Groundwater Flow Interactions in a Seven-Layer Meromictic Pit Lake at the Former Victor Diamond Mine, Ontario Canada

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Abstract

Groundwater interactions with a meromictic pit lake were investigated at the former Victor Diamond Mine, Ontario, Canada, through a comparison of pit lake and pre-mining groundwater conductivity and temperature profiles. The study provides an example of a pit lake where groundwater interactions from thin, flat-lying, bedding-plane aquifers containing waters of differing chemistry create measurable stratification.

Keywords: Pit Lake, meromictic, groundwater, Victor diamond mine, diamond mine

Introduction

The former Victor Diamond Mine (VDM) is located in the James Bay portion of the Hudson Bay Lowlands, approximately 90 km west of Attawapiskat (Fig. 1a). Mining ended in early 2019 after 12 years of operation, allowing the pit to flood (Fig. 1b). Flooding was assisted by pumping freshwater from the nearby Attawapiskat River between April 2020 and December 2022. Most of the water was pumped during the non-winter months because of seasonal pumping constraints. Using this strategy, flooding of the 280 m deep pit ended in 2022. Pit lake levels stabilized by mid-2023.

This paper presents a case study of a pit lake at a non-metallic mine in sedimentary bedrock containing several flat-lying bedding-plane aquifers of differing water quality. The study shows that groundwater flow can produce measurable stratification in the pit lake water quality profile, coincident with aquifer locations. This case study may assist future scientists in assessing pit lake conditions in similar environments, including prospective open pit mines in sedimentary bedrock settings such as the Hudson Bay Lowlands portion of the Ring of Fire area.

Methods

This study compares pit lake water quality data, including profiles and sampling, with similar groundwater datasets collected prior to and during mining to examine the role of groundwater flow interactions with the pit lake. The data for this study come from De Beers Canada (De Beers), which has been responsible for operation and monitoring of the former VDM site. These data include more than 23 years of climate, hydrology, and groundwater information, including drilling records, groundwater and pit lake water quality data, groundwater levels, pumping records, groundwater modelling, and aquifer assessments. They are the primary source of information for this study.

The pit lake profiles were collected between the onset of pit lake flooding in 2019 and 2026 using a YSI EXO3 Sonde. The profile data include total dissolved solids (TDS), electrical conductivity, temperature, pH, and turbidity. A conversion factor is not available for the TDS data. The profiles were collected two to four times per year by lowering the instrument from a boat using approximately 200 m of line. The line length is insufficient to reach the full 280 m depth of the pit lake. Therefore, profiles from two profiling events are used to represent the entire lake profile. The longest profile available, collected in September 2024 after lake levels stabilized in 2023, is used to represent conditions in the upper portion of the pit lake. A profile from 2020, collected at a lower lake level and before

Figure 1 a) Location of former Victor Diamond Mine (left), b) pit lake in 2025 (top right) and c) example of local peat land environment adjacent to the Attawapiskat River (bottom right).

significant augmentation of the pit lake with river water, is used to represent the deepest portion of the pit lake.

The comparable groundwater profiles include electrical conductivity and temperature profiles from a downhole geophysical program completed in 2007, before large-scale dewatering, in drillholes located around the open pit. Available groundwater profiles were screened to select longer profiles showing minimal vertical water movement that would influence water quality. In addition, electrical conductivity profiles from drillholes located downgradient of the kimberlite were excluded to avoid its effects on water quality. The residual dataset included electrical conductivity from two profiles located cross-gradient or upgradient of the kimberlite (drillholes VDW-11 and VDW-17) and one longer temperature profile (VDW-22). Additional groundwater temperature data were taken from depth-specific measurements made in vibrating wire piezometers (VWPs) installed in the country rock around the pit prior to flooding.

