). Tubes were pushed in by hand to refusal, dug out, sealed, stored, and transported in an upright position to minimize sample disturbance. In addition, grab samples were taken of oxidized and non-oxidized tailings at different depths at each tube sample site for laboratory analysis. All piezometers and sample locations were assigned a Universal Transverse Mercator (UTM) planar projection coordinate address established by the GPS control network.

UTM coordinate addresses were assigned to numerous permanent features found on site including anchor bolts and cadastral survey monuments. In addition, iron bars were driven at convenient locations within and surrounding the site, and assigned a coordinate address for future GPS UTM calibrations.

2.3 Laboratory Testing and Analysis

Laboratory testing of the oxidized and non-oxidized tailings included: modified falling head permeability tests, porosity, specific gravity (ASTM D 854-02), bulk density, sieve and hydrometer grain size (ASTM D 422-63, 2002). Water used in the laboratory tests was de-ionized, distilled and de-aired. Soil pH (ASTM D 4972-01) was measured in oxidized and non-oxidized samples from piezometers # 5, # 1, # 15, and # 18.

3. RESULTS AND DISCUSSION

3.1 Topography

Surface topography of the tailings ranges from wide, 100–200 metre, essentially flat areas, to narrow undulating dendritic sections of 30-100 metres. Surface gradients across the site range from localized areas of 10 % to less than 0.01 %. Northerly cross fall from the south side of the site, where the shaft, mill, and tailings discharge point were located, is -4.6 %. The cross fall laterally from the crest of the site, which coincides with the tailings discharge point, is -0.6% westerly, and -0.4% easterly.

Low-lying wide flat areas surrounding piezometers # 8, # 1, and, # 15, have small surface elevation gradients, and show sheet, and interrill erosion. Areas surrounding piezometers # 4 and # 5 have a concentrated volume of surface water runoff due to increased overland drainage from surrounding rock outcrops and encroaching side boundaries.

Erosion of oxidized material in areas of high topographic relief has exposed large quantities of underlying sulphide bearing non-oxidized tailings (Figure 5). Desiccation of the tailings adjacent to the areas of high relief resulted in 0.1 - 0.2 m vertical and 0.1 - 0.3 m horizontal cracks throughout the site perpendicular to the sides of gullies. It is likely that these cracks fill with water during a rainfall event, thereby creating hydrostatic water pressure acting against a block of oxidized tailings material. When the fluid pressure exceeds a critical value, the block of oxidized tailings falls into the gully. This erosion process tends to expose non-oxidized tailings to oxygen and further desiccation and surface crack formation occurs.

Figure 5. Photograph showing erosion and surface drainage near piezometer # 5.

The erosion process continues to occur forming a deeper and wider gully over time. Exposing sulphides contained in the non-oxidized tailings produce acidic conditions, which can promote leaching of metals, such as copper and ferrous iron. Acidic waters are associated mainly with erosional activities of the surficial layers of tailings due to surface runoff (Sherriff et al. 2001). Evaporite minerals precipitate causing red and turquoise colouration.

3.2 Geotechnical Properties

Geochemical reactions, specifically oxidation, taking place on site can affect the grain size of the tailings. Geochemically induced alterations to the grain size cause changes to the porosity and hydraulic conductivity of the tailings, which in turn influence the surface water and groundwater interaction. The low hydraulic conductivity of the tailings limits the amount of infiltration, which in turn affects the local recharge, seasonal variation, and fluctuation in the groundwater table elevation. Groundwater table location controls the thickness of the vadose zone, which limits the depth of oxygen migration into the tailings deposit and therefore the thickness of the oxidized zone.

Average moisture content, hydraulic conductivity, bulk density, porosity, void ratio, and specific gravity of the tailings are summarized in Table 1.

Table 1. Geotechnical properties of oxidized and non-oxidized tailings from tube samples (average values).

