# Designing Meromictic Pit Lakes as a Mine Closure Mitigation Strategy in Northern Canada

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## ABSTRACT

Deep groundwater stored in the Canadian Arctic Shield is characterized by high salinity that increases by orders of magnitude with depth. Mining in these areas has the potential to upwell saline groundwater into the mine workings. Due to the pristine nature of the downstream receptors in Arctic Canada, treatment of saline water is often required prior to being discharged. Mitigation using conventional salinity treatment plants may not be economically feasible due to the remote nature of the northern Canadian mine sites and the harsh climates in this region. Furthermore, treatment of saline waters requires disposal of concentrated brine, rendering this strategy impractical for several mine sites.

An alternative mitigation strategy is to store saline waters on site and use them to create meromictic conditions in mined out open pits at closure. In this manner, the denser saline water is isolated from mixing with freshwater stored in the mixolimnion. This is the proposed strategy for the De Beers Gahcho Kué diamond mine, located in the Northwest Territories, Canada.

This paper focuses on the mine plan for the Gahcho Kué Project and the approach used to evaluate the likelihood of meromictic conditions developing and remaining stable in a flooded, mined-out, open pit. A discussion of the model results is presented to demonstrate the merits of the closure strategy.

**Keywords:** mine closure, mine water quality, pit lakes, meromixis

## INTRODUCTION

Currently, there are three existing diamond mining operations (Diavik, Ekati, and Snap Lake) in the Northwest Territories (NWT), in Northern Canada. The Gahcho Kué mine is under construction, and others are being contemplated. Mining diamonds in the NWT can pose several challenges. The region is dominated by lakes, which can make access to the kimberlite pipes difficult and in the case of mines using open pit methods, often whole lakes, or a portion of a lake needs to be dewatered to facilitate access to the mine workings.

Open pit mining can also induce large volumes of groundwater that need to be managed during operations. Untreated discharge of these flows is not always feasible for the following reasons:

- Groundwater salinity in the Canadian Shield is known to increase by orders of magnitude with depth (Fritz and Frape, 1982);
- The remoteness, harsh weather conditions, and lack of roads during the open water season render all construction activities much more expensive than elsewhere;
- The mines are often located in regions of continuous permafrost limiting the amount of fresh lake water available to recharge the groundwater table during periods of draw down, promoting upwelling of deep seated saline groundwater and rapid increases in mine water salinity;
- Lakes in northern Canada are pristine with very low concentrations of total dissolved solids (TDS) (i.e. <20 milligrams per litre [mg/L]) with aquatic biota that are sensitive to changes in salinity; and,
- Conventional treatment of salinity is through reverse osmosis and disposal options of the treated brine are limited due to the remote nature of the mine sites.

Diamonds will be mined from three open pits at the Gahcho Kué Project (the Project), which will require the partial dewatering of Kennady Lake to access the mine workings. Water quality modelling (De Beers, 2012, Vandenberg et al. (in review)), indicates that mine-related activities at the Project is expected to increase salinity in mine site water during operations. To mitigate the discharge of saline water, De Beers Canada Inc. (De Beers) has developed a zero site water discharge water management plan after year three of operations (EBA 2013). At closure, saline water stored on site will be pumped to the bottom of a mined-out open pit and capped with natural local catchment runoff and supplemental freshwater from a nearby lake (Lake N11), promoting the development of meromictic conditions that will minimize the mixing of saline water with the overlying lake.

To demonstrate the feasibility of the proposed water management strategy to regulators and stakeholders, a numerical model was developed to evaluate the likelihood of meromixis occurring in the pit lake during post-closure. This paper presents the model development and results to illustrate the merits of this approach.

