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TECHNICAL ARTICLE

Multiple Modeling Approach for the Aquatic Effects Assessment of a Proposed Northern Diamond Mine Development

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Abstract Eight water models were used to assess potential aquatic environmental effects of the proposed Gahcho Kué diamond mine on groundwater and surface water flow and quality in the Northwest Territories, Canada. This sequence of models was required to cover different spatial and temporal domains, as well as specific physico-chemical processes that could not be simulated by a single model. Where their domains overlapped, the models were interlinked. Feedback mechanisms amongst models were addressed through iterative simulations of linked models. The models were used to test and refine mitigation plans, and in the development of aquatic component monitoring programs. Key findings generated by each model are presented here as testable hypotheses that can be evaluated after the mine is operational. This paper therefore offers a record of assumptions and predictions that can be used as a basis for post-validation.

Keywords Sub-arctic · GoldSim · MODFLOW · CE-QUAL-W2 · GEMSS · CORMIX · Northwest territories

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Introduction

Many complex processes, interactions, and potential effects must be evaluated in predicting the impact of large mining projects on the aquatic environment. This is particularly true in Arctic Canada, where the region is dominated by aquatic features, such that a more accurate term for this landscape might be "waterscape" (Fig. 1). Potential aquatic effects include changes to levels, flow, and chemistry of both surface- and ground-water systems, which can manifest themselves as effects on aquatic and terrestrial biota. All potentially significant adverse environmental effects must be considered as individual components with specific assessment endpoints, within a holistic framework that accounts for interactions amongst each component.

Aquatic modelling was undertaken for the De Beers Gahcho Kué environmental impact statement (EIS). This project presented a unique set of challenges from a modelling perspective owing to: (1) the dynamic nature of the mine plan and water management plan; (2) the dominance of aquatic features in the region; (3) the different water characteristics between the groundwater and surface waters that will be mixed during operations; and (4) the sensitivity of the pristine waters that will be affected by mining operations. These challenges required an unusually large number of models to interact together, with each model operating within a sub-domain of the overall spatial–temporal domain of the project.

While the EIS findings withstood a thorough review by stakeholders and regulators, the true test of accuracy of predictions can only be conducted once operational data have been generated. Several authors have highlighted the need to publish EIS findings in the peer-reviewed literature and to revisit those findings in a post-audit. For example,

Fig. 1 Photograph of Kennady Lake and environs looking northwest over Exploration Camp, 2007 (photo courtesy of De Beers Canada Inc.)

Dubé et al. (2013) point to a failure to conduct post-audits as a general shortcoming in the EIS process; regulators and local stakeholders have requested additional monitoring and follow up studies to enhance transparency (DFO 2012; LKDFN 2012; YKDFN 2012); Castendyk et al. (2009) noted the paucity of publicly available predictions of pit lake hydrodynamics and chemistry; and Kuipers et al. (2006) highlighted the need to conduct post-audits on EIS predictions. With these considerations in mind, we present herein the key findings from the aquatic assessment. The key findings are re-stated as testable hypotheses that can be verified after the mine has entered construction and early operational phases. Verifying key findings through post-audit monitoring will confirm the accuracy of assumptions and predictions as well as the adequacy of the mitigation.

Project Description

The proposed project is a diamond mine located at Kennady Lake, approximately 280 km northeast of Yellowknife, Northwest Territories, Canada (Figs. 2, 3). The diamond-bearing kimberlite deposits contain an indicated resource of about 30 million tonnes (t), which are hosted in three vertical pipes named 5034, Hearne, and Tuzo. The kimberlite pipes are predominantly located beneath Kennady Lake and extend from near the bottom of the lake down to more than 300 m below the lake. Diamondiferous kimberlite will be extracted by open-pit-mining methods.

The project mine plan was designed with the objectives of minimizing discharges to the environment and limiting the extent of surface disturbance. These objectives will be achieved by isolating and dewatering Kennady Lake, sequenced mining of three open pits, and using the isolated lake for most of the operational water and waste management purposes. Mined-out open pits will be used as repositories to store mine materials or water as mining advances in the other pits.

During construction, a series of dykes will be established to isolate a large portion of Kennady Lake from the rest of the watershed, so that upstream sub-watershed flows can be diverted away from the project area to an adjacent watershed. The isolated area of the Kennady Lake watershed bound by the dykes is referred to as the controlled area (Fig. 4). Diverting water away from the controlled area will change the hydrological regime of the small upper watersheds of Kennady Lake and the adjacent and downstream watersheds. The only outflow from the controlled area will be short, licensed discharges early in the mine operation during dewatering; these will be managed and monitored.

Water stored in the controlled area is predicted to be suitable for discharge during initial dewatering. Monitoring in the controlled area and in nearby lakes indicates that

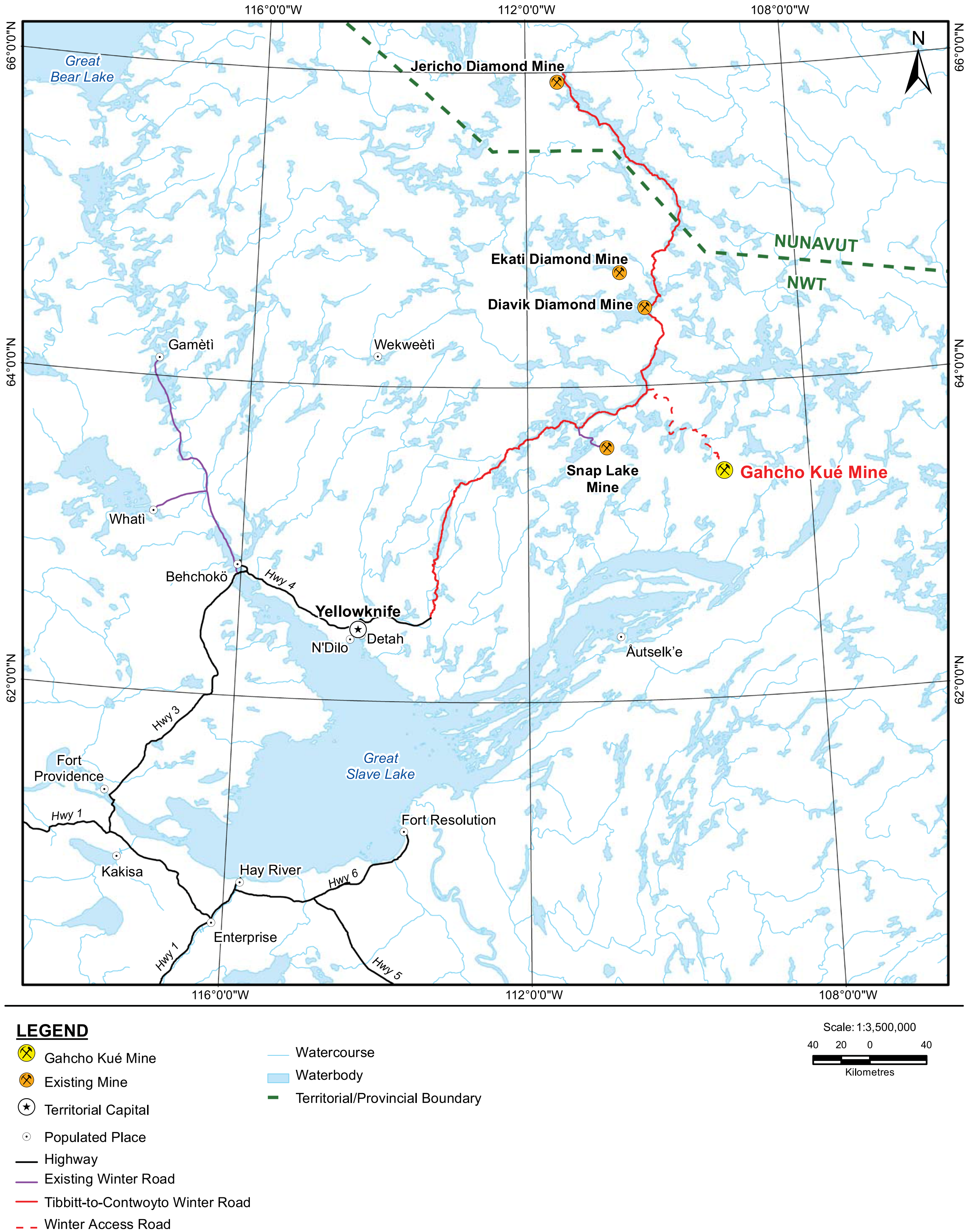

Fig. 2 General location of the Gahcho Kué project, Northwest Territories (De Beers 2012)