Property	Oxidized	Non-oxidized
Moisture Content (%)	28.20	18.57
Hydraulic Conductivity (cm/s)	2.20×10^{-4}	3.90×10^{-5}
Bulk Density (g/cm^3)	1.72	1.95
Dry Unit Density (g/cm^3)	1.34	1.65
Porosity (%)	51.2	40.2
Void Ratio	1.05	0.67
Specific Gravity	2.75	2.76

Hydraulic conductivity of the undisturbed oxidized tailings, collected and tested in the Shelby tubes, were 2.20×10^{-4} cm/s. Undisturbed non-oxidized tailings had a hydraulic conductivity value of 3.90×10^{-5} cm/s. Low hydraulic conductivity values and an observed thin differential oxidation layer at the surface, suggest that downward percolation from infiltration is minimal.

Grain size analysis on the oxidized samples had an average D_{10} of 0.009 mm, coefficient of uniformity (C_u) of 9.53, and coefficient of curvature (C_c) of 1.11. The non-oxidized had an average D_{10} of 0.004 mm, C_u of 7.7, and C_c of 1.5 (Table 2). Tailings can be characterized further based on their gradation, with sands being the coarser fraction retained on the #200 sieve, and slimes being the silts and clay size particles passing the same sieve. Oxidized tailings contained an average of 47% sands and 53% slimes while the non-oxidized tailings represent 27% sands with 73% slimes. These values are within the typical ranges for early gold mining operations, however the upper oxidized layer has a lower slimes content mostly due to the geochemical degradation and weathering, and the surficial erosion and transport of fine grained particles by surface runoff (Priscu 2004).

Table 2. Grain size analysis data from Shelby tube samples in the oxidized and non-oxidized zones.

Sample	D_{60} (mm)	D_{30} (mm)	D_{10} (mm)	C_u	C_c
Oxidized					
S-1	0.086	0.028	0.009	9.56	**1.01**
SH-18	0.076	0.027	0.008	9.50	**1.20**
Average	0.081	0.028	0.009	9.53	**1.11**
Non-Oxidized					
S-1	0.042	0.019	0.005	8.40	**1.72**
S2-18	0.021	0.009	0.003	7.00	**1.29**
Average	**0.032**	**0.014**	**0.004**	**7.70**	**1.50**

There has been some physical alteration of the tailings subsequent to the milling process by oxidation. Oxidized grains have alteration rims of fine-grained mineral “coatings” with high iron and copper content that envelope the non-oxidized tailings core (Salzsauler 2001).

Differential settling resulted in the sand size fraction accumulating closer to the point of discharge along the south side of the deposit and the silt and clay size fraction accumulating further down gradient. Particle size curves for the non-oxidized tailings of samples taken near piezometer # 1 (150 metres from the discharge point) and near piezometer #18 (approximately 500 metres from the discharge point) reveal a dependency of distance from discharge location. The difference in grain size distribution between # 1 and # 18 indicate differential settling with respect to distance from discharge, whereas the oxidized grain size distribution curves from # 1 and # 18 show increased size due to the alteration rim, and not differential settling.

The grain size analysis (Table 2 and Figure 6) indicates that the alteration of the oxidized grains, subsequent to deposition, has increased particle size rather than decreased it by dissolution; however, the specific gravity between oxidized and non-oxidized tailings remained similar.

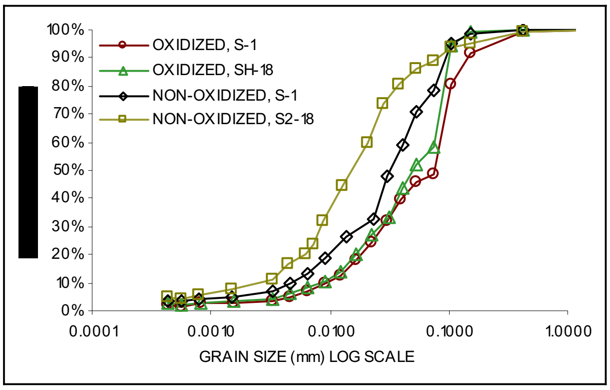

Figure 6. Grain size distribution curves for oxidized and non-oxidized tailings (sieve and hydrometer analyses).

3.3 Surface Water

There are two culverts under PR304, however only one drains the site. This culvert is situated in the middle of the site near piezometer # 12 and provides the major path for west to east drainage of surface water, having large, wide, flat-bottomed gullies on either side of the culvert.