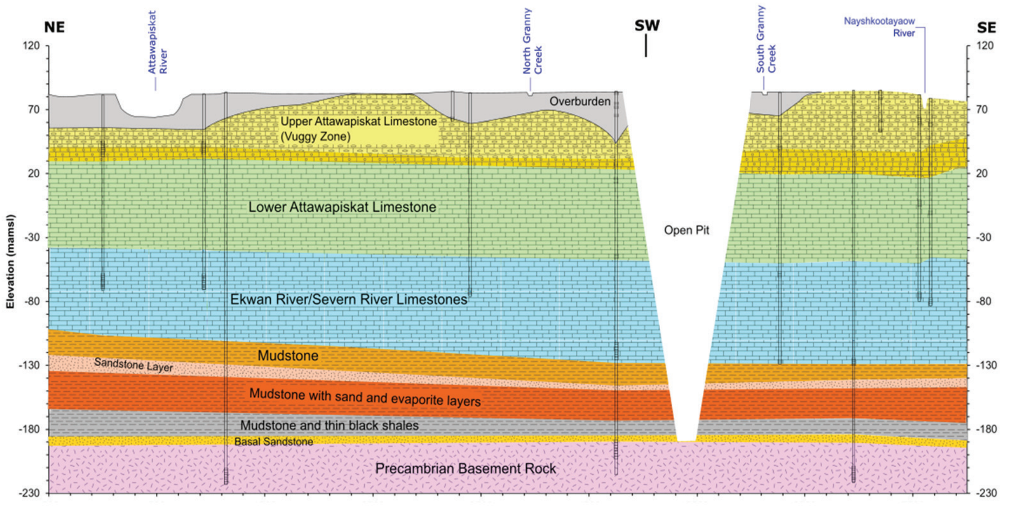
Water quality sampling data include discrete-depth samples from the pit lake collected at the same frequency as the pit lake profiles, and depth-specific groundwater quality samples collected during drilling in 12 regional drillholes from 2003 to 2006 (HCI 2003 and 2007).

The site and hydrogeologic setting are summarized from several sources. These include previous research (Gautrey 2018; Gautrey and Desjardins 2025), pre-mining groundwater investigations (HCI 2003 and 2007), a hydrogeologic and pit lake model developed prior to the end of dewatering (Itasca 2019), author observations from involvement at the mine site from 2004 to 2026, including during mine operations from 2007 to 2019, annual groundwater reporting, and other materials.

Site Setting

The Hudson Bay Lowlands are a vast peatland with thousands of ponds and small lakes that is drained by numerous creeks and a few large rivers. Near the former mine, the terrain is flat and includes one large river, the Attawapiskat River (Fig. 1c). The area has cold winters (mean January temperature of -22.2 °C) and cool summers (mean July temperature of 16.1 °C), and it is relatively dry, with average annual precipitation and evaporation totals of 540.8 mm/year and 462.9 mm/year, respectively (Golder 2020).

Prior to mining, the diamond-bearing kimberlite at the former mine site consisted of two intertwined kimberlite pipes that intruded through the country rock approximately 170 million years ago (Kong *et al.* 1999). Several other kimberlites occur in the region but have not been mined.



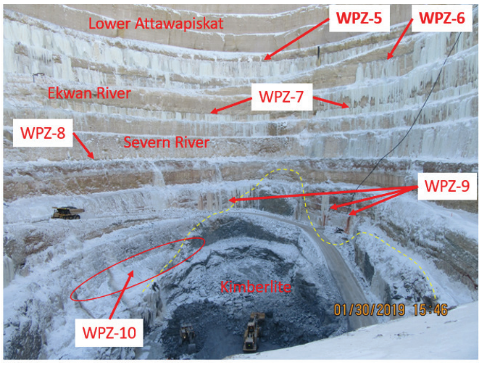


Figure 2 a) cross section illustrating general stratigraphy at the open pit (above), and b) 2019 picture from open pit showing inflow from individual water producing zones in lower portion of open pit (right).