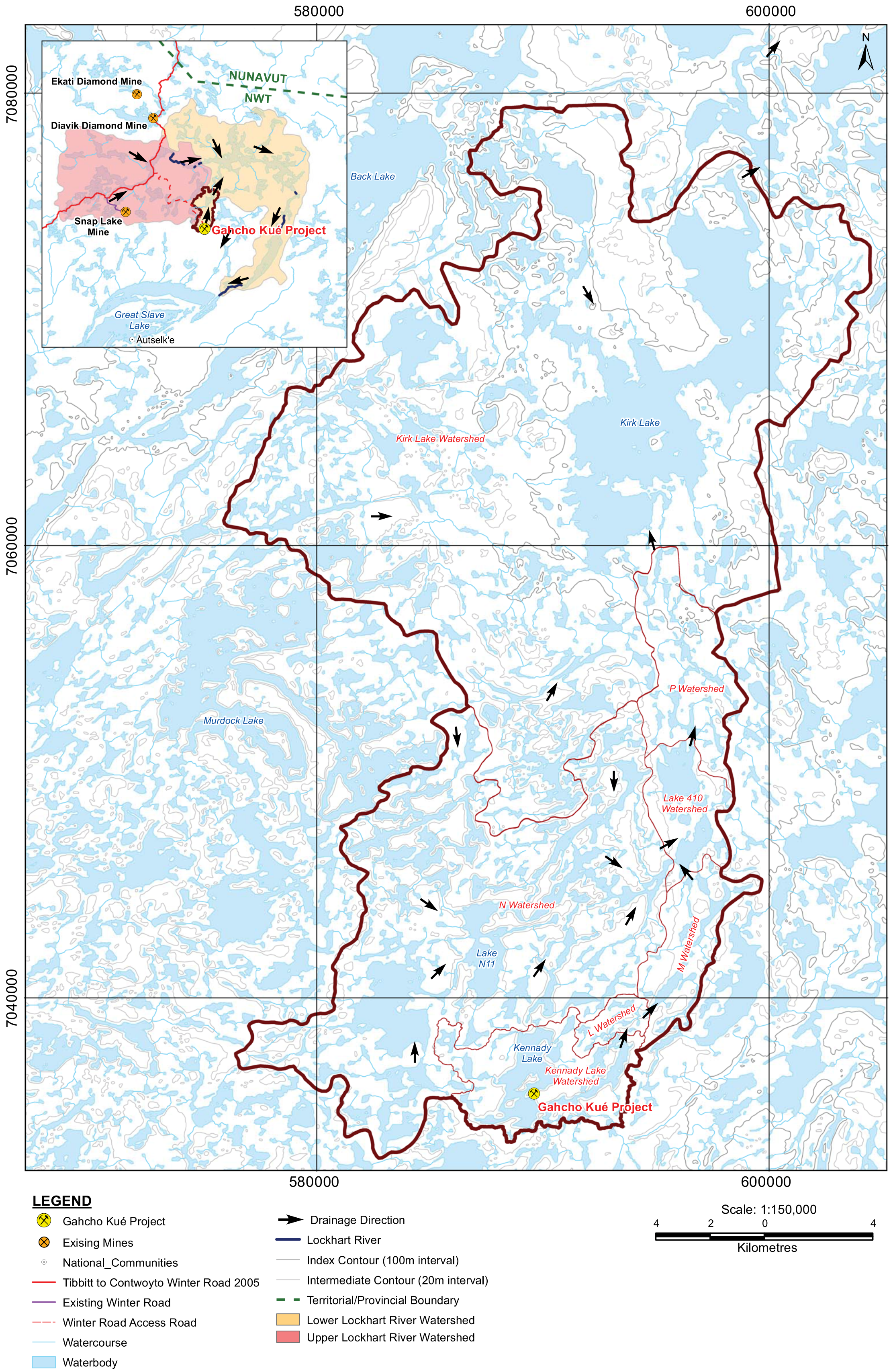

Fig. 3 Regional and local Watersheds near the Gahcho Kué Project

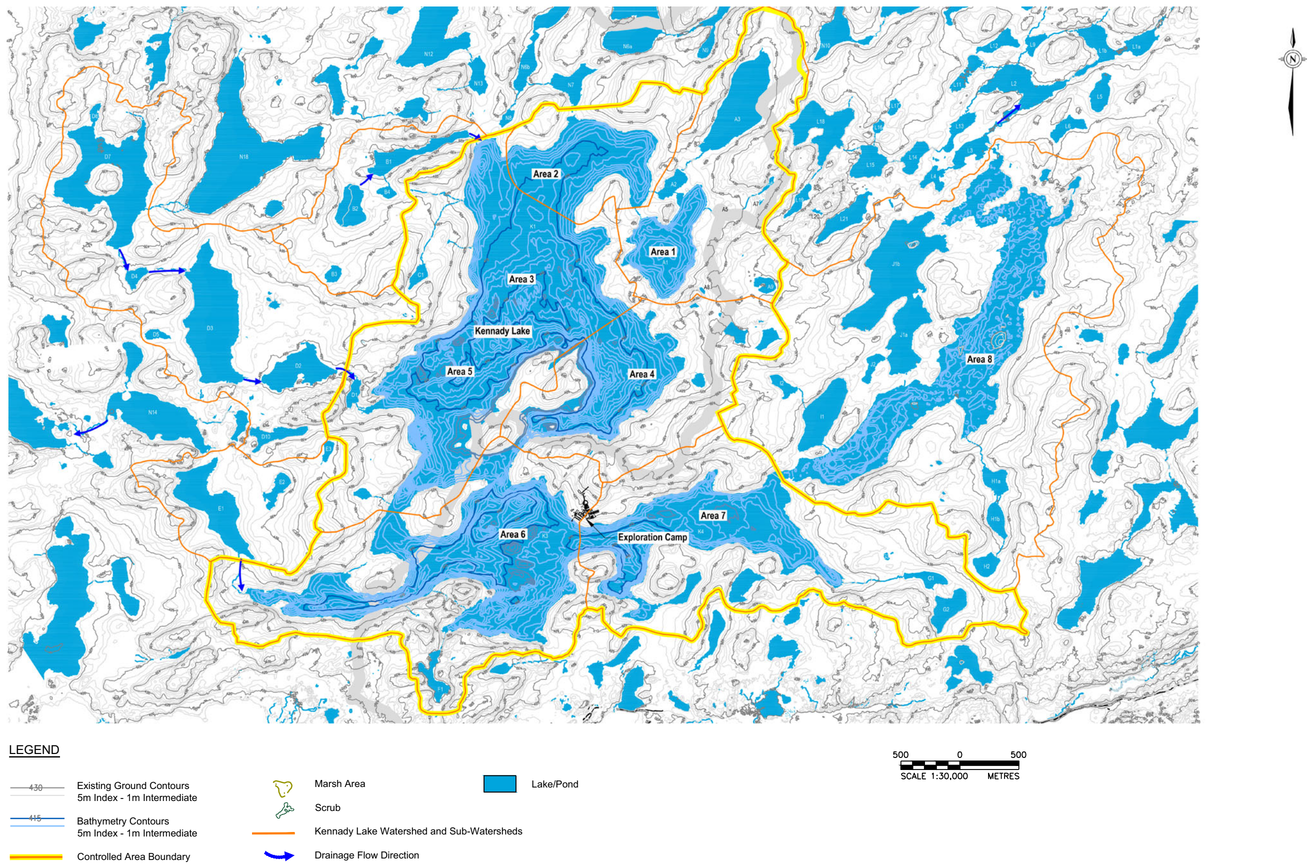

Fig. 4 Kennady Lake water management basins, with the boundary of the controlled area identified (De Beers 2012)

these lakes share similar water quality (De Beers 2012). Total suspended solids (TSS) are expected to increase during the dewatering period, which will be controlled by flocculants to maintain concentrations below licensed limits. Similarly, concentrations of other parameters such as total dissolved solids (TDS) are projected to increase during this operational discharge period, but to remain below risk-based water quality limits in downstream receptors (De Beers 2012).

All major disturbance activities for the project will be contained within the controlled area boundary. During the mine construction phase dewatering activities, Kennady Lake will be segmented into various basins for mining and water management. The southern basins will be dewatered to the maximum extent possible to provide safe access to the open pits, whereas the northern basin (areas 1–5) will be drawn down and transitioned into a water management pond (WMP) that will store mine water, i.e. saline groundwater, process water, and other mine contact waters (Fig. 5).

Mining of diamondiferous kimberlite will produce mine rock, and fine and coarse processed kimberlite (PK). Mine rock will be stored in the controlled area of Kennady Lake and on nearby land in the west and south mine rock piles (Fig. 5). Fine PK will be stored on land and sub-aqueously in the fine PK containment (PKC) facility in the north-eastern region of the controlled area, and in the mined-out 5034 and Hearne pits when they become available (Fig. 5). A portion of the coarse PK will be stored on land just north of the plant site in the on-land carse PK pile (Fig. 5). The remaining portion of the coarse PK will be placed with mine rock and used for progressive reclamation of the fine PKC facility. During operations and into closure, runoff and seepage from these facilities will be managed within the controlled area and transferred to the WMP. After mining, these areas will be re-integrated into the receiving environment.