The digital terrain model DTM provides a graphical representation of the surface water drainage patterns at the site (Figure 7). Three separate surface water regimes can be identified, the western, eastern, and the blue pond. The eastern regime has an area of 9.2 ha with surface water flow constricted by the culvert under PR 304. Upon exiting the culvert, surface water flow follows a dendritic pattern traversing the remainder of the site easterly, finally dispersing into a bog. The western regime has an area of 5.8 ha and one central stream flows west draining the tailings area into a bog. The third and smallest surface water regime is the blue pond regime with an area of 1.0 ha. This regime is circular, bowl shaped and hydraulically isolated from the eastern and western regimes. The blue pond drains the surrounding outcrops that included the mill and shaft sites (Figure 7). The surface elevation of the blue pond was approximately 0.30 metres higher than the green pond in June 2003.

Flow lines generated by the DTM coincide with the rock outcrop boundaries, rills, and streams, which were surveyed in June 2003. Each flow line extending from the tailings boundary represents a path for water to drain onto the site from surface drainage from the surrounding soils, outcrops, and/or water discharge from fractures adjacent to the tailings (Figure 7). The green pond is hydraulically isolated due to impoundment from the road on the east, the rock outcrop to the north and topographically high elevations on the south preventing flow into the culvert. Water drains into the green pond from approximately one quarter of the tailings west of PR 304, excluding the blue pond regime (Figure 7).

An aerial orthophotograph of the surrounding area, as shown in Figure 1, suggests that the tailings may be hydraulically connected on a regional scale along the South Carbonate Shear with Halfway Lake, 1.8 km to the west, and Dove Lake, 1.2 km south, and along the North Carbonate Shear, Wentworth Lake, 1.0 km to the east. Lonely Lake is approximately 0.8 km north of the site and does not have a readily identifiable geologic structure connecting it to the site.

3.4 Groundwater

Groundwater level rise was measured in the 23 piezometers, one day after installation in June 2003, then again in August 2003, October 2003, and May 2004. Results are plotted along two cross sectional profiles, A-A’ and B-B’ shown in Figure 8. Cross section A-A’ traverses the site longitudinally while cross section B-B’ bisects the site along its widest transect closest to the mill.

The piezometers were installed with no screen or end cap, thus they consist of a straight open-ended pipe.

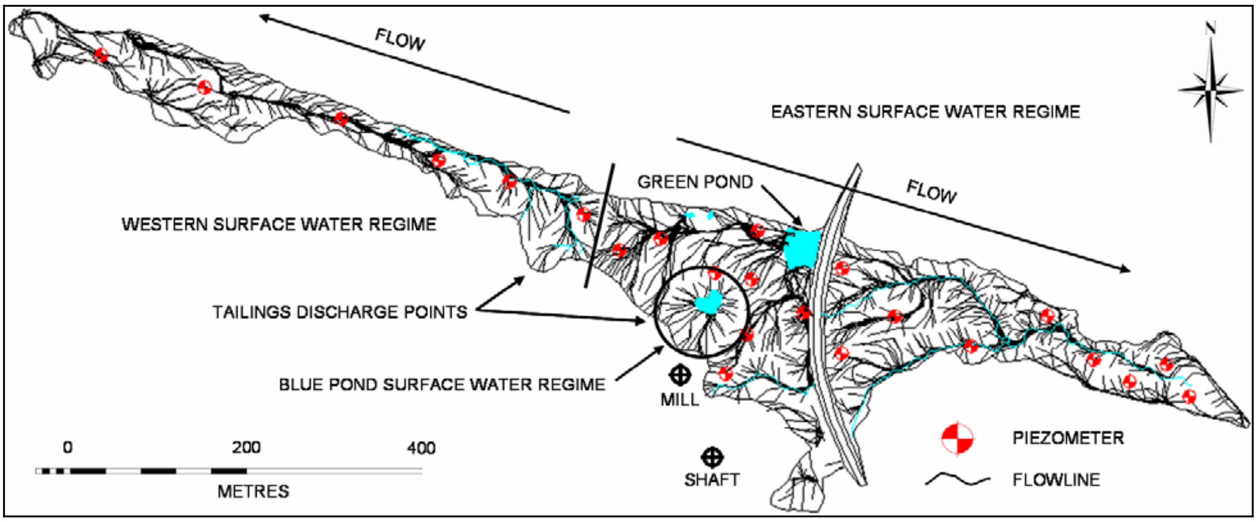

Figure 7. Digital Terrain Model DTM of the site showing surveyed gullies, flow lines, and the Western, Eastern and Blue Pond surface water regimes.