At the VDM, the country rock consists of up to approximately 270 m of Paleozoic sedimentary rock that overlies Precambrian crystalline bedrock of the Superior Craton (Fig. 2a). Most groundwater flow occurs through near-flat-lying, thin, bedding-plane aquifers in the Paleozoic rock. These bedding-plane aquifers developed in bedrock layers that were slightly more prone to dissolution than others. They also developed where flat-lying aquitards, usually mudstones, concentrate horizontal groundwater flow and hence dissolution of the carbonate rock. In total, ten such horizons were identified in the sedimentary bedrock sequence at the VDM (Gautrey and Desjardins 2025). During mining, when there was sufficient groundwater to support the inflows, curtains of water were observed to ring the open pit at the horizons of these aquifers (Fig. 2b). The crystalline bedrock at the base of the sedimentary sequence and the overburden, consisting mostly of clayey silt Tyrrell Sea deposits and till, are not considered aquifers.

In terms of groundwater chemistry, some groundwater is in equilibrium with the carbonate bedrock, including gypsum layers in the deeper mudstone layers. Previous investigators (Mahoney and Howell 2006) also hypothesized that relic Tyrrell Sea water was trapped in some deeper aquifers and within Quaternary sediments laid down before the retreat of the Tyrrell Sea. Following the retreat of the sea between ≈8.2 ka BP and ≈6.1 ka BP (Gao and Turon 2025), this former seawater has been progressively flushed by freshwater recharge. As a result, groundwater occurs in layers of differing water quality depending on regional groundwater flow patterns.

The crystalline bedrock holds ancient, pre-Quaternary water. Tyrrell Sea deposits containing relic seawater and kimberlite intrusions can also influence groundwater quality downgradient of these features.

Pit Lake Development

The pit lake was created following the end of mining in 2019, when the open pit was allowed to flood. During the mine life, a large-scale dewatering operation was required to operate the mine. Upon initial cessation of dewatering, groundwater was the primary source of water flooding the pit lake. Beginning in 2020 and continuing until late 2022, the mine site's dewatering infrastructure was repurposed to pump water from the Attawapiskat River to the open pit. The rapid pit-filling pumping system was turned off after pit lake levels exceeded the anticipated final steady-state level. Filling the pit lake above its final level was intended to assist in aquifer recovery.

Approximately 28,000,000 m^3 of freshwater from the Attawapiskat River and 1,400,000 m^3 of freshwater from an onsite pond were pumped to the pit lake during flooding. Based on site sampling data, the average concentrations of TDS and chloride in the river water were 121 mg/L and 10.5 mg/L, respectively. The temperature of the pumped water would vary seasonally; however, given that most of the water was pumped during the summer, it is anticipated that the pumped water was largely representative of warmer months.

Based on a stage storage curve for the pit lake developed by De Beers, the stabilized pit lake contains approximately 36,982,000 m^3 of water. A total of 29,400,000 m^3 of freshwater was added to the pit, representing 79.5% of the lake's total volume if all the water remained in the pit lake.A comparison of pit lake levels with the stage storage relationship and recorded pumping rates indicates that net inward groundwater gradients were maintained during flooding until May 2021 (Piteau 2025). At that time, the pit lake elevation reached 46.5 metres above mean sea level (mamsl). After this point, pit lake pumping exceeded groundwater inflows, leading to a net loss of water from the lake to the aquifers. Data reported by Piteau (2025) indicate that the net contribution of water from the pit lake to the aquifer from May 2021 to March 2023 was 11,418,000 m^3. By that time, the pit lake level had stabilized. This net contribution represents 39% of the water added to the pit lake and highlights how the pumping system contributed to recovery of groundwater levels in surrounding aquifers.

The final pit lake elevation in 2025 is approximately 78.3 mamsl, varying from 78.0 at the end of winter to 78.4 in the spring. The pit lake is approximately circular, with a radius of between 330 and 460 m. It has a surface area of approximately 545,000 m2 and is close to 280 m deep. There is no surface water outlet for the pit lake.