At closure, the 5034 Pit will be backfilled with fine PK and mine rock, the Hearne Pit will be partially backfilled with fine PK and then flooded to form a pit lake, while the Tuzo Pit will remain open and entirely filled with water to form a pit lake. The lower portions of the two pit lakes will be filled with water from the WMP, as well as from other water storage areas within the controlled area, and will have elevated concentrations of TDS and other constituents. The upper portion of the pit lakes and Kennady Lake will then be refilled with supplemental inflows of fresh water pumped from Lake N11, located north of the

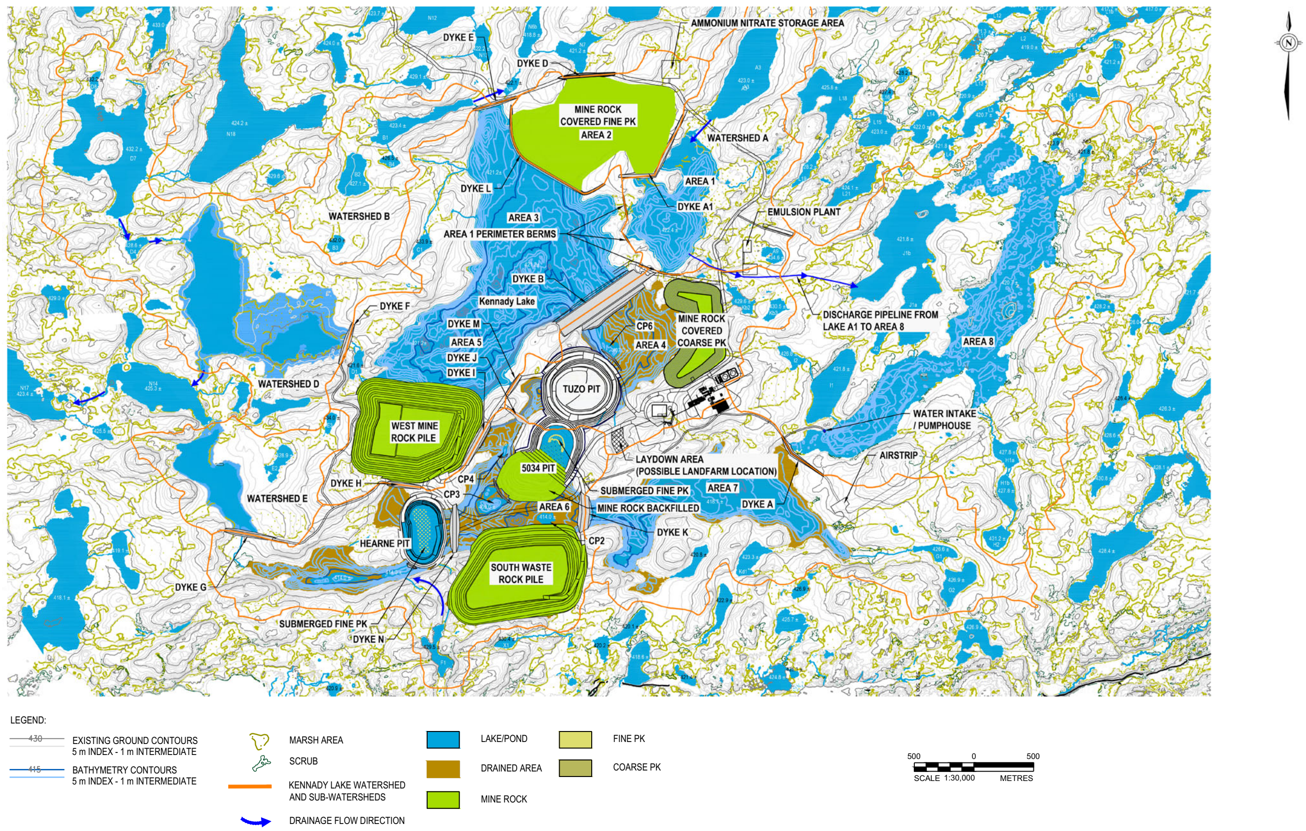

Fig. 5 Gahcho Kué Mine site facilities layout, operations year 8 (De Beers 2012)

controlled area. Once Kennady Lake has re-established its original level and water quality in the refilled lake meets closure objectives, it will be reconnected to the downstream watersheds, and pre-development flow paths will be re-established.

Study Area

The study area is located in the watershed of Kennady Lake, a small headwater lake within the Lockhart River watershed (Figs. 2, 3). Kennady Lake discharges to the north, via a series of small lakes, into Kirk Lake and then into Aylmer Lake. Aylmer Lake is located on the main stem of the Lockhart River about midway along its length. The Lockhart River system drains into the north-eastern arm of Great Slave Lake.

The region is dominated by a series of interconnected lakes set in low-lying tundra. The lakes are naturally developed in granite in the Canadian Shield, which are largely non-erodible and non-soluble, and thus the water quality of the waters draining this geologic formation are virtually pristine (i.e. typical TDS of about 10 mg/L, with many constituents below standard detection levels).

Permafrost in the study area extends to a depth of 300 m below grade, which is a typical permafrost thickness under similar climate conditions (Brown 1970). In areas of continuous permafrost, there are generally two groundwater flow regimes; a deep groundwater flow regime beneath permafrost and a shallow groundwater flow regime in the active, seasonally thawed layer near the ground surface. Because of the thick, low permeability permafrost, there is generally little to no hydraulic connection between the two flow regimes. However, taliks (unfrozen ground surrounded by permafrost) exist beneath lakes that are deep enough to prevent freezing to the bottom during the winter. Taliks beneath larger lakes can extend down to the deep groundwater, acting as a conduit between the shallow and deeper groundwater regimes. Consequently, recharge to the deep groundwater flow regime is predominantly limited to areas beneath large water bodies. Groundwater beneath the permafrost is also influenced by density differences due to upward diffusion of deep-seated brines. In the study area and the wider region, the salinity of groundwater increases with depth, such that groundwater at the ultimate depth of the open pits, 305 m below grade, ranges from 1000 to 10,000 mg/L TDS (Frape and Fritz 1987).

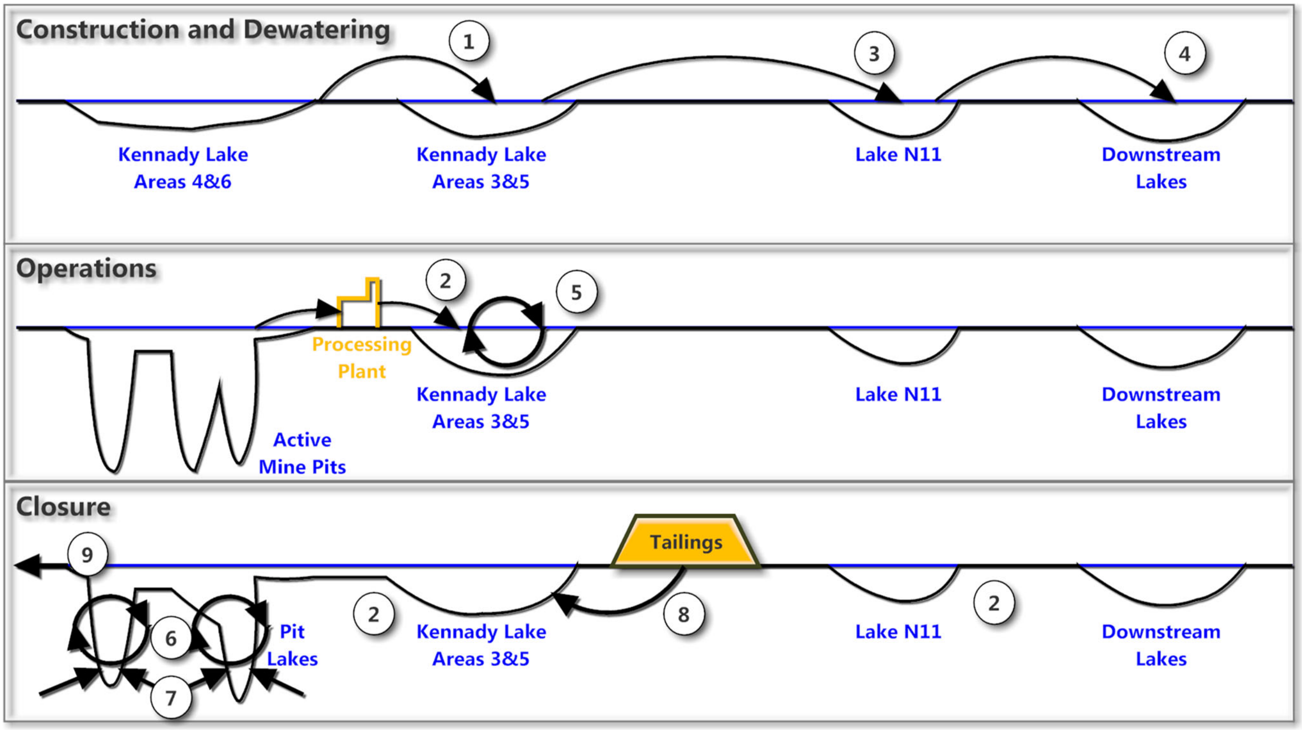

Fig. 6 Conceptual model of potential project effects on the aquatic environment of Kennady Lake and the downstream receiving environment; figure shows conceptual cross section of lakes during stages of project (not to scale)