## PROJECT DESCRIPTION

The Project is located approximately 280 kilometres (km) northeast of Yellowknife, NWT, Canada (Figure 1). Diamondiferous kimberlite will be mined from three open pits (5034, Hearne and Tuzo), located below Kennady Lake (Figure 2). Mining of the three open pits will take place over an

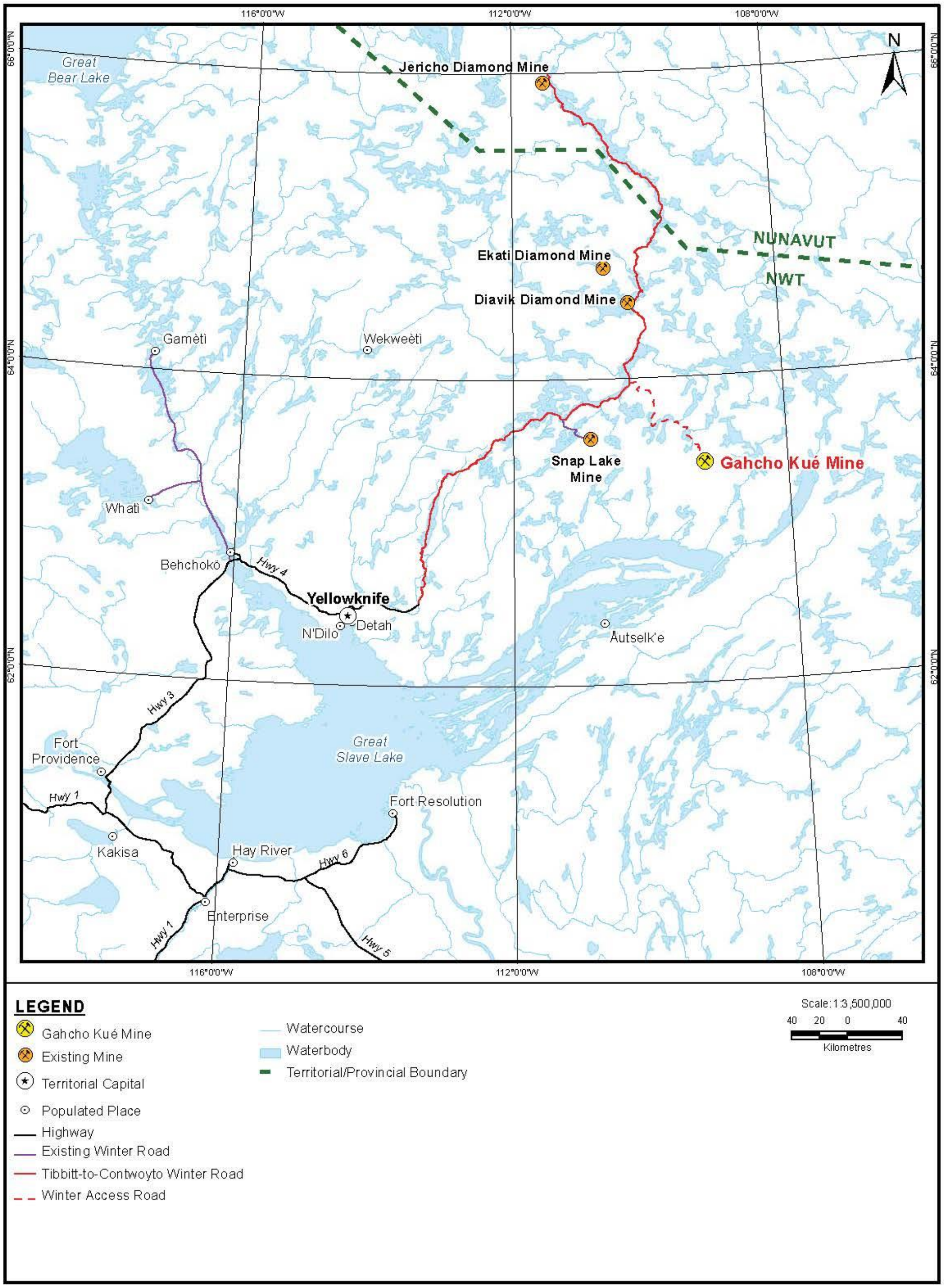


**Figure 1** Location of the Gahcho Kué Project

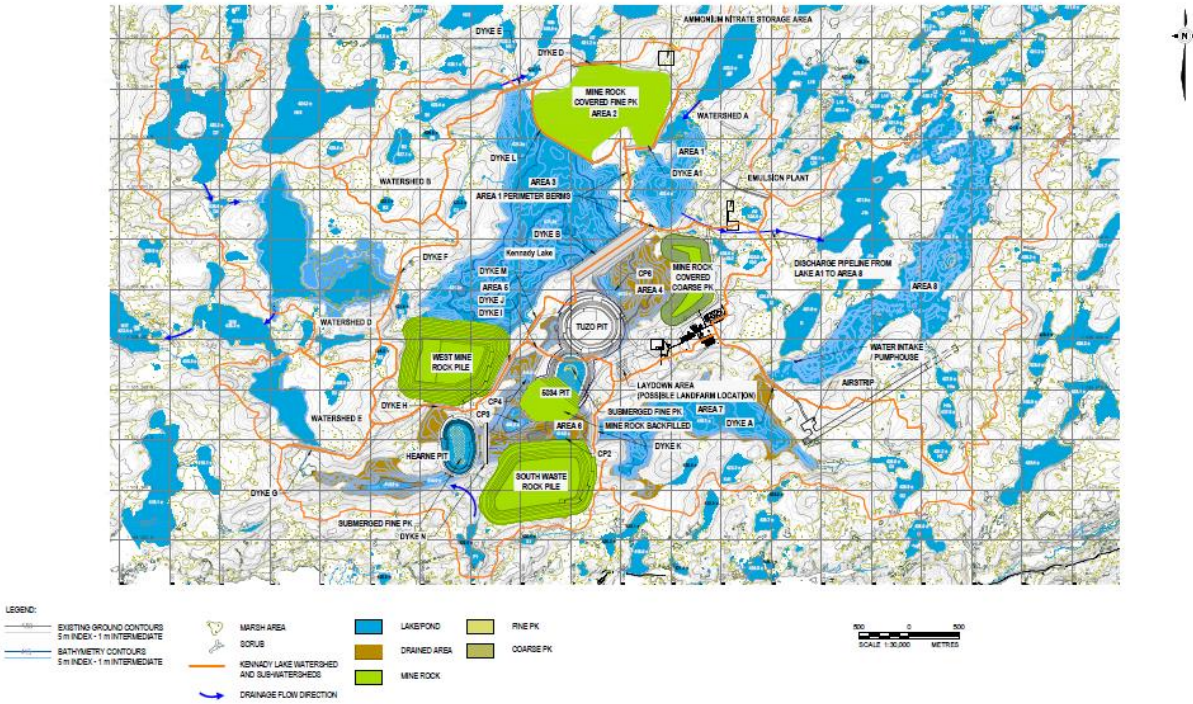


**Figure 2** Gahcho Kué Mine Site Facilities

operational period of 11 years and produce 33.4 million tonnes [Mt] of ore, 300 Mt of mine rock, 10 Mt of fine processed kimberlite [PK] and 23.4 Mt of coarse PK (EBA 2013). The mine plan for the Project has been designed to minimize the surface disturbance and to facilitate progressive reclamation of mine site facilities during operations. The 5034 and Hearne pits will be mined first. During this period, fine PK will be stored in the Fine PK Containment (PKC) Facility in Area 2 and mine rock will be stored in the West and South Mine Rock Piles (Figure 2). Following the cessation of mining in the 5034 and Hearne pits, they will be used to store mine rock and fine PK, respectively, as well as process water and other mine site flows (e.g. pit groundwater inflows and natural runoff). Reclamation of the Fine PKC and mine rock piles will begin at this stage of the mine life. Mining of the Tuzo Pit will commence in Year 4 of operations. At completion it will remain an open void space.

The kimberlite pipes extend from near the bottom of the lake to approximately 300 metres (m) below the lake. To access the open pits, Kennady Lake will be segregated into six water management areas (2 to 7) separated by permeable and impermeable dykes. Area 2 is designated for deposition of fine PK. Areas 3 and 5 (referred to as Area 3/5) will be partially dewatered and converted into a water management pond (WMP) to settle solids in site discharges and to store process water during operations, open pit groundwater inflows, and natural catchment runoff from within the site area. All other areas (4, 6 and 7) will be fully dewatered to allow access to the mine workings.