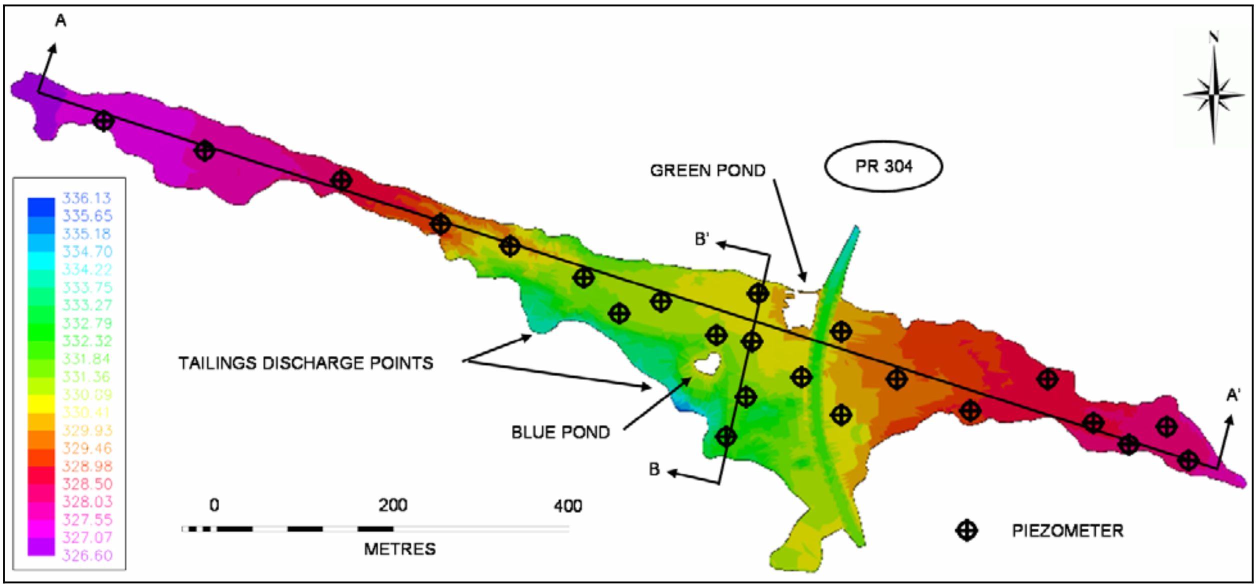

Figure 8. Digital terrain model showing elevation change, piezometers locations, and cross sections A-A’ and B-B’.

In August 2003, tailings had pushed up into the piezometer pipe about 0.023 - 0.850 m in 17 of the 23 piezometers. In May 2004, tailings had completely filled piezometers # 2, # 5, and # 6. This observation indicates that there is an upward component of groundwater flow in the tailings, which created a hydraulic gradient exceeding a critical value for piping to occur.

The upward component of groundwater flow may be the result of groundwater discharging from fractured bedrock beneath the tailings related to the North Carbonate Shear. Rock fractures 0.001 - 0.010 m wide were observed in the outcrop along the north boundary of the site measured 0.10 - 0.50 m striking 110° azimuth, dipping 60° with fractures measuring 0.10 - 0.30 m normal to those (Figure 2). Water was observed flowing from several fracture locations that were sourcing increasingly expanding rills sprawling onto the tailings in May 2004.In cross-section A - A’ (Figure 9) the hydraulic head for October 2003 follows the general shape of the surface topography. May 2004 measurements of hydraulic heads were the highest recorded. Water was observed seeping up out of piezometers # 5 & # 6 further confirming an upward component of groundwater flow at the site. In addition, water was observed seeping from the bottoms and sidewalls of V-channelled gullies, which was supplying active rills and streams.