Methods and Results

An overview of the conceptual assessment model is provided below, along with a brief description of the numerical models used to address each potential effect. Detailed descriptions of each model are provided in subsequent sections. Numbered processes described in this section are illustrated conceptually in Fig. 6. This conceptual diagram outlines the potential effects to the aquatic environment as a result of various project activities during each project phase. These are shown by arrows with circled numbers: (1) increased salinity of surface waters due to dewatering of saline groundwater; (2) change in water quality due to input of mine waters during operations and closure; (3) near-field change in water quality due to dewatering of Kennady Lake; (4) changes in downstream flows due to dewatering of Kennady Lake; (5) TSS in water management pond during dewatering; (6) vertical mixing in mine pit lakes with deep disposal of process water; (7) saline water intrusion to pit lakes over several millennia; (8) nutrient and dissolved oxygen concentrations in Kennady Lake due to nutrient loadings from tailings, and; (9) reconnection to downstream watersheds.

Conceptual Model and Numerical Models

Eight models were applied to assess effects to groundwater and surface water flows and quality:

1. *Groundwater model* two hydrogeologic numerical models, MODFLOW/MT3DMS (McDonald and Harbaugh 1988; Zheng and Wang 1998) and FEFLOW (Diersch 2010) were used to predict the quantity and quality of groundwater inflows to the three open pits over the life of the mine, and the groundwater flow regime during closure.
2. *Geochemical and water quality model* a GoldSim (Goldsim Technology Group 2010) model was used to predict surface water quality resulting from saline groundwater discharges and geochemical loadings from mine materials during operations and closure in Kennady Lake and in downstream lakes.
3. *Near-field dispersion model* a CORMIX model (Doneker and Jirka 2007) was used to evaluate water quality in Lake N11 resulting from licensed discharges from the controlled area.
4. *Hydrologic model* a GoldSim model was applied to predict flows in the downstream receiving environment.

5. *Suspended sediment model* a sediment transport model was developed using a combination of fundamental wave and sediment resuspension equations (Sheng and Lick 1979; U.S. Army Corps of Engineers 1984) along with the hydrodynamic component of the three-dimensional GEMSS model (Buchak and Edinger 1984) to determine TSS concentrations in the WMP during operations.
6. *Hydrodynamic model* a CE-QUAL-W2 (Cole and Wells 2008) model was developed for the refilled Hearne and Tuzo pits in Kennady Lake to determine the amount of water and associated constituent load that would circulate upwards and re-enter the surface water system at closure.
7. *Vertical slice model* A spreadsheet model was developed to predict long-term salinity in the refilled pits (up to 15,000 years after closure), based on groundwater inflows to the pits predicted by the groundwater model.
8. *Nutrient and dissolved oxygen* (*DO*) *model* a three-dimensional model was developed in GEMSS to evaluate nutrient and DO concentrations in Kennady Lake.

Groundwater Model

During the development of the open pits, the pits will be dewatered to safely access and mine the ore bodies. While much of the groundwater will be re-used for ore processing, all of it will eventually be discharged or integrated into the surface water system.

Hydrogeologic numerical models were developed to predict the quality and quantity of groundwater inflows to the three open pits over the life of the mine and during closure. The site-wide hydrogeologic numerical model applied to mining and closure scenarios was developed using MODFLOW/MT3DMS codes. Predicted groundwater inflows from this model were used as inputs to the GoldSim model to estimate water quality in Kennady Lake.

Post-closure changes in the groundwater flow regime once the pit lakes and Kennady Lake are completely refilled were simulated using a separate, local-scale, hydrogeologic numerical model developed to support the evaluation of water quality in pit lakes. Predicted groundwater inflows from this model were used as inputs to the hydrodynamic model.

Separate models were required to represent groundwater flow during operations and post-closure because, during operations, hydraulic gradients induced by the mine overwhelm density-driven flow, while at post-closure, hydraulic gradients will be weak or absent, and groundwater flow will be dominated by density–driven flow. The FEFLOW modelling code was selected to represent local-scale hydrogeologic conditions during post-closure, as this code is capable of simulating density-driven flow with complex boundary conditions.

Hydrostratigraphy

Field investigations have identified bedrock units with hydraulic characteristics as follows: shallow exfoliated bedrock, kimberlite, a contact zone of enhanced permeability between kimberlite and the surrounding bedrock, competent bedrock, and potential enhanced permeability zones (De Beers 2012). Consistent with other sites in the region (Stober and Bucher 2007), results of hydrogeologic testing indicate that the hydraulic conductivity of all of these units decreases with depth. Air photos, gravity, and aeromagnetic data indicate that three enhanced permeability zones of potential importance for governing pit inflow quantity and quality may be present. Enhanced permeability zones are associated with structural features with greater permeability than the surrounding rock due to greater fracturing or larger fracture apertures. However, results of single-well response testing across these potential enhanced permeability zones have been inconclusive. Because these zones can be composed of sparsely spaced, highly-permeable discontinuities within a lower-permeability matrix, these zones have been difficult to identify by hydraulic testing alone. At other mines in the Canadian Shield, the locations and hydraulic significance of these zones has only been revealed during mining (Bieber et al. 2006). Therefore, these zones of enhanced permeability were included in the groundwater model to maintain the conservative approach adopted for the assessment. Permafrost was assumed to be virtually impermeable, and no flow boundaries were assigned along the edges of permafrost. Specified head boundaries were assigned along the bottoms of lakes that were thought to overlie open taliks.

The predominant flow direction in the deep groundwater flow regime is to the southeast. Kennady Lake is a groundwater recharge zone, with water discharging from the lake to several lower-elevation lakes with open taliks to the north, south, and east. Two large, higher elevation lakes with open taliks are located to the west of Kennady Lake; however, these lakes are predicted to discharge to lakes to the north and south. Therefore, the groundwater flow divide is interpreted to be west of Kennady Lake.

Groundwater Quality Data

In the region beneath continuous permafrost, groundwater mineralization in the Canadian Shield is expected to follow the relationship developed by Fritz and Frape (1987), which shows increasing TDS with depth. Measured TDS values for groundwater samples collected at the project site (within the talik zones and below the permafrost) together with three other profiles developed from samples collected from deep groundwater at other Canadian Shield sites (De Beers 2002; Kuchling et al. 2000) are presented in Supplemental Figure 1. (All supplemental files can be downloaded, along with the on-line version of this paper, for free, by all subscribers and IMWA members).

The groundwater quality in the area of the mines has considerable variability for samples collected at similar depths. The variability between groundwater samples may be due to local variations in the vertical and horizontal components of the convective flux due to variations in the hydraulic and density gradients and hydraulic conductivity. In addition, local variations in the diffusive flux from the deep-seated saline groundwater may be present due to variations in the relative interconnection of pore space in the rock mass. The project TDS vs. depth profile assumed in the groundwater model was based on a best fit to the TDS of groundwater samples at the site to the maximum depth of groundwater sampling of 450 m; below this depth, the profile was assumed to follow the Frape and Fritz (1987) profile.

Feedback Loop with Geochemical and Water Quality Model

During mining, the open pits will act as groundwater sinks; seepage faces are anticipated on the pit walls. Water will be induced to flow through the bedrock and through enhanced permeability zones towards the open pits. Water reporting to the open pits will originate from nearby lakes and from deep bedrock. The overall quality of mine inflow will be a mixture of surface water flowing from the WMP and brackish water flowing from deep bedrock. Groundwater inflows to the open pits will be pumped back to the WMP, which will increase concentrations of constituents in the WMP. Therefore, a positive feedback mechanism will be established, whereby concentrations in both the WMP and mine inflows will "cycle up" over time. The feedback loop between the WMP and the three pits was represented in the models by estimating the amount of lake water that enters each of the three pits over time. The contribution to the water quality of pit inflows originating from the WMP was then accounted for within the geochemical and water quality model, which applied chemistry to the mine inflow rates predicted by the groundwater model.