The natural elevation of Kennady Lake is 420.7 metres above sea level [masl] with a total capacity of approximately 35 million cubic metres [$Mm^3$], in Areas 2 to 7 (EBA 2013). During the first year of dewatering, approximately 1 $Mm^3$ of water will be pumped from Area 7 to Area 8, a lake located downstream of the mining disturbance (Figure 2). Subsequently, water stored in Area 7 will be pumped to Area 3/5 since it is expected that, at this point, total suspended sediment (TSS) concentrations will be elevated and preclude discharge from this area.

To maximize the operational storage capacity of the WMP, approximately 22 $Mm^3$ of water will be pumped from Area 3/5 to Lake N11 (located to the north of the Project) during the dewatering period, lowering the elevation of Kennady Lake to 418 masl. During the first three years of operations, 3.5 $Mm^3$ of water will be pumped annually from Area 3/5 to Lake N11. A total volume of 33.5 $Mm^3$of water will be discharged from the Project during dewatering and operations. Open pit groundwater inflows, process water, and natural catchment flows will be stored in the WMP and mined out open pits after the third year of operations.

At closure, the elevations in Area 3/5, Area 6 and Area 7 will be 422, 421.3, and 420.5 masl, respectively. The water level in these areas will be lowered to 417 masl and all the water stored above this elevation will be siphoned to the mined out Tuzo pit. Following the water transfer to the Tuzo pit, the available water storage capacity in the Tuzo pit and the overlying Kennady Lake will be filled primarily with natural catchment runoff and water pumped from Lake N11, a nearby lake in the adjacent watershed. Some residual groundwater flows will continue to report to the mined out Tuzo pit. Conceptually, this approach will promote the development of meromictic conditions in Kennady Lake, permanently isolating the high density saline water in the Tuzo pit (the monimolimnion) from interacting with the overlying low density water stored in Kennady Lake (mixolimnion). The phenomenon of meromictic conditions being established in pit lakes has been observed at several mines (Boehrer and Schultze, 2006).

Once Kennady Lake has re-established the natural lake elevation of 420.7 masl, and the water quality in the lake is of a suitable water quality and meets closure objectives, the lake will be reconnected to the downstream watershed. Water balance modelling (EBA 2013), indicates approximately eight years will be required to refill Kennady lake during the closure period of the Project.

## METHODOLOGY

A site mass-balance water quality model was developed in GoldSim (GoldSim 2010) to assess the expected discharge concentrations during operations (from Area 3/5) and the average water quality in Kennady Lake following refilling. This model calculated the site water quality on a monthly basis using inputs from hydrology (EBA 2013, De Beers 2012), hydrogeology (De Beers 2012) and geochemistry (De Beers 2012). Details of the site water quality model are provided in De Beers (2012) and Vandenberg et al. (in press). As GoldSim does not have the inherent ability to simulate the hydrodynamic properties of water bodies, the stability of stratification in the Tuzo Pit was analyzed using two methods:

- hydrodynamic modelling of the first 100 years after refilling, using CE-QUAL-W2 (Cole and Wells 2008); and
- mass balance calculations over 15,000 years using a vertical slice spreadsheet model.

The spatial extent of the hydrodynamic model was Kennady Lake and Tuzo Pit. A model grid was developed based on GIS shapefiles of these connected water bodies. The grid was optimized to account for the full fetch of the lake with higher resolution near the pit.

**CE-QUAL-W2 Model**

The CE-QUAL-W2 (W2) model was used to compute TDS, temperature and density in Tuzo Pit. Near-surface layers were spaced at 1 m intervals, and deeper layers were spaced at 3 m intervals. The model also requires meteorological forcing data to drive currents and thermal behaviour in the lake. Meteorological data were obtained from weather stations at the nearby De Beers Snap Lake Mine and the Yellowknife, NWT Airport. Data were selected preferentially from the Snap Lake station because this station is closer to the Project, and data gaps were filled in using data from Yellowknife Airport. The required meteorological data were air temperature, dew point, wind speed and direction, and solar radiation.