Post-2023, under stable lake elevation conditions, the annual water balance for the pit lake can be calculated using the following equation and estimates:

$$P + SWin + GWin = E + SWout + GWout \pm \Delta S$$

For this equation, precipitation (P) is calculated to be 294,700 m^3/year, surface water inflow (SWin) is 605,000 m^3/year (pro-rated by area from flow data from nearby Tributary 5a), evaporation (E) is 252,280 m^3/year, surface water outflow (SWout) is zero (no outlet), and ΔS is zero (stable annual water level). These values result in net non-groundwater inputs of 647,400 m^3/year. Groundwater inflow (GWin) was estimated by Itasca (2019) in its groundwater model of post-closure conditions to be 169,700 m^3/year for the entire pit lake. This gives a total inflow in excess of evaporation of 817,000 m^3/year, which, given the lack of a surface water outlet, must be equal to groundwater outflow. Given that the volume of the lake at 78.0 mamsl is 36,818,000 m^3, the time required to flush one lake volume by the above inflows is 45 years.

Pit Lake Water and Groundwater Quality Profiles

Pit lake water quality profiles from 2020 and 2024, together with groundwater quality profiles, are compared to illustrate similarities between groundwater and pit lake water chemistry and their relationship to aquifer horizons (Fig. 3). The two pit lake profiles converge below -110 mamsl, indicating that the deepest part of the pit lake has been stable since 2020, and the 2020 pit lake profile is interpreted as representative of current water quality below this elevation.

From the surface down, the pit lake profiles reveal that the upper portion of the water column to approximately -10 mamsl contains water with much lower TDS and

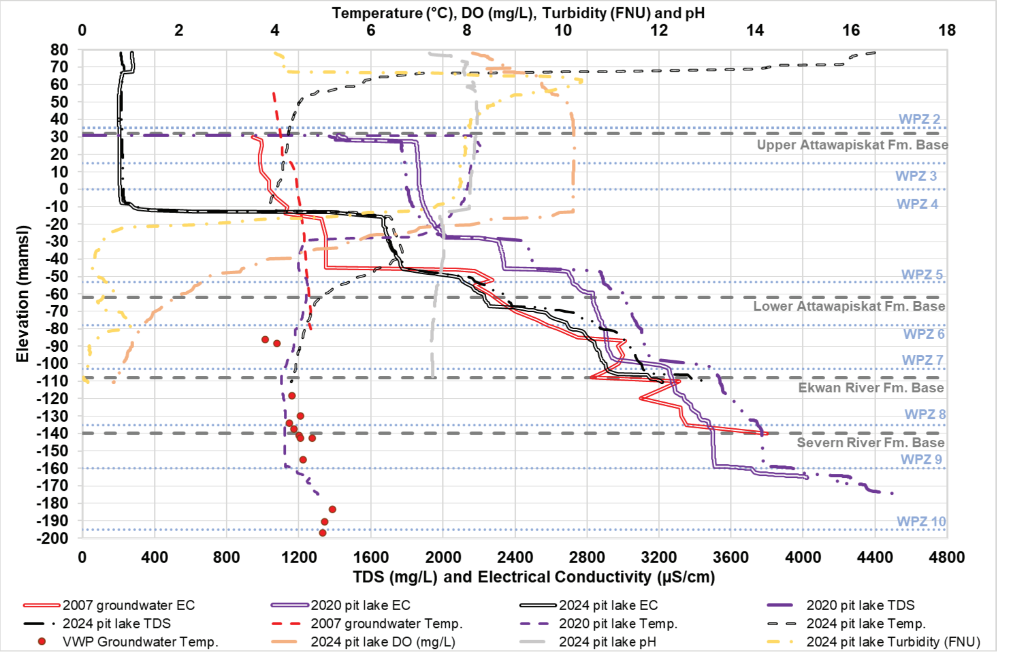


Figure 3 *2020 and 2024 pit lake and pre-pit lake flooding groundwater quality profiles.*

higher DO, turbidity, and pH than the deeper portions. The change at -10 mamsl is interpreted to separate an upper ≈90 m thick interval of freshwater from a lower ≈190 m thick interval of groundwater-influenced water.

The TDS and other profiles below -10 mamsl also show stepwise changes in water quality coincident with aquifers (water-producing zones, WPZ) in the pit walls. Moreover, below -45 mamsl, the 2024 pit lake electrical conductivity and groundwater profiles match (Fig. 3). These observations suggest that there is a lens of water between -10 and -45 mamsl that is influenced by the aquifers, overlying deep pit lake water that closely matches that of the adjacent aquifers.