Groundwater Model Results

Predicted hydrogeologic conditions when the 5034 Pit reaches its ultimate depth are presented in Supplemental Figure 2. Predicted mine inflow rates to each of the open pits are presented in Table 1. At 300 m below grade, the elevation of the bottom of the permafrost, the drawdown resulting from mining in the 5034 pit is predicted to extend up to 3.5 km from the mines in the surrounding bedrock. Mining in the open pits also results in the upward migration of high-TDS groundwater from deep bedrock. Groundwater inflows to the open pits are predicted to range up to approximately 4200 m^3/d in mining year 6, when all three pits are being mined. Approximately 45 % of groundwater inflow to the pits is predicted to originate from the WMP at this time (Supplemental Table 1). These flow rates and TDS concentrations represent key findings that can be tested in post-audit monitoring.

After the Tuzo Pit floods and the large hydraulic head gradients around the mines dissipates, conditions that create the near-hydrostatic fluid pressures that characterize the pre-mining groundwater regime will be re-established. These conditions permit the development of a density-driven groundwater flow system near the mine workings, due to the high-TDS groundwater that will have upwelled during mining. The magnitude of flow rates and predicted mass fluxes were evaluated using the post-closure groundwater model. Results indicate that groundwater flows to the Tuzo Pit will decrease from 3 to 0.5 m^3/d in the first 100 years post-closure.

Geochemical and Water Quality Model

The geochemical and water quality model was the central model in evaluating effects to the aquatic environment. Each of the other seven models had some interaction with this model; some fed into this model as inputs, some used outputs from this model for their inputs, and some did both, which required iterative modelling to convergence. The geochemical and water quality model is a GoldSim flow and mass-balance model that was developed to account for chemical loadings and processes that were anticipated to affect water quality in Kennady Lake and in downstream lakes.

Model Setup

The spatial domain includes the controlled area of Kennady Lake and downstream lakes for a distance of approximately 20 km. Within the controlled area, each basin was treated as a distinct reservoir in the model. Downstream lakes were also set up as individual reservoirs. Within each reservoir, volumes and concentrations were calculated on a monthly time step for 200 years after the start of construction. The model simulated 59 water quality constituents, including TDS, major ions, nutrients, and total and dissolved metals. Inflow volumes and concentrations were included as inputs to each reservoir to account for loadings from natural areas, disturbed areas, mine rock runoff, fine and coarse PK contact runoff, and groundwater discharge. The model assumed complete mixing within each basin at each time-step while the dykes are operational. At closure, when the dykes will be breached, the model reported fully mixed conditions in Kennady Lake. Water that will be isolated under a pycnocline within the pits was not included in the calculation of fully-mixed lake conditions (see "Hydrodynamic Model" section). No chemical reactions or sinks were assumed to occur, except where a proportion of water was sequestered in mine rock pore space. Processes, such as TSS resuspension and DO dynamics, were simulated using separate models, as described later.

Baseline Input Data

Background data were collected by a number of different consultants as part of 16 different studies that were conducted in the study area between 1996 and 2011. Full details of these studies, as well as tables of compiled data, are provided in De Beers (2012). Because the systems being modelled are lake-dominated, and therefore less prone to fluctuations, mean concentrations were used to represent baseline conditions. The following screening process was used to develop a probability distribution and long-term mean for each constituent:

- Step 1 remove outliers from the measured data using three statistical outlier tests (Beckman and Cook 1983; Hampel 1985; Pearson 2001)
- Step 2 fit suitable probability distributions to the remaining data (normal, lognormal, delta-lognormal, constant or uniform);
- Step 3 assess the goodness of fit for all applicable distributions to determine the most appropriate distribution type (Sokal and Rohlf 1981; Stedinger et al. 1993);
- Step 4 generate a long-term time series according to the chosen distribution, and;
- Step 5 calculate the mean from the time series

Mine Water Geochemical Data

Mine rock and PK will be produced while mining the three kimberlite pipes. Approximately 95 % of the mine rock is expected to be granite; geochemical testing indicated that 4 % of the granitic mine rock will be potentially acid generating (PAG). Mine rock will be placed in mine rock piles and in the mined-out pits as they become available during operations, and used as cover materials at closure for the fine and coarse PK on-land storage facilities. Saturated and unsaturated mine rock and fine and coarse PK are expected to exhibit different weathering rates, and individual source terms for leachate quality were developed for these materials and incorporated into the model. PAG material will be isolated and encapsulated within the mine rock piles and located below the water table, and within the mined-out pits to mitigate any potential for acidic leachate.

Water coming into contact with mine waste materials placed above ground was assigned individual water quality source terms to account for differences occurring between freshet during the month of June and the remaining months. Geochemical tests such as saturated column and humidity cell tests were completed on mine rock and fine and coarse PK. Based on these tests, separate water quality profiles were derived for granite, granodiorite, altered granodiorite, diorite, diabase mine rocks, and kimberlite material. To derive inputs for each type of material, a 75th percentile was calculated from each cell to represent the first-flush (first 5 weeks of testing) and steady-state (last 5 weeks of testing) water qualities. Saturated materials are less susceptible to seasonal flushing and were assigned the 75th percentile concentrations observed in saturated column tests.

The humidity cell procedure (ASTM 2007) is designed to provide empirical weathering rates under controlled conditions. Readily soluble salts in sample charges are generally flushed from the sample in the first 5 weeks of humidity cell testing, based on concentrations in the lixiviant, and this period was selected to provide a reasonable analogue of drainage concentrations resulting from flushing of accumulated winter weathering products during freshet. The last 5 weeks were considered to be a reasonable analogue for steady-state since individual humidity cell and column tests continued for periods up to 207 weeks, and, due to the low propensity of the materials to become acid generating, it can be assumed with some confidence that steady-state concentrations were achieved. The 75th percentile was selected because it yielded slightly conservative estimates while omitting anomalous values from the dataset. A comparison of the waste rock model input concentrations to the drainage from an analogous facility at the Ekati Diamond Mine (Golder 2014) indicated that the model input concentrations were greater than what has been observed under ambient conditions. Therefore, the 75th percentile first-flush and steady-state input water qualities were deemed to provide reasonably conservative inputs.

During operation, water from the open pits will be pumped to the WMP. The quality of this water will be altered by groundwater inflow, pit wall runoff, and blasting residue. Groundwater inflow was predicted by the MODFLOW groundwater model and were input directly to the geochemical and water quality model. Major ions and metals that exhibited concentration increases with depth were correlated to groundwater TDS; 75th percentile concentrations were applied to other groundwater constituents. Pit wall runoff quality was derived as per the mine rock materials described above, using the proportions of lithologies that are expected to be encountered during mining.

The open pits will be mined using ANFO and emulsion explosives in a ratio of approximately 70 % ANFO: 30 % emulsion. Blasting residue was accounted for by adding a load of nitrate, ammonium, and sodium (from emulsion) based on the total life-of-mine explosives tonnages using a modification of the Ferguson and Leask (1988) approach. Ferguson and Leask (1988) indicated that waste rates of ANFO and emulsion are approximately 0.1 and 5.1 %, respectively, when greater than 20 % slurry explosives are used. For the Gahcho Kué Project, a waste rate of 2.5 % was used for both ANFO and emulsion explosives. Since ANFO accounts for approximately 70 % of the explosives to be used, this approach assumes approximately 1.5 times more explosives will be wasted compared to the Ferguson and Leask (1988) approach and therefore provides a conservative estimate of the nitrogen load originating from blasting activities.

The total mass of explosives was assumed to be released linearly over the mine life. Water reporting to active open pits is expected to mobilize most of the explosives residues, and the total mass of explosives released during each month was added to the WMP. This is a conservative assumption since these waters will be reclaimed to the process plant, and some of the nutrient species will be locked up in water entrained in fine PK stored in the fine PKC facility or in the mined-out open pits.

Process water that will report to the WMP through active discharge and passive seepage was added to the model based on processing volumes in the mine plan. Treated sewage effluent that will be discharged with process materials to the WMP was added to the model based on observed water quality of the treated sewage effluent at the nearby Snap Lake mine.

The principal source of aerially-deposited material to Kennady Lake during operations is expected to be fugitive dust from fleet and milling activities. Because this dust will be composed of finely-ground rock, it is anticipated that most will settle out during the nine-year closure period while Kennady Lake is being refilled. The settling of dust was modelled using the CE-QUAL-W2 hydrodynamic model, which predicted that less than 1 mg/L of solids would remain in suspension after any given ice-cover period. Therefore, 1 mg/L of particulate matter and associated constituents were added to the water column. The dust was not allowed to further settle in the geochemical and water quality model; it was advectively transported into the pits during pit refilling and to downstream lakes after lake refilling. The solid geochemical composition of kimberlite was selected to represent the concentration of aerially-deposited particulate matter in Kennady Lake.

During the closure period, water will be pumped to the open pits, some of which may re-circulate back to the surface. The iterative modelling used to represent this circulation is described in the "Hydrodynamic Model" section.