In the W2 model, initial concentrations in the pit lake were determined by concentrations in Kennady Lake at closure, as simulated in the site mass balance water quality model. The 23 $Mm^3$ of water in the bottom of the pit was set equal to the concentration in the water storage areas Kennady Lake (e.g., the WMP) prior to refilling, because this volume will be drawn from the surface to fill the pit until Kennady Lake is lowered to 417 masl. 1.2 $Mm^3$ of groundwater is predicted to flow into the pit during the refilling period, so this was added as well, at time-varying constituent concentrations predicted by the hydrogeological model (De Beers 2012; Vandenberg et. al. in review). The upper portion of the lake was assumed to have a TDS concentration that was equal to the refilled Kennady Lake.

It is recognized that these layers will not form a sharp boundary due to turbulence caused by refilling and other factors. Therefore, the gradient was assumed to span a vertical transition depth of 40 m, and concentrations were calculated for the upper and lower portions respecting the mass of TDS in both layers and within the gradient.

It is not known exactly when the pit will be filled in terms of months of the year. Therefore, an average temperature of Kennady Lake was calculated based on samples that were skewed toward available site-specific, open-water sampling data. The resulting average temperature (5 degrees Celsius [ºC]) is anticipated to be reasonable, because refilling activities are also expected to be most intense during open water periods. The uniform temperature of 5ºC was used to initialize the pit lake water column. The temperature profile could be manipulated to increase the stability in the pit, but that manipulation was not examined as part of this modelling to conservatively assess pit lake stability.

Once the model was initialized, it was run for 100 years to predict the change in elevation of the pycnocline (i.e., the layer within the refilled pit where the density, or TDS gradient is greatest), and therefore the volume of water that will essentially be isolated from Kennady Lake. Groundwater discharge from the hydrogeological model was input to the hydrodynamic model at several vertical points according to time-varying volumes and constituent concentrations throughout the modelled time frame, and natural inflows to Kennady Lake were also included.

**Vertical Slice Spreadsheet Model**

To estimate the long-term stability of Tuzo Pit, long-term TDS profiles were calculated using a vertical slice spreadsheet model. A spreadsheet model was used because it was not feasible to run a hydrodynamic model for this length of time due to the computational limitations. The vertical slice spreadsheet model incorporated long-term inflows that were predicted by the hydrogeological model (De Beers 2012; Vandenberg et al. in review) to simulate TDS profiles over 15,000 years at 25 m vertical intervals in Tuzo Pit. This simplified approach is intended to evaluate directional changes to TDS concentrations at depth over the very long-term and does not consider all processes influencing pit lake stability (e.g. climate change, diffusivity).

The main inputs used in the mass balance calculation were initial conditions in Tuzo Pit, which were the same as those used for the W2 model, and long-term groundwater inflows and outflows. Groundwater inflow volumes and constituent concentrations and outflow volumes were predicted for the first 1,000 years after Tuzo Pit is filled. After 1,000 years, the inflows were assumed to continue at constant volumes and concentrations.

To complete the calculations, inflow volumes and concentrations were directed to the appropriate 25 m interval within the pit. Within each interval, a mass-balance calculation was performed, and excess water (difference between inflow and outflow) was directed upwards to the next segment. The vertical slice spreadsheet model generated annual time series at 25 m intervals over a 15,000 year timeframe.

## RESULTS AND DISCUSSION

The results of the W2 model are presented in Figure 3. The W2 model results indicate meromixis will occur in the Tuzo pit following refilling of Kennady Lake and remain permanently stratified; however, the model also indicates there will be some interaction between the monimolimnion and the mixolimnion during the 100-year model period (Figure 3). During the 100-year modelling period, the transition zone increases, reflecting an upward transfer of mass from the monimolimnion into the mixolimnion. This vertical movement is predicted to occur relatively rapidly after refilling, and gradually thereafter.