Cross-section B - B' groundwater table measurements (Figure 10) show the hydraulic head is higher at the edges of the site compared to the middle which also indicates recharge to the tailings from the underlying bedrock near the edges of the deposit.

Blowes et al (2003) state that after deposition of tailings is complete and the discharge of water as a tailings transport medium ceases, precipitation becomes the dominant source of groundwater recharge to the tailings impoundment and that evapotranspiration, surface runoff and seepage through underlying sediments become important components of the water balance.

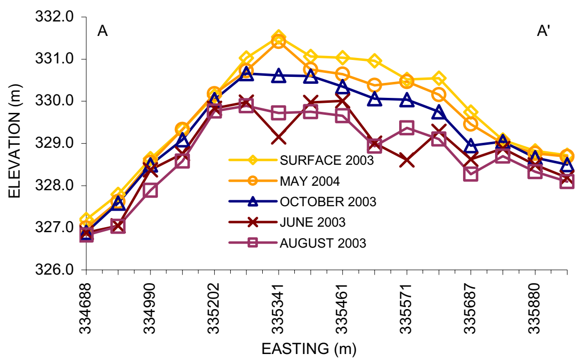

Figure 9. Cross section A-A' showing the surface elevation and groundwater table elevations measured in June, August, October 2003, and May 2004.

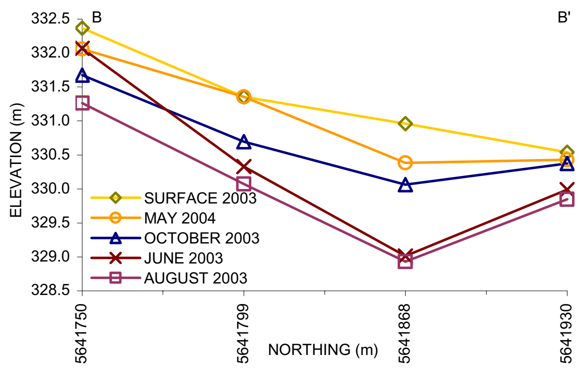

Figure 10. Cross section B-B' showing the surface elevation and groundwater table elevations measured in June, August, October 2003, and May 2004.

However, the data collected during this study suggest that the main contributor to water availability is upward flow from the regional groundwater regime into the tailings and drainage of water from the surrounding fractured bedrock onto the tailings surface.In addition, because of low hydraulic conductivity of the oxidized layer, surface water infiltration is anticipated to be small. Furthermore, the absence of vegetation on the surface will limit the amount of evapotranspiration taking place. Groundwater fluctuations control the thickness of the vadose zone, which will control the proportion of oxygen present in the air-filled voids of the tailings and thus the magnitude of geochemical reactions within the zone.

4. CONCLUSIONS

There are three distinct surface water regimes at the Central Manitoba Tailings. The smallest regime is the Blue Pond covering approximately one hectare, featuring a closed-catchment basin fed overland by drainage of the mill site. Secondly, the Western regime covers approximately 5.8 hectares and features the greatest amount of erosion and topographic relief. The third and largest is the Eastern regime, which covers approximately 9.2 hectares and is bisected by PR 304. The Eastern regime contains the least amount of topographic relief and surface erosion. Erosion exposes non-oxidized material to the atmosphere and facilitates oxidation and acid production.

Low hydraulic conductivity values of the surficial oxidized layer of tailings limit the amount of water infiltration from surface runoff.

Grain size distributions show that oxidized tailings have relatively uniform distribution while non-oxidized particle size varies with distance from point of origin, due to differential settling of larger, heavier particles.

There is an upward component of groundwater flow in the tailings, which may be the result of groundwater discharging from the fractured bedrock located below the tailings deposit. In addition, the main contributor to water availability may be upward flow from the regional groundwater regime into the tailings and drainage of water from the surrounding fractured bedrock onto the tailings surface.

This project is part of a broader research initiative that studies abandoned gold mine tailings sites in Manitoba. The findings presented in this paper contribute to understanding the hydrology of the Central Manitoba mine tailings and provide input to future remediation alternatives that may be considered for this site.

5. ACKNOWLEDGEMENTS

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