Geochemical testing (De Beers 2010, 2012) indicated that saturated fine PK would be a source of phosphorus loading to Kennady Lake, and this source would not be depleted within the timeframe considered in the model. As such, phosphorus concentrations were predicted to increase in Kennady Lake during the operations and remain elevated in post-closure periods. Since the GoldSim model assumed all parameters behave conservatively, more detailed eutrophication modelling was undertaken to address the fate and transport of phosphorus, as described in the "Nutrient and Dissolved Oxygen Model" section.

Model Results

Concentrations were output monthly for the 59 water quality constituents over the life of mine and 100 years after mine closure in Kennady Lake and in downstream lakes. Concentrations of TDS and major ions in the main areas of Kennady Lake were projected to increase during operations due to the management of water within the controlled area (e.g. runoff, groundwater inflows, process water) and decrease during the closure phase when the lake is refilled (Supplemental Figure 3A). Concentrations of TDS and major ions in downstream lakes were predicted to increase after the primary dyke is breached at closure; downstream concentrations were expected to peak within 5 years of dyke removal, as water is replaced with water from the refilled Kennady Lake (Supplemental Figure 3B). Over time, concentrations of TDS and major ions were generally predicted to decline, but for some constituents, mainly those associated with the storage facility inputs, concentrations were predicted to increase during the post-closure period and reach a steady-state concentration within a few decades. TDS and all major ions were predicted to remain above background conditions, but below levels that would affect aquatic health. Details of the aquatic health assessment are provided in De Beers (2012).

Nutrient levels were predicted to increase in Kennady Lake during operations, with nitrogen projected to decrease during the closure phase as nitrogen residue in the stored mine waste becomes depleted. By the time the primary dyke is removed, modelled nitrate and ammonia concentrations were expected to be below Canadian Council of Ministers of the Environment (CCME) water quality guidelines and decline thereafter to near background levels.

In downstream lakes, all forms of nitrogen were expected to peak in concentration within 5 years of breaching the dyke, then return to near-background concentrations.

Of the 23 modelled trace metals, two patterns were predicted in the main areas of Kennady Lake over operations and closure:

1. Eleven of the 23 metals are projected to increase in concentration during the operations phase, and then decline in concentration as the lake is flushed during post-closure.
2. The remaining 12 metals are projected to increase during operations, decrease during closure, and reach a steady-state condition soon after closure that continues through post-closure. Of these metals, only copper is expected to be slightly higher than CCME water quality guidelines in post-closure. However, copper was measured as being above guidelines in baseline conditions.

Concentrations of all modelled constituents were assessed for potential effects on aquatic health, which concluded that changes in concentrations of all substances considered in this assessment would result in negligible residual effects to aquatic life in Kennady Lake and in downstream lakes. Notwithstanding this conclusion, the water quality model indicated which constituents are likely to increase during mining and into closure. These predictions are presently being used to derive water quality objectives and to design environmental monitoring programs for Kennady Lake and downstream lakes to verify that predictions were accurate and that significant adverse environmental effects to aquatic life do not occur. These predictions are focused on mining year 3, which is the last year of active discharge, when the highest concentrations will be discharged from the WMP to the receiving environment. Like all model predictions, there is uncertainty due to the inputs and assumptions applied; however, given that conservative assumptions were applied, the predictions are thought to err on the high side. Thus, the testable key findings of the geochemical and water quality model are that by mining year 3, the WMP will not exceed the following concentrations: 300 mg/L TDS; 8.4 mg/L NO_3; 150 mg/L chloride; 0.13 mg/L fluoride; 1 μg/L chromium; and 0.1 μg/L silver. All other water quality constituents are predicted to remain below guidelines during this period.

Near-field Dispersion Model

During construction and the early stages of operation, water will be discharged from the WMP to nearby Lake N11 (Fig. 3). The WMP will be drawn down initially to increase storage capacity, and discharge will continue as long as TSS and other constituent concentrations remain low enough to meet regulatory discharge criteria, so they do not result in adverse effects in Lake N11. To estimate plume characteristics, dilution efficiency of the discharges, constituent concentrations in Lake N11, and to derive site-specific water quality objectives for that lake during the discharge period, near-field mixing was modelled using CORMIX.

Two diffuser configurations were considered to evaluate mixing zone concentrations: a piped outfall and a submerged diffuser. A number of locations in the lake were evaluated, including a deep point in the southern basin that was selected to minimize infrastructure needs (Supplemental Figure 4). Separate simulations were completed for each outfall design under open-water and ice-cover conditions.

Ambient Water Characteristics

Inputs required by CORMIX to define ambient characteristics include water temperature or density, current velocity, depth, wind speed, and Manning's Coefficient. The effective water depth was estimated using bathymetric data at the proposed outfall and diffuser locations. Meteorological data, including temperature and wind speed, were obtained from the Snap Lake mine, located approximately 80 km northwest of the project site. The modelled temperature time series was extracted from the nutrient and DO model and applied to Lake N11 as ambient temperature. A typical Manning's Coefficient for lakes, a measure of the roughness of a channel, 0.015, was applied to all scenarios.

As discharge is limited to open-water conditions, mixing was simulated for three ambient velocity conditions: (1) velocity calculated from total inflow and cross-sectional area; (2) co-flow with wind-driven currents; and (3) cross-flow with wind-driven currents. Simulations (2) and (3) assumed lake velocity is 2 % of wind velocity. The lowest mixing ratio obtained from the three ambient velocity conditions was carried forward for calculating concentrations.

Pumped Discharge Characteristics

Pumped discharge characteristics required by CORMIX include discharge flow rate, density, and concentration. The discharge temperature was assumed to be the same as ambient temperature since both will be neighboring open surface waters. The discharge concentrations were generated by the geochemical and water quality model. Open-water discharge was assumed to occur each year from June 1st to Nov. 30th in accordance with the water management plan. The minimum ambient TDS concentration and maximum discharge concentration over each simulation period were used so that mixing would not be overestimated.

The mixing ratios predicted by the near-field dispersion model were used in combination with discharge water quality predicted by the geochemical and water quality model to calculate the water chemistry in Lake N11 at the edge of the mixing zone for each modelled scenario. Concentrations for all 59 modelled water quality constituents at the edge of mixing zone were calculated using the following equation:

$$C_{MZ} = \left(C_{Eff} - C_{FM}\right)/D + C_{FM}$$

where C_{MZ} = concentration at the edge of the mixing zone (mg/L); C_{Eff} = effluent concentration (mg/L); C_{FM} = maximum concentration in the fully mixed Lake N11 (mg/L), calculated for each basin; D = mixing ratio at 200 m (dimensionless).

Near-field Mixing Model Results

Mixing ratios were predicted for the edge of the mixing zone, which was assumed to be 200 m from the diffusers, similar to the approved regulatory mixing zone at the Snap Lake mine. The mixing ratio represents the reduction in concentration of discharge water in the lake from its end-of-pipe concentration. Minimum mixing ratios were approximately 32 for the piped outfall and 40 for the submerged diffuser. Under these mixing conditions, site-specific water quality objectives are predicted to be met at the edge of the mixing zone during the discharge period.

A decision on whether to construct a piped or submerged outfall has not yet been made. However, for the purposes of post-validation, the mixing ratios of 32–40 are presented as key findings that can be verified after construction, depending on which configuration is ultimately built.

Hydrologic Model

A GoldSim hydrologic model was developed to estimate surface water flows in the downstream environment. Licensed discharges from the controlled area will be managed such that potential effects on bed and bank erosion and on fish and fish habitat can be minimized.

The design of the hydrologic model was based on the following considerations:

1. Compatibility with the site operational water balance, which was developed and provided by another consultant. The site water balance consisted of monthly flow quantities based on derived median annual (i.e. two year return period) climate input including precipitation and lake surface evaporation, in addition to runoff coefficients to simulate runoff over various catchment areas, and monthly runoff distribution.
2. Compatibility with the geochemical and water quality model, which was subsequently coupled with the hydrologic model; the geochemical and water quality model required a surface water quantity platform extending over the downstream environment to evaluate the assimilation of site drainage.
3. Inclusion of mitigation strategies such as flow regulation to verify that downstream flow criteria would be met. Limitations on daily magnitude of flows at several downstream lake outlets were imposed to minimize potential effects on bed and bank erosion, and on fish and fish habitat.

Based on these considerations, the hydrologic model was developed to extend over the downstream environment, using monthly licensed flow input from the site operational water balance, available daily climate input including mean daily temperature, rainfall, snowfall, evaporation, in addition to lake and land areas of modelled watersheds, runoff coefficients, and lake outlet stage-discharge rating curves.