Concentrations of TDS decrease in the mixolimnion from approximately 170 mg/L to 60 mg/L (Figure 3). The gradual replacement of Kennady Lake waters with natural runoff will continue to reduce the TDS of the overlying water, thereby strengthening the stratification by increasing the density difference between the surface and deep water zones. A small influx of groundwater to the pits predicted by the groundwater modelling is not projected to increase TDS at depth over the modelled 100-year time frame and concentrations remained stable at approximately 915 mg/L.

The vertical slice mass-balance model projected a rising and strengthening stratification in Tuzo Pit in the long term (Figure 4). Although the hydrodynamic simulation indicated very little change in TDS in the monimolimnion in the first hundred years, the mass-balance slice model indicated that groundwater inflows would begin to change TDS at depth in the first thousand years. After 15,000 years, the model predicted that the monimolimnion would increase in TDS and expand upwards due to the slight net inflow (Figure 4). The deeper pit water will eventually, over the very long-term, take on the characteristics of the surrounding deep, high TDS groundwater.

While the general trend of increased TDS and upward expansion of the pycnocline is likely reliable, this model may over-predict the extent to which these phenomena may occur. The model did not account for upward diffusion due to a concentration gradient, and it extrapolated groundwater inflows beyond the timeframe modelled by hydrogeological modelling. Nevertheless, it may be concluded with some confidence from this modelling, that stratification in Tuzo pit, and hence its meromictic state, will strengthen with time.