The temperature profiles indicate that, other than a lens between -10 and -60 mamsl, the groundwater and 2024 pit lake temperature profiles are similar (Fig. 3). Between -10 and -60 mamsl, pit lake temperatures exceed those of groundwater by up to two degrees Celsius. The upper contact of this interval is sharp and coincident with the lower boundary of the freshwater interval. The lower contact is gradual, with the middle of the transition close to -45 mamsl, coincident with the boundary between the groundwater-influenced and groundwater-matching zones described above. This warm lens of pit lake water likely retains heat from when freshwater was pumped into the open pit. This lens appears to have decreased considerably in volume and cooled between 2020 and 2024, indicating that this portion of the pit lake is evolving.

Pit Lake Water and Groundwater Quality Sampling

Pit lake water samples were collected from depths between five and 130 m below lake level. This largely precluded sample collection from the deepest part of the pit lake. The results indicate pit lake chemistry is dominated by chloride, calcium, sulfate, sodium, potassium, and magnesium. Relative to groundwater data obtained at comparable depths prior to dewatering, primarily from shallow formations, the concentrations in pit lake samples are lower than the mean values of groundwater results, yet they remain within the overall range of measured concentrations.

Pre Mine-Closure Pit Lake Modelling

Itasca (formerly HCI) maintained a numerical groundwater model for the mine that was updated over the years of operation, with the final update developed prior to closure in 2019 (Itasca 2019). For the long term, the model predicted the creation of a meromictic lake. Meromictic indices for the entire 280 m deep lake and the upper 35 m of the lake were 691 and 25, respectively. These values indicate that the lake profile would be largely stable, with the possibility of turnover in the upper 35 m. Most of the stability in the full-lake profile was attributed to the higher salinity at depth.

The model did not include a scenario that is directly comparable to the current state of the pit lake, but the observed pit lake salinity at depth is higher than in the model-predicted profile, indicating that the pit lake will have equal or greater stability than predicted by the model. The model also did not include the bedding-plane aquifers, instead incorporating their flow contributions into thicker rock packages with a similar overall transmissivity. As a result, the model predicts a relatively smooth salinity profile without the stepwise changes in pit lake water quality associated with the discrete water-producing features.

Discussion

The pit lake water quality profile is still evolving following the addition of large quantities of surface water. However, the timing of the freshwater addition later in the flooding process appears to have contributed to pit lake stability. By then, the deeper 236 m portion of the pit lake was already filled with higher-TDS groundwater. As a result, the pit lake profile mimics the general pattern of water quality seen in the surrounding aquifers, with more saline water at depth.

The water quality profiles show stepwise changes coincident with the elevations of discrete bedding-plane aquifers of differing groundwater quality in the pit walls. The near-coincident occurrence of pit lake water quality changes with the aquifers suggests that, where groundwater inflow and outflow occur at similar elevations, measurable stratification of the pit lake can result. At the VDM, this effect is most noticeable in the deeper parts of the pit lake, below the augmented freshwater zone, where pit lake volume is smallest and the differences in groundwater chemistry between aquifers are most significant.

Conclusions

Pit lake water quality profiles from the Victor Diamond Mine record changes in pit lake quality coincident with the elevations of aquifers with groundwater of differing water quality. Thin, flat-lying, bedding-plane aquifers are postulated to contribute to measurable stratification of a pit lake. This requires inflow and outflow of water with distinct quality at the same horizon through a stable pit lake. Such stratification may take time to evolve where large volumes of freshwater are found in a pit lake with relatively small groundwater inflows.

Sedimentary bedrock covers 73% of the Earth's land surface (Goudie 2024). Many open pits are developed through similar flat-lying bedrock aquifers to those found at the Victor Diamond Mine. Inclusion of distinct water-producing intervals may improve predictions made with pit lake models in environments where such features are present and have distinct water chemistry.

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