Median climate data for the site's operational water balance were derived from 46 years of available daily climate data for Lupin Airport and Contwoyto Lake stations from 1960 to 2005 (Environment Canada 2005). Total annual precipitation quantities, corrected for undercatch, were screened to identify a year with total annual precipitation similar to the median annual value used in the operational water balance. A secondary screening was completed by deriving water yields from the hydrologic model at several nodes using each year with similar total annual precipitation to assess monthly runoff proportions. Year 1964 of the available climate dataset had nearly identical total annual precipitation and associated monthly runoff proportions during the freshet period, and was therefore chosen for daily climate input, representative of median climate input used in the site operational water balance. Monthly evaporative losses and licensed flows were distributed uniformly on a daily basis, which was suitable for the water management and impact assessment objectives of the hydrologic model.

Hydrologic Model Results

Limitations set by the flow mitigation were exceeded at certain nodes and required refinement of water management activities from the site operational water balance. This process underwent several iterations until the flow mitigation limitations were no longer exceeded. Once this process was complete, the hydrological model was coupled with the geochemical and water quality model to evaluate the effects of the project on downstream lakes. The key finding of the hydrologic model was that dewatering and diversion plans, with the assumed flow mitigation in place, could be implemented without causing adverse water levels and velocities in downstream lakes and channels. Post-validation will include continuous monitoring of water levels and stream flows in downstream lakes and channels during construction and operations to confirm that these hydrologic variables remain within biological tolerances.

Post-validation will include collection and review of continuous monitoring and spot measurement data of water levels and stream flows in downstream lakes and channels as part of the aquatic effects monitoring program during construction and operations. For example, maximum and mean monthly discharge and water surface elevations of key lakes (e.g. Area 8 and Lake N11) will be compared to baseline and model outputs for the construction/operations case. Critical model components, including snowmelt model coefficients, runoff coefficients, and lake outlet stage-discharge rating curves may undergo additional validation by running the model with measured inputs (e.g. snowpack and rainfall depths, air temperatures) and comparing the resulting continuous hydrographs to those measured concurrently with the input data. Additionally, where discharges are part of the flow diversion routes (i.e. during dewatering or operational discharges), flows and water level measurements in these lakes will be compared to thresholds, i.e. diversions will not cause flows and water levels to exceed baseline 1:2 year flood conditions at the lake outlets.

Suspended Sediment Model

During the construction phase of the project, the WMP will be closed-circuited and fish will be salvaged to the extent practicable. Previous experience at similar mines has shown that water from the upper portion of the lake will meet regulatory requirements for TSS concentrations in the discharge. It is anticipated that more than half the water in Kennady Lake (about 17 Mm^3) can be pumped and discharged to the receiving environment without being treated. Nevertheless, an assessment of TSS in the WMP was required as a supplement to the EIS.

Model Setup

Three linked systems were used to predict TSS concentrations in Kennady Lake after it is drawn down by 3 m from an initial water level of 420.7 meters above sea level (masl) to become the WMP. The first system predicted wave geometry for a single wind storm on the lake by applying classic forecasting equations for waves in shallow water, as presented in U.S. Army Corps of Engineers (1984). Second, the model used equations developed by Sheng and Lick (1979) to predict wave-induced resuspension of bed sediment. Finally, TSS concentrations estimated using these equations were input into the GEMSS hydrodynamic module of the nutrient and DO model to simulate dispersion and settling of TSS.

Calibration could not be completed because most of the baseline data had TSS levels below the detection level of 2 mg/L. Instead, a sensitivity analysis was conducted that consisted of 72 individual model simulations for a 6-hour storm event to assess all combinations of the following conditions:

- water surface elevations of 420.7 and 417.7 masl;
- wind speeds of 6, 8 and 10 m/s;
- wind directions from the southwest and northeast;
- sediment settling velocities of 1.0, 0.10 and 0.01 m/d, and;
- a single storm event during the open-water season and just before the ice-covered season.

Model Results

In general, the mass of sediment resuspended into the water column was predicted to increase as the magnitude of the wind speed increased from 6 to 10 m/s, and TSS concentrations in Kennady Lake were predicted to be greater over time as the settling velocity decreased from 1.0 to 0.01 m/d. The model predicted that a 6-hour duration storm event with wind speeds of 6, 8, and 10 m/s would have little effect on TSS concentrations in Kennady Lake at a water surface elevation of 420.7 masl. TSS concentrations in most areas of the lake were predicted to remain within the observed background TSS range. At a water surface elevation of 417.7 masl, the model results predicted that localized areas of high TSS would occur in shallow areas along the downwind shorelines with maximum concentrations ranging from 35 to 3100 mg/L within 24 h of a storm event (Supplemental Figure 5). Wind-induced mixing would cause elevated levels of TSS throughout most of the basin for longer periods of time. On average, 16 storms with wind speed conditions evaluated in this study occur during the open-water season each year. If multiple storm events are considered, there is potential for greater long-term TSS concentrations in the WMP at the lower water level.

This modelling confirmed anecdotal evidence from similar operations indicating that TSS would be frequently elevated above a generic guideline of 25 mg/L (based on CCME 1999) after the lake was drawn down by 3 m. This finding will be tested in the post-audit monitoring after the lake has been drawn down.

Hydrodynamic Model

During the closure period of the project, water from the WMP, which will have elevated concentrations of constituents due to inputs from mine waters, will be pumped to two of the pits for long-term disposal. While the 5034 Pit will be backfilled with waste rock, Hearne Pit, which will be partially backfilled, and Tuzo Pit, which will remain open void space, will be partially filled with WMP water and capped with fresh water. To determine the amount of water and associated load of constituents that would circulate upwards and re-enter the surface water system, a hydrodynamic model was developed for Kennady Lake and the two down-gradient pit lakes.

Model Setup

The two-dimensional CE-QUAL-W2 model was selected to simulate hydrodynamic behavior in the closure lake and pit lakes to balance geometric representation and model run times. Because Hearne and Tuzo pits have not been constructed, this model could not be calibrated to this system. However, to obtain estimates of hydrodynamic coefficients, a CE-QUAL-W2 model was calibrated to match the vertical profiles of simulated and observed temperature in Kennady Lake under pre-development conditions. Coefficients were also adjusted to produce a reasonable match of ice-cover periods in the range of observations from the region. The calibrated coefficients obtained from the pre-development model were then applied to the closure model.

The model grid was matched to bathymetric data from existing conditions and planned mine pits at 1 m intervals. Segments and branches were aligned such that the fetch of each basin and connecting channels were represented. Meteorological data were obtained from Yellowknife Airport and the Snap Lake mine. Groundwater inflow rates and TDS concentrations were predicted at 1 m intervals by the FEFLOW groundwater model. The flow and loads were summed at five vertical intervals and input to the CE-QUAL-W2 model as vertically-placed tributaries. Surface water inflow rates and TDS concentrations during the filling period and over the next century were extracted from the geochemistry and water quality model.

Model Results

The hydrodynamic model indicated that the elevation of the pycnocline will remain unchanged at the initial elevation for both the Hearne and Tuzo pits, but that the thickness of the transition layer will increase with time (i.e. the elevation of the transition between high- and low-TDS waters will not change appreciably, but the gradient will become less sharp, reflecting a diffusive transfer of mass from the pits to the overlying water). This upward movement is predicted to occur rapidly after refilling, and gradually thereafter. Vertical profiles of TDS concentrations for Tuzo Pit are depicted in Supplemental Figure 6; profiles for Hearne Pit were similar.

Because some transfer of constituents from the monimolimnion to the mixolimnion was predicted, a feedback mechanism was built into the geochemistry and water quality model. To estimate the rates of constituents released from the monimolimnion, a tracer constituent was included in the hydrodynamic model. The initial tracer concentration was set to 1 mg/L in the monimolimnion of both pits and 0 mg/L in the mixolimnion. Based on the simulated vertical profiles of tracer concentrations, the volume of water mixing upwards from the monimolimnion was calculated. The calculated volume and associated mass of constituents were then transferred to the geochemical and water quality model as a time series from each pit into Kennady Lake. This process was completed iteratively to account for the feedback loop, whereby surface concentrations would affect mixing and mixing would in turn affect surface concentrations.

It is likely that the mine closure plan will undergo several refinements in the intervening decades before the key findings of the closure hydrodynamic model can be tested. However, the following findings are presented as worthy of further investigation to advance the practice of mine closure:

- This modelling uncovered an important data gap in pit lake hydrodynamic modelling. Specifically, pit floor temperatures are expected to be warmer than surface temperatures because of the known temperature gradient at depth. If the pits are warm enough, and if they transfer enough heat to the water column, the warmer water could rise, causing instability of the pycnocline. A literature search yielded no insight into how best to represent this process in the model. Thus, a sensitivity analysis was conducted using various sediment temperatures and heat exchange coefficients, and the values that resulted in the largest amount of vertical mixing were adopted for the EIS. In the case of the two pit lakes, the saline groundwater flowing into the pits was predicted to maintain pycnocline stability regardless of water temperature. Nonetheless, heat transfer from pit lake floors is a process that warrants further investigation as it may drive mixing in other pit lakes that have a lower salinity gradient.
- While detailed filling strategies are premature at this stage, the hydrodynamic model may be used in the future to determine the best timing and water source for

filling the pits. Specifically, it may be preferable to pump water from the WMP during spring and fall, when water temperature is close to 4 °C and at its highest density. Additionally, a fresh water cap can be placed during the ice-cover period, so that turbulence caused by pumping does not disturb pycnocline stability. These options could be evaluated using a more detailed model prior to filling.