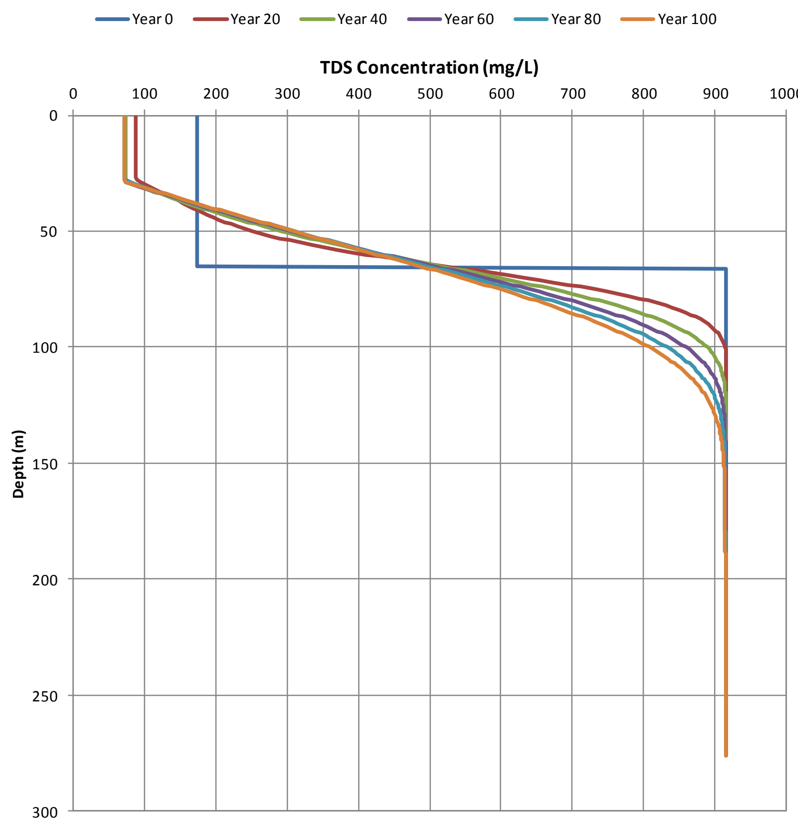


**Figure 3** Hydrodynamic Model Results

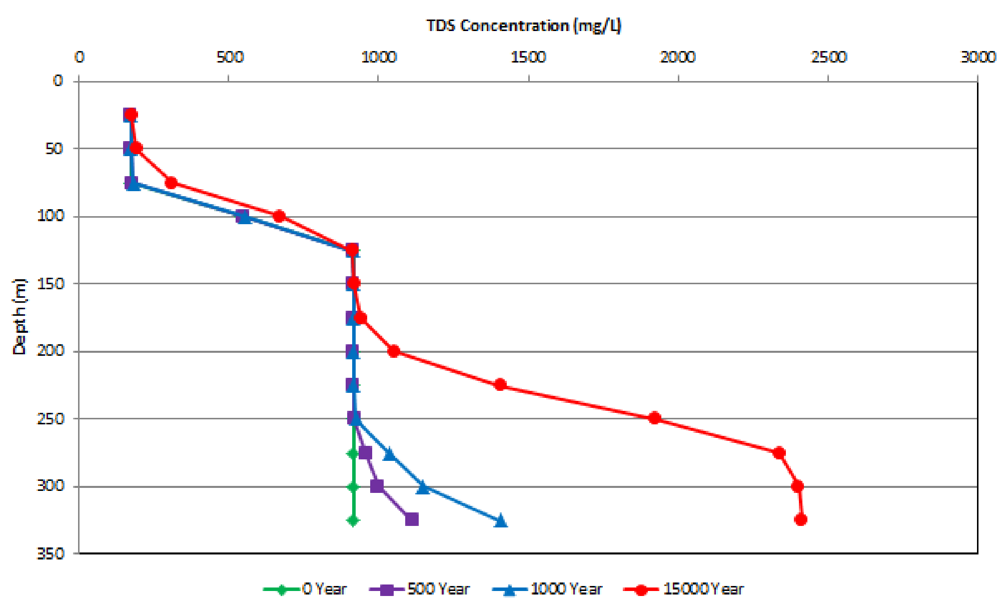


**Figure 4** Vertical Slice Mass Balance Model Results

## CONCLUSION

De Beers proposes to mine diamonds from three open pits (5034, Hearne, and Tuzo) at the Gahcho Kué Project. The mine waste and water management plan developed for the Project (EBA 2013), maximizes the use of mined out facilities for storage of mine waste and mine water to minimize the amount of discharge required from the Project during operations. In this manner, De Beers will only be required to discharge for the first three years of operations and water originating from natural runoff, groundwater inflows, or process water during the remaining years of operation can be stored on site.

Simulated water quality conditions in water storage facilities at the site, including the WMP and mined out Hearne pit during operations, indicate that TDS concentrations will increase (De Beers 2012; Vandenberg et al., in review). A pit lake hydrodynamic water quality model demonstrated that the transfer of the high TDS water stored in these areas during operations to the bottom of the Tuzo pit at closure will produce a density difference and meromictic conditions will be established following refilling, permanently isolating the high TDS water from interacting with the overlying freshwater stored in Kennady Lake after approximately 100 years (Figure 3). The vertical slice spreadsheet model indicates that as groundwater inflows increase TDS concentrations at depth in the long-term (i.e. >1000 years) in Tuzo pit, the continual replacement of Kennady Lake water with natural runoff and direct precipitation, lowers the concentrations near the surface, increasing the density difference and stratification stability of the pit lake (Figure 4).

In general, for mine sites where it can be demonstrated that density differences can be established and maintained over the long term, storage of mine waters in pit lakes is a viable option for permanent disposal of these solutions. This paper focused on the salinity (e.g. TDS) of the mine water to be produced at the Project; however, the Project water management strategy has the indirect benefit of managing elevated concentrations of other constituents of concern. For example, use of ammonium nitrate fuel oil (ANFO) can lead to elevated nitrogen concentrations in mine waters during operations. If it can be reasonably demonstrated that density differences can be used to segregate operational mine waters at closure, other constituents with elevated concentrations during operations can also be mitigated through being permanently stored in the pit lake monimolimnion.

It is recognized that the purpose of modelling is not to produce predictions of forecasts of future conditions, but rather to provide an estimate of the direction and magnitude of impacts from proposed mining operations, and to provide projections that are suitable for the assessment of effects. Therefore, mining projects that are relying on the use of pit lakes to mitigate the potential for effects of mine waters originating during operations to the surrounding environment (i.e., downstream waters), it is of utmost importance that the water quality model is periodically evaluated and updated in the context of field-based water quality monitoring during operations and closure to allow for calibration to existing conditions and to more accurately project future conditions. Furthermore, it is necessary to have alternate mitigation strategies available in the instance that the future performance of the modelled system does not behave as projected.

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