Vertical Slice Model

While the two-dimensional hydrodynamic model was used to evaluate mixing over the next hundred years, the stability of the pycnocline over the very long term (i.e. millennia) required a simpler tool with shorter run times. Therefore, a spreadsheet, mass-balance vertical slice model was developed to predict TDS concentrations in the pit lakes, at 1-m intervals, over the next 15,000 years.

Initial conditions of each 1-m interval were set equal to the volume and mass of each layer at the 100-year, post-closure concentration predicted by the hydrodynamic model. Aside from initial conditions, the only inputs to the vertical slice model were the lateral inflow volume and TDS concentration and outflow volume at each layer predicted by the FEFLOW groundwater model. Given that the net groundwater flow was into the pit lake, water was expressed upward into overlying 1-m layers and mass was transported advectively. At annual time steps, the model calculated a new mass and volume in each layer and expressed surplus volume and associated mass upward to the next layer, sequentially from the bottom to the top of the pit lake.

The vertical slice model projected a rising and strengthening stratification in the pit lakes over the long term. Although hydrodynamic simulation indicated very little change in TDS in the monimolimnion in the first hundred years, the vertical slice model indicated that groundwater inflows would begin to change TDS at depth over the first 1000 years. After 15,000 years, the model indicated that the monimolimnion would increase in TDS and expand upwards due to the slight net inflow (Supplemental Figure 7). The deeper pit water will, over the very long-term, take on the depth profile characteristics of the surrounding deep, high TDS groundwater (Supplemental Figure 1).

While the general trend of increased TDS and upward expansion of the pycnocline is likely realistic, 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 the FEFLOW groundwater model. Nevertheless, the key finding may be concluded with some confidence that stratification in the pit lakes will strengthen with time.

Nutrient and Dissolved Oxygen Model

As described in the "Geochemical and Water Quality Model" section, operational and closure water concentrations were projected by a mass-balance model, assuming mixing and advective transport, but no fate or transformation processes. Modelling under these conservative assumptions indicated that potential phosphorus leaching from waste materials would cause excessive increases in phosphorus concentrations in Kennady Lake and downgradient lakes at closure. Initial estimates indicated that phosphorus increases would lead to a change in trophic status and potentially reduced DO concentrations under ice each winter, reducing fish habitat over the long term. Understanding that the initial estimates were based on oversimplified assumptions, a more detailed approach was pursued to refine estimates of trophic status and DO concentration in closure lakes. A three-dimensional GEMSS model was set up with the modified WASP5 water quality module to predict nutrient and DO concentrations at closure.

Because the geochemical tests indicated that phosphorus concentrations would be high in the PK waste leachate, particularly the fine PK, it was anticipated that phosphorus increases would be problematic if unmitigated, regardless of the prediction approach. Therefore, a design engineering study was conducted on waste cover materials to mitigate leachate from the closure landscape. Additional mitigation was implemented that included reducing the footprint of the on-land fine PKC facility, diverting more fine PK to the pit lakes at closure, as well as additional materials testing to reduce uncertainty. The mitigated leachate concentrations were then used as inputs to the refined nutrient model as described below.

Model Setup

A three-dimensional model grid was set up over the closure Kennady Lake with 1-m vertical spacing and 200 m horizontal spacing. In the closure model, pit lakes were included in the grid to a depth of 40 m. Below this depth, the lake was considered to be biologically inactive.

Inputs to the lake were consistent with those described for the geochemical and water quality model, plus meteorological inputs from the Yellowknife Airport and the Snap Lake mine weather stations. The nutrient and DO model differed from the geochemical and water quality model in that it calculated three-dimensional water circulation within the lake, and accounted for nutrient cycling, phytoplankton growth and decay, and DO dynamics. It also accounted for salt rejection during ice formation, as well as pure water return during melting.

The model was configured to output the volume of water that remained above the CCME (1999) DO guideline of

6.5 mg DO/L, which is protective of all native fish at all life stages. Thus, available fish habitat in pre-development conditions could be compared to available habitat under closure conditions.

The model was calibrated to measured field DO and laboratory chemistry data from Kennady Lake collected between 2001 and 2011. However, the dataset presented two challenges to calibration. First, the water quality data were limited and discontinuous, so calibration mainly focused on two distinct periods of 2004 and 2011. Second, much of the nutrient data were near or below analytical detection limits. Thus, the calibration was considered to be approximate because the true values of a large proportion of the measured data were not known. Accordingly, a sensitivity analysis was conducted on the variables and coefficients that had the largest influence on model outputs, so that a range of predictions could be provided for each constituent.

Sensitivity Analysis

The sensitivity analysis included simulations of high and low values for 17 model input variables and coefficients. High and low values were obtained from model manuals for GEMSS, CE-QUAL-W2, and WASP5 where available, and from literature values where ranges were not provided in these manuals. Literature values were selected to represent a reasonable range of constituents from similar systems. Of the 17 inputs, it was determined that sediment oxygen demand (SOD) was by far the most important driver of DO in the closure lakes. SOD is the sum of biological and chemical processes in the sediment that consume oxygen from the water column, including microbial and macrobenthic respiration and oxidation of reduced solids (Matisoff and Neeson 2005). Changes to other inputs did not change the volume of Kennady Lake, which is predicted to remain more than 2 % above a targeted DO threshold. Coefficients such as the carbon to chlorophyll *a* ratio and the maximum phytoplankton growth rate had a significant effect on predicted phosphorus concentrations, but these did not translate to large changes in the volume of lake that remained above the DO threshold.

The chosen SOD value for the base run was −0.375 g $O_2/m^2/d$, which represents the SOD calibrated for the nearby Snap Lake mine (for which a robust dataset is available), using the same model, plus 50 % as a conservative measure. This value is on the high end of literature values for similar systems (Babin and Prepas 1985). Values of −0.25 and −0.50 g $O_2/m^2/d$ were also simulated to estimate a range of outcomes, acknowledging that it is impossible to predict a closure value for such a coefficient before mine construction.

The sensitivity analysis indicated that the volume of Kennady Lake with a DO concentration greater than 6.5 mg/L at all times could range appreciably, with a potential decrease of 36 % to a potential increases of 11 % compared to pre-development conditions. Thus, while the model did not generate a narrow range of predictions for post-validation, the model highlights the importance of gathering site-specific SOD data and managing mine waste to minimize SOD as part of mine closure planning.

Conclusion

There is no set template or universal framework for developing models for assessing aquatic effects of large, complex mining projects. No single model is capable of simulating the multitude of potential effects in groundwater and surface waters over the various spatial and temporal domains of interest. Instead, environmental assessment practitioners must collaborate to integrate specialized models developed from within their discipline into a linked or coupled set of models. Each model may have different data requirements, time-steps, spatial and temporal domains, and output formats. In some cases, feedback loops that exist in nature must be simulated through iterative model simulations. Each of these challenges must be addressed within a coupled model framework to produce meaningful results. While all projects will have site-specific issues and challenges associated with representing project effects, we have presented one such set of integrated models to illustrate a holistic method for assessing water impacts on a major mining project.

Each of the individual models requires a number of inputs and assumptions to simulate physical, geochemical and biological characteristics of the natural and disturbed systems, particularly the reclaimed systems that have yet to be created. All of these inputs and assumptions carry inherent variability and uncertainty, which impose and propagate uncertainty on model predictions. Linking a series of models in time and space adds an additional layer of uncertainty to the predictions. While methods such as Monte Carlo simulations can be used to quantify uncertainty surrounding a single prediction, there is no method that would meaningfully quantify the effects of propagating error through a system of models such as the one described above. Rather, input data and assumptions must be carefully considered and applied in a conservative manner, so that when models are wrong, they are biased towards overprotection.

Models should be not be viewed as sophisticated calculators that produce one value or another, but rather as tools to outline potential environmental risks, and to aid in developing mine planning, mitigation, and monitoring strategies to manage those risks. The absolute value of any single variable predicted by these models will almost certainly prove to be incorrect once post-validation monitoring is available. Instead, the success of the modelling will be measured by whether the models have highlighted the actual risks, and whether they tended to directionally under- or over-predict values of key variables in ways that are protective of the physical and biological environment.

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